Further Development and Acceptability of a Sensor-based Movement Analysis Feedback Toolkit (SMAFT) for Physiotherapy Rehabilitation of People with Knee Pain

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Abstract

Background: Chronic knee pain is a common clinical symptom presented by individuals with musculoskeletal conditions. Chronic knee pain can have several significant physical and functional impacts on individuals, potentially resulting in reduced effectiveness of physiotherapy treatments and a lower quality of life. Limitations in functionality of the knee joint and physical activity may result from the alterations in movement presented in individuals with knee pain when performing everyday functional activities, as suggested by the pain adaptation theory. This theory proposes that unnecessary altered movement patterns can endure long-term, resulting in further pain and functional restrictions. Therefore, physiotherapy rehabilitation designed for individuals with knee pain should consider unnecessary altered movement patterns, by identifying and individualising treatments accordingly. This suggests a need for a portable clinic-based movement analysis system. Inertial measurement sensors could represent a promising movement analysis system within clinical practice, offering feedback about individuals' kinematics and targeting treatment. Moreover, reporting and interpreting the huge volume of kinematic data provided by a three-dimensional (3D) movement analysis system is subjective and varied among its users, which might restrict its clinical access and utility. To eliminate this limitation, standardising the way of interpreting kinematic data designed in a user-friendly format is needed, which can enhance accuracy and consistency among users. Therefore, the aim of this PhD thesis is to further develop and evaluate the acceptability of a sensor-based movement analysis feedback toolkit (SMAFT) for clinical practice using an iterative process.

Methods: This PhD thesis was undertaken in two phases. In the first phase, an exploratory study was conducted to inform the development of SMAFT. The study aimed to create a standardised reporting framework designed to improve clinicians' accuracy and consistency when interpreting the kinematic data provided by a sensor-based movement analysis. Six raters, each with varying levels of experience in musculoskeletal clinical practice and movement analysis, were identified as participants. The raters interpreted 252 kinematic waveform graphs by identifying the presence of the altered movement patterns and describing them in writing. Within- and between-rater agreements were quantified using the observed agreement and Gwet's agreement coefficient, and the qualitative descriptions of the movement alterations were analysed using quantitative content analysis. This study was integrated with other developmental studies conducted by another PhD student to inform the development of a preliminary version of SMAFT.

In the second phase, a mixed-methods case study was implemented to explore the acceptability of SMAFT when used alongside physiotherapy treatment as usual for individuals with knee pain within the physiotherapy clinical practice. The data was collected from multiple sources. Qualitative interviews for SMAFT's users (individuals with knee pain and clinicians) were analysed by employing a thematic analysis. Furthermore, quantitative descriptions of the individuals' pain and function levels, their altered movement patterns identified, and their treatments given by clinicians were conducted.

Results: In Phase one, the average score for the between-raters agreement when identifying the altered movement patterns was substantial (Gwet's AC1 = 0.64) for all kinematic waveform graphs across all the lower limb joints, planes of movement, and functional tasks. The within-rater agreement presented a range from substantial to almost perfect agreement (Gwet's AC1 = 0.70 – 0.99) across all the waveform graphs and over all joints, planes, and tasks. However, the way in which raters described and interpreted the identified movement alterations varied. Thus, a reporting template was created to standardise the process of interpreting the waveform graphs. The findings from this study were combined with other developmental studies to inform the development of a preliminary version of SMAFT that consists of portable inertial sensors, a movement analysis feedback report, avatar videos, and a standardised reporting template. This was used in Phase 2 to explore its acceptability among users within physiotherapy clinical practice.

In phase two, integrating quantitative and qualitative components gave a more comprehensive view of SMAFT's acceptability within clinical practice. The study's findings suggested that the users showed broad acceptability towards the use of SMAFT alongside physiotherapy treatment from the perspective of being beneficial, practical, and usable. However, some challenges regarding its usability and practicality were identified. The findings afforded a clearer understanding of the design and delivery of SMAFT within clinical practice, which requires further refinements and investigations.

Conclusion: The findings from the two phases of this PhD thesis contributed to the development of SMAFT to be used alongside physiotherapy treatment as usual for individuals with knee pain within clinical practice. A refined version of SMAFT was clearly described using the Template for Intervention Description and Replication (TIDier) checklist. Recommendations for the next stage of SMAFT development were also discussed.

Table of Contents

List of tables

List of figures

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Chapter 1. Introduction

This chapter provides an overview and background to this PhD thesis. It begins by setting the scene with regard to chronic knee pain, also detailing its impact on movement and physical function. It then introduces contemporary physiotherapy treatments for managing individuals with knee pain, and explains the importance of movement assessment. After this, feedback and its role in modifying movement patterns are introduced. This is followed by an overview of technology in the form of inertial sensors, which can be used for analysing movement. Next, reporting and interpreting kinematic data provided by 3D movement analysis is introduced. The chapter concludes by setting out the structure of this PhD thesis.

1.1 Chronic knee pain

The human musculoskeletal system contains varied components (joints, muscles, bones, ligaments, tendons, and nerves) that work together to support the body's structure (Dieppe 2013). The phrase 'musculoskeletal condition' is a broad umbrella term used to cover a plethora of aspects that impact the components of the musculoskeletal system (Versus Arthritis 2021b; McCall et al. 2014). The musculoskeletal conditions are common and affect millions of individuals during their lifetimes, ranging from minor injuries to long-term conditions (Versus Arthritis 2021b). In the UK, musculoskeletal conditions are the greatest cause of disability, accounting for close to a third of all years lived with disability (Murray et al. 2013). Annually, a fifth of the population seeks General Practitioner (GP) consultations to address musculoskeletal conditions (Versus Arthritis 2013).

One of the most common symptoms associated with musculoskeletal conditions is pain (Cimas et al. 2018; Versus Arthritis 2021b), and 74% of individuals with a musculoskeletal condition state that they experience pain during their daily activities (Versus Arthritis 2019). Musculoskeletal pain can be experienced and defined based on the body region impacted (e.g., low back pain, neck pain, knee pain, shoulder pain, ankle pain, hand pain, and widespread pain). Musculoskeletal pain can be categorised depending on its duration into three categories: acute (lasts a maximum of 4 weeks), subacute (lasts between 4 and 12 weeks), and chronic (lasts more than 3 months) (Qaseem et al. 2017). In England, 15.5 million (27%) individuals suffer from chronic pain, of whom 80% report that the pain affects the neck, back, and upper and lower extremities and is most commonly attributable to musculoskeletal conditions (Versus Arthritis 2021a). Severe chronic pain affects 10% of individuals with chronic pain, resulting in a loss of ability to conduct daily functional activities (Versus Arthritis 2021a).

The knee is the largest weight-bearing synovial joint in the human body, formed by articulations between the femur and tibia (tibio-femoral joint) and the femur and patella (patellofemoral joint). The knee joint is a common site of musculoskeletal pain resulting from knee injuries (e.g., anterior cruciate ligament injury, torn meniscus, fracture, and bursitis) or changes occurring that affect the tissue (e.g., Osteoarthritis, rheumatoid arthritis) (Versus Arthritis 2013). Chronic knee pain is considered one of the leading causes of musculoskeletal presentations at clinics due to its high level of incidence and prevalence (Keenan et al. 2006; Ingham et al. 2011; Fejer and Ruhe 2012). In the UK, 21.7% of individuals aged 65 to 74 and 26.4% of individuals aged over 75 have reported pain in the knee joint lasting for more than 6 weeks (Keenan et al. 2006). Two of the most prevalent chronic knee conditions are knee Osteoarthritis (OA) and Patellofemoral Pain Syndrome (PFPS). In the UK, 4.71 million individuals aged over 45 years old have sought medical consultations for knee OA over a period of seven years, and this number is expected to have risen to 6.4 million individuals by 2035 (Versus Arthritis 2013). Similarly, the percentage of annual prevalence of the PFPS condition is 22.7% among the general adult population in the UK (Dey et al. 2016). Therefore, in view of the high prevalence of chronic knee pain, a substantial ongoing burden on the individual level and healthcare systems is anticipated.

1.2 Physical impact of chronic knee pain on the individual

Chronic knee pain can have a number of significant physical and functional consequences for individuals (Dunlop et al. 2011; Wallis et al. 2013; Hurley et al. 2015; Glaviano et al. 2017). Quality of life is a multi-factorial concept that is influenced by physiological, psychological, and social wellbeing. Individuals with chronic knee pain describe a significantly lower quality of life compared to healthy controls (Alkan et al. 2014; Mahir et al. 2016; Coburn et al. 2018). This substantial decrease in quality of life relates to pain and limitations on physical function (Dunlop et al. 2011; Wallis et al. 2013; Alkan et al. 2014; Hurley et al. 2015; Mahir et al. 2016; Coburn et al. 2018; Glaviano et al. 2017). Reduced mobility can even result in complete loss of function and disability in individuals with chronic knee pain (Vos et al. 2020). In the UK, OA is considered the 8th ranked leading cause of years lived with disability (YLDs) (Vos et al. 2020). Moreover, one of the potential impacts of chronic knee pain on individuals is that it alters the way they move during the performance of daily activities (Hodges 2011; Hodges and Tucker 2011).

1.3 Altered movement patterns

Pain plays a crucial physiologic role in protecting the body's tissues from any perceived or potential harmful damage caused by stimulating the motor system (Boyer 2018). When a load is imposed upon the knee joint and surrounding tissues, the motor system is designed to adapt in response to pain by altering the mechanical behaviour of the body to minimise further potential injury to the knee tissues (Hodges 2011). Several theories explain the underlying mechanism of motor response behaviours to pain, e.g., Vicious Cycle (Roland 1986), Pain Adaptation theory (Lund et al. 1991), and Motor adaptation to pain theory (Hodges and Tucker 2011). All these theories suggest that due to pain, a range of motor alterations may occur from subtle alterations in muscle activity to movement avoidance (Roland 1986; Lund et al.1991; Hodges and Tucker 2011). Therefore, altered movement patterns could be present in individuals with knee pain, serving as a protective response to pain. As motor adaptations can occur at multiple levels of the nervous system, these altered movement patterns could remain long-term due to reduced movement variability and increased load on the same tissue structures causing further pain and restriction of movement (Hodges 2011; Hodges and Tucker 2011; Merkle et al. 2020). Therefore, it is crucial for clinical rehabilitation to identify the unnecessary altered movement patterns associated with the presence of knee pain to individualise treatment based on them and monitor the individual's progress.

1.4 Physiotherapy treatment for chronic knee pain

Physiotherapy treatment is one of the options that can assist with chronic knee pain. Physiotherapy treatment aims to reduce knee pain and enhance functional capability (Juhl et al. 2014; DeVita et al. 2018; National Institute for Care and Excellence (NICE) 2022). Several treatment interventions have been used in physiotherapy practice to manage individuals with chronic knee pain (e.g., exercise therapy, knee taping, and orthotic devices) (Zhang et al. 2008; Hochberg et al. 2012; Willy et al. 2019). However, successful treatment outcomes using different physiotherapy interventions can be limited in some individuals with knee pain (Ferber et al. 2015; Kobsar et al. 2015). It has been suggested that the limited effectiveness of some treatment interventions in terms of capacity to achieve improvement in pain and physical function, may result from the presence of unnecessary movement alterations during the functional performance (Hodges 2011; Hodges and Tucker 2011; Kobsar et al. 2015; Watari et al. 2016). Several studies have proposed that the altered movement patterns associated with knee pain are considered to be a crucial element influencing varied individuals' responses to exercise therapy (Kobsar et al. 2015; Watari et al. 2016). For example, Kobsar et al. (2015) evaluated the success rate of a 6-week hip strengthening treatment programme based on baseline gait kinematics. The findings revealed that individuals with knee OA that presented an increase in hip adduction during the gait stance phase responded best to the hip strengthening programme (Kobsar et al. 2015). Therefore, physiotherapy treatment can be optimised based on the availability of information about kinematics, as provided by applying the movement analysis method. This could assist physiotherapy clinicians with their clinical decision making, ensuring they choose to employ the optimal treatment intervention.

1.5 Feedback

Movement retraining using feedback is an individualised treatment intervention used to manage movement alterations and consequently develop a new movement pattern (motor learning) (Charlton et al. 2021). Feedback is a key concept in motor learning since retraining with no feedback could increase the use of kinematic alteration during the functional performance (Michaelsen et al. 2006; Cirstea and Levin 2007). Several studies have reported that providing individuals suffering from knee pain with individualised movement feedback about their kinematics during functional activities is effective as a way of modifying and altering movement patterns (Noehren et al. 2011; Willy et al. 2012; Shull et al. 2013a; Shull et al. 2013b; Hunt and Takacs 2014; Hunt et al. 2014; Roper et al. 2016). In addition, the effects of feedback and movement retraining on altering kinematics can be retained over the long term and translate to other unrelated tasks (Noehren et al. 2011; Willy et al. 2012; Shull et al. 2013a). Movement retraining using individualised feedback seems to be effective in permanently modifying movement patterns in individuals with chronic knee pain. This reveals that the individualised feedback provided during retraining sessions plays an important role in motor learning.

Feedback can be provided using various methods in terms of the information provided, delivery timing and frequency, and modes. Therefore, further examination of the multiple feedback methods possible is required to understand their impact on modifying or acquiring movement patterns. This is vital to inform the best type of feedback to apply in clinical practice. Reportedly, visual feedback provided by optoelectronic three-dimensional (3D) motion capture systems has superiority over other methods in terms of changing movement patterns, such as mirrors or videos (Willy et al. 2012; Hunt et al. 2014). However, visual feedback based on an optoelectronic 3D motion capture system is challenging to implement in the context of clinical practice and difficult to be accessible to all individuals who need feedback due to its lack of portability and ease of use (Dingenen et al. 2014; Schurr et al. 2017). This may be because of the specialist motion analysis equipment required, the advanced training needed, and the high associated costs (Schurr et al. 2017). Therefore, a clinic-based, portable, less expensive, and less time-consuming motion analysis method is required for use in providing visual feedback about movement patterns.

1.6 Clinic-based movement analysis

Using a two-dimensional (2D) video analysis may offer a fundamental method to overcome the aforementioned limitations of laboratory-based optoelectronic motion capture systems within clinical practice in terms of portability, training required, and time, and cost-effectiveness (Schurr et al. 2017). However, the 2D method has some limitations. First, its validity in assessing kinematics compared to gold-standard optoelectronic 3D motion capture systems is unclear as a result of conflicting findings (Maykut et al. 2015; Herrington et al. 2017; Schurr et al. 2017; Alahmari et al. 2020; Mousavi et al. 2020; Neal et al. 2020). Second, evaluating complex dynamic movements in the transverse plane is not feasible using a camera-based 2D method. Finally, issues of privacy and obtaining consent for video recordings might limit the use of the 2D method. Therefore, an alternative, using a 3D motion analysis system that can accurately quantify movements in varied planes during dynamic functional activities within the context of clinical practice, is still needed.

1.7 Inertial sensors

Wearable technology such as inertial sensors, also known as inertial measurement units (IMUs), have been utilised to evaluate joint movement objectively across all planes of movement (Aminian 2006; Fong and Chan 2010). Compared to optoelectronic motion capture systems, IMU is cost-effective and smaller in size, which makes it a more promising alternative for use outside of laboratory environments, such as in clinics (Cuesta-Vargas et al. 2010). The advantages of inertial sensors are that they allow for the assessment of movement patterns in large cohorts of individuals within a less controlled environment.

Several studies have examined the validity and reliability of sensor-based movement analyses using healthy populations (Favre et al. 2008; Jakob et al. 2013; Laudanski et al. 2013; Zhang et al. 2013; Palermo et al. 2014; Lebel et al. 2017; Robert-Lachaine et al. 2017; Al-Amri et al. 2018; Karatsidis et al. 2018; Teufl et al. 2018; van der Straaten et al. 2019; Shuai et al. 2021). In general, these studies have demonstrated that sensor-based movement analysis provides the necessary accuracy and consistency for quantifying angular kinematics during a variety of functional activities. However, sensor-based movement analysis generates a massive amount of kinematic data, which may impact users' ability to report and interpret it within the context of clinical practice. Hence, it is unclear whether kinematic data can be reported and interpreted by physiotherapy clinicians in an accurate and consistent way in clinical settings.

1.8 Interpretation of kinematic data provided by 3D movement analysis

The interpretation of 3D kinematic data is subjective and can produce variability that may affect treatment planning and recommendations, and/or suboptimal care, within clinical practice (Skaggs et al. 2000). Although a limited number of previous studies evaluated users' interpretation of the kinematic data provided by 3D movement analysis during gait tasks, some researchers suggested that standardising the means of reporting and interpreting kinematic data may enhance the accuracy and consistency of the interpretation process (Brunnekreef et al. 2005; Nieuwenhuys et al. 2017; Wang et al. 2019). However, this has not been done for evaluating the movements involved in a wide range of functional activities in populations with knee pain. This should therefore be considered when developing a movement analysis feedback toolkit for use in clinical practice.

1.9 What is needed?

The work to date highlights a need for a portable clinic-based movement analysis method to deliver visual feedback information about the kinematics of individuals with knee pain to be integrated into physiotherapy practice. Such a method could further optimise physiotherapy when managing individuals with knee pain by informing the physiotherapy clinician's choices of treatment interventions and individualising treatment plans according to the identification of unnecessary altered movement patterns. In addition, physiotherapy treatment can benefit from feedback information when retraining individuals in order to modify and correct movement alterations associated with knee pain. Furthermore, it is necessary to standardise the process of reporting and interpreting the kinematic data generated by the movement analysis tool among users, to enhance its clinical access and utility in clinical settings. Therefore, developing a toolkit containing inertial body-worn sensors, a feedback report based on movement analysis, and a standardised reporting template is necessary.

1.10 Theoretical framework underpinning this PhD thesis

1.10.1 MRC framework for developing and evaluating complex interventions

The UK Medical Research Council (MRC) has developed a framework for the development and evaluation of complex interventions in healthcare contexts (Skivington et al. 2021). This framework comprises four distinct stages: development, feasibility or piloting, evaluation, and implementation (Figure 1) (Skivington et al. 2021). In brief, the MRC guideline framework recommends that the best available evidence and theories be identified and evaluated and that a series of feasibility studies be conducted, and that any recommended intervention be explored and evaluated.

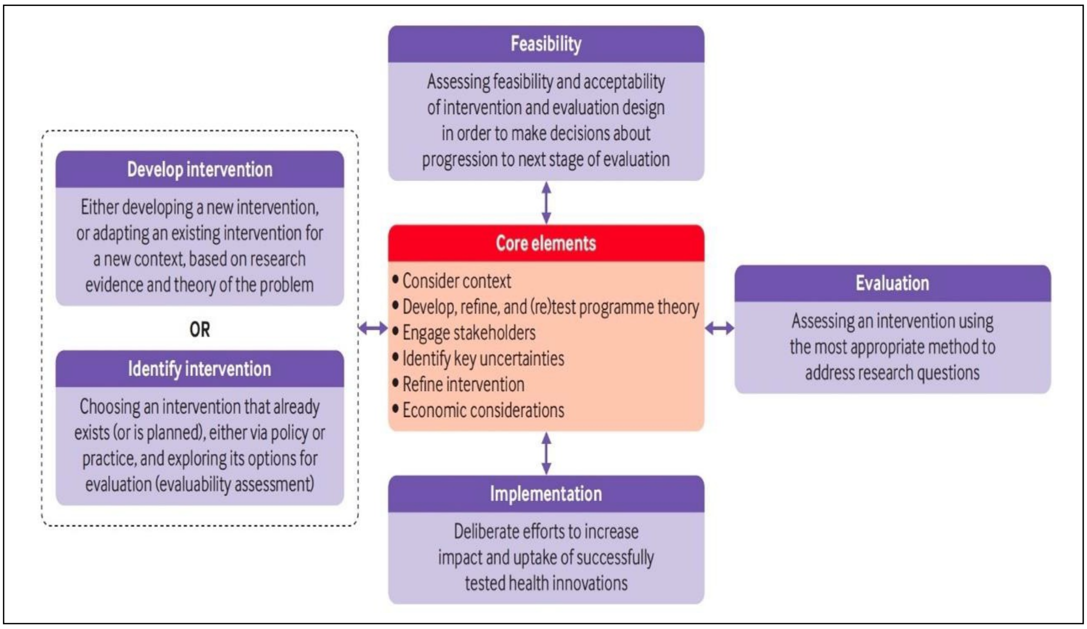


Figure 1: MRC guideline framework stages adapted from Skivington et al. (2021)

This MRC guideline was chosen to inform the development of the sensor-based movement analysis feedback toolkit (SMAFT) due to its systematic approach to the development of a new complex intervention. Furthermore, this guideline can assist in identifying the appropriate methodology for developing a complex intervention. This PhD thesis encompasses the first stage of the framework (development stage) and will inform subsequent stages. Each stage should consider six core elements according to the most recent update of the MRC framework for evaluating complex interventions:

consider context; develop programme theory; engage stakeholders; identify key uncertainties; refine intervention; economic considerations (Skivington et al. 2021). For any complex intervention, all six elements should be used to support the development stage, and to ensure the intervention has reasonable potential to exert a worthwhile effect and impact on defined outcomes (Skivington et al. 2021). The elements recommended in accordance with this thesis are discussed in Table 1.

Table 1: MRC framework elements within the current PhD thesis

MRC framework stages	MRC element	How and where addressed within PhD thesis
Development stage	Consider context	• Exploring acceptability of SMAFT within a real-world context (physiotherapy clinical practice) (Chapter 4)
	Develop, refine, or test programme theory	• The use of the Theoretical Framework for Acceptability (TFA) to guide qualitative exploration of SMAFT's acceptability. This theoretical framework helps to inform the design, content and delivery of SMAFT in clinical practice. (Chapter 4) • The use of the Behaviour Change Wheel (BCW) to investigate whether the use of SMAFT may influence individuals' behaviours (Chapter 4)
	Engage stakeholders	• Involvement of people who are targeted by SMAFT (individuals with knee pain and physiotherapy clinicians) to explore their acceptability of SMAFT in terms of its design, content and delivery (Chapter 4)
	Identify key uncertainties	• Identifying the evidence base for SMAFT through reviewing contemporary literature concerning the value of targeting altered movement patterns associated with chronic knee pain conditions as a treatment approach based on feedback (Chapter 2)

		• Inform the most effective feedback method to use as part of SMAFT by reviewing and discussing varied applications of feedback in terms of modes, timing, and methods (Chapter 2) • Inform the design of SMAFT by reviewing and discussing different clinic-based movement analysis methods (Chapter 2) • Standardising the way of interpreting the kinematics waveform graphs obtained by SMAFT by developing a reporting template (Chapter 3)
	Refine intervention	• A refined version of SMAFT was clearly described using the TIDier checklist (Chapter 4) • Recommendations for the future development of SMAFT are discussed (Chapter 4)
	Economic considerations	• This element is beyond the scope of this PhD thesis and is recommended for the future development of SMAFT

1.11 Thesis aim

The aim of this PhD thesis was to further develop and evaluate the acceptability of a sensor-based movement analysis feedback toolkit (SMAFT) for clinical practice using an iterative process. SMAFT contains a pre-existing kinematic report based on data from inertial sensors combined with a standardised reporting framework, which was created in this PhD (more details about the development of SMAFT will be presented later in chapter 3, section 3.2). Using SMAFT for individuals with knee pain in clinical settings may assist physiotherapy clinicians with their clinical decision making, and in tailoring physiotherapy treatments.

1.12 Thesis structure

This introductory chapter has provided a brief overview and background to set the scene with regard to chronic knee pain, physiotherapy treatment, and kinematic feedback. It has also introduced the technology of inertial sensors, which can be used for assessing movement. This is followed by a discussion of the theoretical framework underpinning this PhD thesis. This chapter concludes by presenting the structure of the thesis.

Next, the literature review chapter (Chapter 2) is a narrative literature review focusing on the altered movement patterns associated with knee pain. It also explores individualised physiotherapy treatment and the role of feedback in motor learning. This is followed by a review of the literature concerning the movement analysis methods used within clinical practice and inertial sensor technology. In addition, reporting and interpreting kinematic data provided by 3D movement analysis methods is discussed. This was designed to identify the evidence base for developing SMAFT and inform its design and content.

This thesis comprises two phases that are presented in Chapters 3 and 4. Phase I (Chapter 3) concerns the development of a standardised reporting template. This was research that was undertaken as part of this PhD. This study was conducted to create a standardised reporting template that can assist clinicians with their reporting and interpretation of kinematic data in an accurate and consistent manner. The study in this chapter comprises its own methods, results, and discussion sections. This standardised reporting template was then combined with a pre-existing kinematic report for sensor data to create a preliminary version of SMAFT that needed to be evaluated within clinical practice.

Phase II (Chapter 4) is a mixed-method case study that evaluated the acceptability of using SMAFT for people with knee pain within the physiotherapy clinical practice of a University Health Board (UHB). The acceptability of SMAFT to users (individuals with knee pain and treating clinicians) was investigated to clearly define and describe the next version of SMAFT and inform any future development of the toolkit in clinical practice.

The final chapter of this thesis (Chapter 5) presents the overall conclusion, explicating the key findings, strengths and limitations, and recommendations for education, clinical practice, and future research.

Chapter 2. Literature review

2.1 Introduction

This chapter first provides an overview and background about the prevalence and incidence of chronic knee pain, its physical impact on individuals, and the relationship between pain and movement. This is followed by a presentation of a narrative literature review focused on the altered movement patterns associated with knee pain during a variety of functional activities. The review then offers an overview of individualised physiotherapy treatment using kinematics assessment feedback, with a focus on feedback and motor learning. Next, a variety of clinical-based movement analysis methods addressing accuracy, consistency, strengths, and limitations is presented and critiqued. Finally, interpretation of the kinematic data provided by 3D movement analysis methods is discussed. This will be based on an extensive systematic search of the literature, and the search strategy is detailed on pages 23 - 26.

These tasks were performed to identify the evidence base for developing SMAFT and guide its design. Based on this review, the rationale behind the reasons for developing SMAFT to be applied in clinical practice will be identified.

2.2 Prevalence and incidence of knee pain

Knee pain is considered one of the leading causes of musculoskeletal presentations at clinics. However, accurate estimates of the epidemiology of knee pain as a general symptomatic presentation vary across studies, reflecting differences in the categorisation of the causes and definitions of pain (Rothermich et al. 2015). A systematic review aimed at assessing the prevalence of estimates of unspecified musculoskeletal chronic knee pain in the elderly population (60+ years) using varied self-reporting outcome measures, reported estimates ranging from 6% to 63.4% (Fejer and Ruhe 2012). This significant variation in prevalence estimates was suggested to result from the varied knee pain definitions used across studies (Fejer and Ruhe 2012). Specifically, in the UK, two studies assessed prevalence estimates for knee pain in the elderly population within varied communities (Croft et al. 2005; Keenan et al. 2006).

Knee pain was defined differently across studies based on its period of duration (Croft et al. 2005; Keenan et al. 2006). Keenan et al. (2006) defined knee pain as swelling, pain, or stiffness in the knee joint that lasted for more than six weeks during the last three months, and reported prevalence estimates of 21.7% for individuals in age ranges from 65 to 74, and 26.4% for individuals over 75 years old. In contrast, the prevalence rate of knee joint pain, which lasted for more than one day only during a period of one month, was reported to be 63.4% for individuals aged 65-74 and 60.4% for individuals aged over 75 years old (Croft et al. 2005).

In terms of incidence, according to a UK study by Ingham et al. (2011, p. 848), the annual incidence of knee pain defined, as "pain around the knee for most days for at least a month," was 32 per 1000 person-years (3.2% per year) in people aged over 40 years old. In a three-year study conducted in the United Kingdom by Jinks et al. (2008), the incidence rate of severe knee pain, defined as the prevalence of significant pain or physical functioning limitations on the Western Ontario and McMasters Universities Osteoarthritis Index (WOMAC) in adults over the age of 50, was 7%. An even greater number of individuals may present with knee pain, either in isolation or in association with other musculoskeletal pain conditions, based on population-level data indicating that up to 10% of the population experience chronic knee pain and lower limb pain resulting in disability (Kusnezov et al. 2016). Indeed, evidence suggests that such epidemiological studies may underestimate the true burden of knee pain at the population level, due to the significant burden of illness in individuals who do not present to professionals, including those who manage independently with analgesia (Pal et al. 2016).

Although common in nature, the epidemiology of knee pain varies in relation to the underlying causes of pain and the pathology present in each individual (O’Neill et al. 2018). Osteoarthritis (OA) and Patellofemoral pain syndrome (PFPS) are two of the most prevalent knee disorders, resulting in pain and symptoms. The estimation of the annual incidence rate for the adult population (age between 55–64 years) with symptomatic knee OA ranged from 0.37% to 1.02%, based on gender and obesity (Losina et al. 2013). According to Versus Arthritis (2013), roughly 4.71 million individuals aged over 45 years old in the United Kingdom have sought a medical consultation for knee OA based on the prevalence of 7-year general practice consultations, and the number is estimated to reach 6.4 million individuals by 2035. Moreover, a meta-analysis conducted by Pereira et al. (2011) stated that the overall prevalence rate for symptomatic knee OA for a pooled prevalence estimation ranges from 5.4% to 24.2% (Pereira et al. 2011). Two of the most common risk factors for developing OA are age and obesity (Versus Arthritis 2013; Wluka et al. 2013), and UK national data indicates that the population is increasing in terms of both age and obesity levels (Butland et al. 2007; Arber 2013). Consequently, the number of individuals with knee OA is expected to rise considerably in the future. Considering both these factors, it has been suggested, based on this estimation, that the number of individuals seeking treatment for knee OA could increase to 8.3 million in 2035 (Versus Arthritis 2013).

PFPS is another prevalent knee pain condition. The rate of new cases of PFPS in adult female novice runners was 16/77 cases over a period of 10 weeks (~20%) (Thijs et al. 2011). Among adolescent populations, two studies conducted by Myer et al. (2010) and Herbst et al. (2015) in the USA reported incidence measured by percentage to be 9.7% and 14.9% during a single athletic season, respectively. In the UK, a study conducted by Dey et al. (2016) demonstrated that the annual prevalence of PFPS is 22.7% among the general adult population. In addition, a systematic review and meta-analysis conducted by Smith et al. (2018) reported that the prevalence of PFPS in the general adolescent population (mixed gender) was 7.2% based on a pooled estimation (95% confidence interval 6.2%- 8.3%) and 22.7% in female adolescents (95% confidence interval 17.4%-28%). The prevalence rate for PFPS has been found to be higher in females than males (Dey et al. 2016; Molgaard et al. 2011). A prevalence percentage of 29.2% for the adult female UK population presenting with PFPS over a period of one year, can be contrasted with 15.5% in the male population (Dey et al. 2016). Similarly, Molgaard et al. (2011) determined that more than two-thirds of PFPS cases among adolescents occurred in females (69% of whom were females and 31% males).

The burden and costs associated with chronic knee pain affecting healthcare systems are substantial. The lifetime cumulative percentage reports that knee pain accounted for about 13% of all adults visiting their general practitioner (GP), and 6.8% of referrals to secondary care (Webb et al. 2004). According to estimates in 2015, approximately 200 million individuals worldwide suffer from knee OA, which has increased by a third over the last decade (Vos et al. 2016). OA represents a substantial burden upon the National Health Service (NHS) in the UK and was responsible for 3 million GP consultations and 115,000 admissions to hospitals in 2000 (Webb et al. 2004). In the US, the estimated average lifetime costs for people with knee pain were $140,300, with direct medical costs associated with pharmacological or nonpharmacological treatment, surgeries, and hospital resources and treatment of OA complications equating to $129,600 (Losina et al. 2015).

In conclusion, chronic knee pain caused specifically by OA and PFPS pathologies has a high level of prevalence, which may burden healthcare systems and incur considerable costs. Therefore, understanding knee pain including its impacts and consequences on physical function is crucial.

2.3 Physical impact of chronic knee pain on the individual

Chronic knee pain is associated with reduced physical activity levels (Dunlop et al. 2011; Wallis et al. 2013; Hurley et al. 2015; Glaviano et al. 2017). A systematic review and meta-analysis reported that only a small to moderate proportion of individuals with knee OA achieved the level of physical activity recommended by the current guidelines (Wallis et al. 2013). Moreover, only 13% of individuals (95% CI = 7-20) achieved the recommended ≥150 minutes per week of moderate to intense physical activity, and only 19% of those individuals (95% CI = 8-33) achieved the daily steps recommended (≥ 10,000 steps). These results reflected those of cross-sectional studies that used accelerometers to assess the physical activity levels in individuals with knee OA (Dunlop et al. 2011; Hurley et al. 2015). In their study, Hurley et al. (2015) compared the number of steps taken per day by individuals with knee OA, and by healthy controls, and found that there was a statistically significant difference between the two groups

($p < 0.001$). The typical daily step counts were lower for individuals with knee OA than those of the healthy controls. Also, Dunlop et al. (2011) reported that only 13% of the males and 8% of the females in a sample of 1,111 individuals with symptomatic knee OA were sufficiently active to follow the recommended physical activity criteria, namely ≥150 minutes of moderate to vigorous physical activity per week.

From a PFPS perspective, Glaviano et al. (2017) compared the physical activity levels of 20 individuals with PFPS and 20 healthy controls, using a Fitbit monitoring device that measured the number of steps, and duration of mild, moderate, and intense physical activity per day. The results demonstrated that the individuals with PFPS took fewer daily steps ($p = 0.004$) and performed fewer minutes of mild and vigorous physical activity per day ($p = 0.007$ and 0.012, respectively) than the healthy controls. Specifically, the individuals with PFPS completed less mild and vigorous activity per day by 40 and 10 minutes, respectively, compared with the controls, and only 20% of these individuals met the physical activity guideline of ≥ 10,000 steps per day. Moreover, in the PFPS group, the individuals with more pain were found to undertake fewer daily steps, with a strong and significant correlation identified between the daily step rate and two subjective questionnaires, the Anterior Knee Pain Scale (AKPS) and the worst pain in the last week (WVAS).

A reduction in physical activity is therefore the main characteristic of individuals with chronic knee pain (Dunlop et al. 2011; Wallis et al. 2013; Hurley et al. 2015; Glaviano et al. 2017). Over time, individuals with knee pain may gradually lose their ability to perform their primary daily functional activities (Vos et al. 2020). Reduced mobility can even cause a complete loss of function and subsequent disability in these individuals (Vos et al. 2020). In the UK, OA is ranked the 8^{th} leading cause of years lived with disability (YLDs) (Vos et al. 2020). This can lower the quality of life of the individuals affected significantly, and increase their mortality rate (Alkan et al. 2014; Mahir et al. 2016; Coburn et al. 2018).

Improving the physical activity of individuals with knee pain is therefore a crucial component of physiotherapy treatment that can improve its effectiveness (NICE 2022).

According to NICE, exercise and physical activity are the most effective treatment recommendations for individuals with musculoskeletal pain, as it can reduce pain and improve physical function (Kraus et al. 2019; NICE 2022). In order to enhance physical activity, there is a need to understand knee pain, including its mechanisms and the consequences for movement, and the key factors that can cause a reduction in the level of physical activity and functional capability in individuals with chronic knee pain. The next section considers the association between pain, motor adaptations, and physical activity within the clinical context of physiotherapy care.

2.4 Pain and movement relationship

Pain plays a crucial physiologic role in protecting the body's tissues from any perceived or potentially harmful damage when stimulating the motor system (Boyer 2018). Nociceptive afferents located within the knee joint and surrounding tissues, such as the joint capsule, ligaments, menisci, subchondral bone, and cartilage, send signals to the central nervous system when any threat of damage is identified (Hunter et al. 2008). The result is that the motor system is expected to adapt by altering the mechanical behaviour of the body to remove noxious stimuli, thereby reducing any further potential injury to the knee's tissues (Hodges 2011). Understanding the relationship between pain and motor response may therefore assist in explaining the underlying mechanisms of motor adaptations to pain experienced within the knee joint and its impact on the functionality of the joint. To date, various theories have been proposed to explain the link between pain and common motor adaptations (Roland 1986; Lund et al. 1991; Hodges and Tucker 2011).

The first theory is the Vicious Cycle Theory, proposed by Roland (1986). It suggests that as a result of pain, all muscles (agonist and antagonist) will sustainably increase their activity, which will, in turn, produce more pain and dysfunction due to muscle spasms and fatigue. Limited experimental and clinical pain studies have supported this theory, demonstrating a subtle increase in muscle activity of jaw muscles associated with jaw pain (Peck et al. 2008). Several examples have criticised the current theory, which indicates that reduced muscle activity is present in relation to pain (Zedka et al. 1999;

Falla et al. 2007). For instance, Falla et al. (2007) investigated the impact of experimentally induced neck muscle pain on neck muscle activity. The result exhibited a consistent decrease in the agonist muscles during flexion and extension movements in the neck (Falla et al. 2007). Therefore, this may indicate that agonist and antagonist muscles do not necessarily increase their activities as a response to pain.

Contrary to the Vicious Cycle theory, the Pain Adaptation theory suggests that the muscles primarily responsible for a painful movement (agonists) inhibit activity, while the activity of the muscles that restrict the painful movement (antagonists) increases sustainably (Lund et al. 1991). It has been proposed that the changes in muscle activity caused by pain could restrict movement (reduce force, amplitude, velocity, and displacement), consequently avoiding further tissue damage and improving healing (Lund et al. 1991). Several clinical pain studies have noted that in Pain Adaptation Theory, pain leads to restricted movement when compared to pain-free controls (Svensson and Graven-Nielsen 2001; van Dieën et al. 2003; Moseley and Hodges 2005). However, there is controversy across clinical pain studies in terms of the recruitment of the agonist and antagonist muscles in response to pain.

For example, it was reported in several clinical pain studies that pain resulted in inhibition of muscle activity in the agonist's muscles during voluntary jaw movements (Svensson et al. 1996), trunk movements (Zedka et al. 1999), and neck movements (Falla et al. 2007), which supported the predictions associated with the theory. Similarly, increased facilitation of antagonist muscle activity has been observed to result from pain during dynamic movements of the jaw (Stohler et al. 1988; Mongini et al. 1989; Lund et al. 1991) and leg (Graven-Nielsen et al. 1997). Meanwhile, alterations have been detected in muscle activity among both muscle groups (agonist and antagonist) resulting from low back pain (van Dieën et al. 2003) and jaw pain (Murray and Peck 2007). Thus, Hodges et al. (2006) proposed that pain arising during voluntary movements is associated with a redistribution of muscle activation among multiple agonist and antagonist muscles according to each individual problem rather than the stereotypically predicted activation of a particular muscle group.

Hodges and Tucker (2011) suggested a new inclusive motor adaptation to pain theory, which progressed from the two previous theories. The mechanism for the motor response, based on the new theory of adaptation to pain, is shown in Figure 2. The theory posits that a wide range of motor behaviour adaptations may be produced, due to induced pain, or to the threat of tissue injury. Such adaptations can range from a minor redistribution of muscle activation within a single muscle, or among multiple muscles, to altering body movement within single or multiple joints, or even restricting movement completely (Hodges and Tucker 2011). Arguably, these motor behaviour changes might result in modifications to movement patterns that can be advantageous over a short-term period when protecting the body tissue affected, improving the healing process (Hodges and Tucker 2011). However, these same alterations in motor behaviour, despite their short-term protective benefits, may have negative long-term consequences reducing physical function and risking further pain (Hodges and Tucker 2011; Merkle et al. 2020). This is due to reduced movement variability and increased load on the same tissue structures (Hodges and Tucker 2011; Merkle et al. 2020).

For example, an ankle sprain is associated with reduced dorsiflexion movement to splint the joint and reduce the load on the painful structures (Friel et al. 2006) by redistributing the load on other structures at the proximal joints (Davis and Seol 2005). Although this can theoretically be advantageous for reducing pain over a short period of time by unloading the painful structures, increasing the load on the proximal joint structures with each repetition might lead to tissue irritation and further pain. Over a long period of time, the level of physical activity can be reduced significantly, and further pain can develop.

The theory was validated by an empirical study, which reported that back pain causes increased spinal stability as a protective motor adaptation behaviour ($P < 0.017$) that was associated with inconsistent non-stereotypical muscle activity patterns across the study's participants (Hodges et al. 2013). The variability in muscle activation and movement patterns in response to pain suggests an individualised, specific response in the form of motor adaptation behaviours.

Motor adaptation theory proposes that the individual variability in motor adaptations may be explained by the biopsychosocial influences that can potentially affect neuromuscular responses within the nervous system on multiple levels (Hodges and Tucker 2011; Merkle et al. 2020). Specifically, adaptations are not explained by simple changes in the excitability and organisation of the motor cortex, rather they involve more complex changes in the planning and coordination of motor responses, namely the modification of the distribution of load throughout the painful structure. Accordingly, chronic pain conditions are influenced heavily by central mechanisms (higher level of the nervous system) rather than peripheral ones (Hodges and Tucker 2011; Merkle et al. 2020). Thus, with chronic conditions (similar to the conditions of interest for the current thesis), unresolved alterations may be sustained over a long period of time, even when the pain is resolved and tissue healing occurs, becoming unnecessary (dysfunctional) (MacDonald et al. 2009; Hodges and Tucker 2011). The persistence of unnecessary movement alterations can also result in suboptimal tissue loading, causing a significant reduction in functional level over time, as well as further pain and damage.

This motor adaptation to pain theory may have crucial rehabilitative implications. As movement alterations can occur at multiple levels of the nervous system, treating pain alone using pharmaceutical pain therapies is insufficient to ensure improvement, particularly in the case of chronic musculoskeletal conditions, when pain mechanisms are considered central rather than peripheral (Hodges and Tucker 2011; Merkle et al. 2020). Therefore, physiotherapy clinicians need to identify unnecessary movement alterations produced (cause) and establish an individualised treatment plan, when treating individuals with chronic musculoskeletal conditions, so as to restore motor control (Hodges 2011). In addition, treatment interventions directed towards the higher level of the motor system, which is responsible for planning and coordinating motor responses, may be needed (Hodges and Tucker 2011). Treatment interventions, such as movement retraining using individualised feedback to enhance the process of motor learning to acquire a new movement pattern (Noehren et al. 2011; Willy et al. 2012; Roper et al. 2016) could be key here. These would be crucial to improve the level of physical function (effect) according to recommendations to optimise physiotherapy treatments for populations with knee pain, as discussed previously in section 2.3. To achieve this, access to an objective portable movement analysis within clinical practice is needed. Thus, it is vital to understand the common unnecessary altered movement patterns associated with chronic knee pain conditions, as presented below.

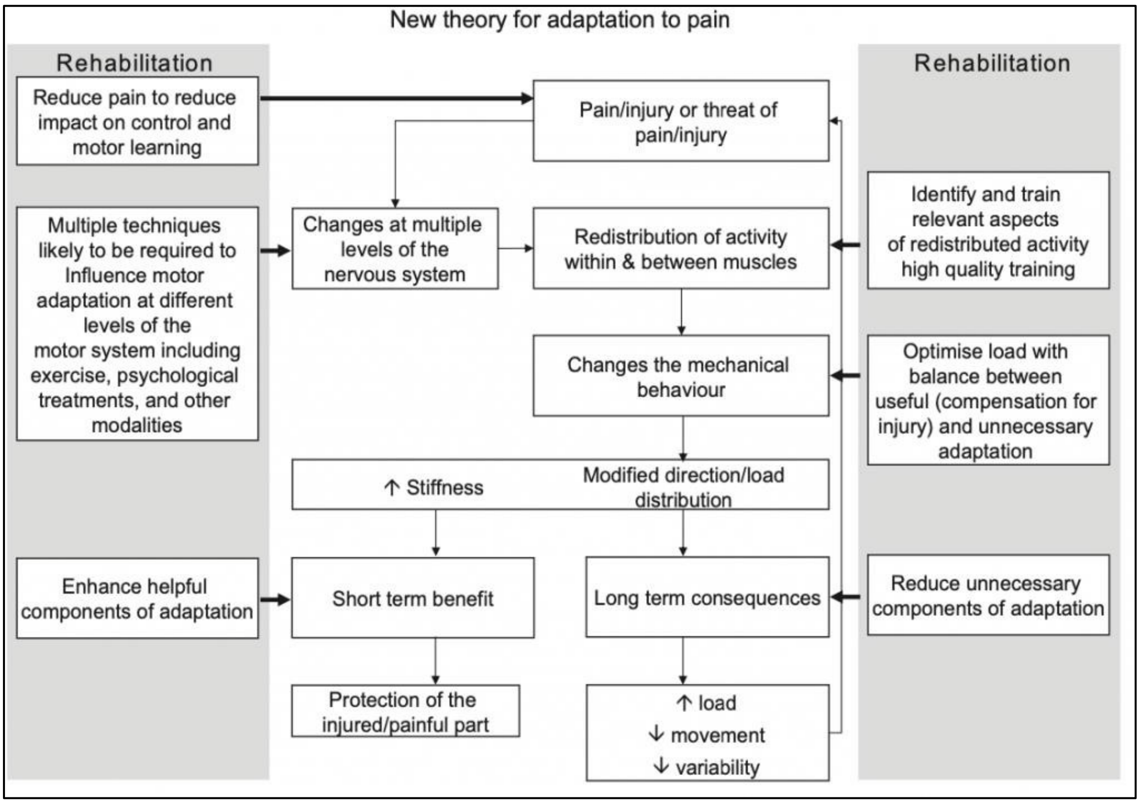


Figure 2: The mechanism of motor adaptation to pain based on the new theory of adaptation to pain adapted from Hodges (2011)

2.5 Search strategy

A search strategy was developed to investigate the literature surrounding the altered movement patterns associated with knee pain, as well as the use of feedback for the purpose of modifying these movement alterations and the clinical movement analysis methods used to provide feedback. Key online databases were introduced to facilitate the search process, including the National Library of Medicine Database (MEDLINE), the Cumulative Index of Nursing and Allied Health Literature (CINAHL), and the Physiotherapy Evidence Database (PEDro). The search strategy was informed by the selection of key terms related to the topic of knee pain in biomechanics contexts, as shown in Table 2. The relevant search terms were combined using Boolean operators to maximise the efficiency of the search, with the operator 'OR' used within categories and the operator 'AND' used to combine search terms (Aveyard 2014). The search was limited to a time frame from 2000 to the present. This period was selected because little relevant data was available concerning the movement analysis method provided by portable wearable technology prior to this date.

Inclusion and exclusion criteria were also identified to refine the search process and ensure only the most relevant studies were included in the review. These criteria were selected to guarantee a relevant data set would be available for analysis. Only English language publications were included to avoid the time and costs associated with translation. Full-text versions of articles were necessary to ensure the full data set and method for the individual studies could be evaluated (Jesson et al. 2011). The population of interest was human subjects aged 18 years or older. The search was limited to the following functional activities, which were included in relation to kinematics assessment: gait, squat, jump, and stair ascent and descent. These functional activities are common everyday functional activities (Dobson et al. 2013; Willy et al. 2019). Also, they represent the standard functional activities evaluated in a physiotherapy clinical context as assessment tests, which are related to individuals' function and performance (Dobson et al. 2013; Willy et al. 2019) (justifications for the use of functional activities are presented later in the current chapter, section 2.6.1). Individuals with traumatic sports injuries, rheumatological disorders, and post-knee surgery were excluded, as these conditions may vary in nature and are not necessarily representative of chronic knee pain. The inclusion and exclusion criteria were as follows:

<u>Inclusion criteria</u>

- English language
- Individuals with knee pain on the most days of at least 3 months
- Kinematics assessment during the functional activities of gait, squat, jump, and stair ascent and descent
- Kinematic outcome measures

Exclusion criteria

- Non-English articles
- Non-full text versions of studies
- Non-human studies
- Knee pain due to sports injuries, rheumatoid disorders, and knee surgeries
- Adolescents and children under 18 years old

The search and refinement process applied to the studies identified in the search strategy is presented in the PRISMA flow diagram. An example of the PRISMA flow diagram used for refining studies, as provided under the search strategy for feedback and altered movement patterns, is presented in Appendix A. A narrative synthesis method was used to combine the findings and inform a critical discussion of the evidence base. This narrative approach allows for a combination of diverse data sets based on the identification of recurrent themes (Aveyard 2014). The search findings are presented across the following sections of the literature review: altered movement patterns associated with knee pain; individualised physiotherapy treatment interventions based on movement assessment; clinical movement analysis; wearable inertial sensor technology; and interpretation of kinematic data provided by 3D movement analysis.

Table 2: Search terms included for literature searches

	Search strategies		
	Altered movement patterns associated with knee pain	**Feedback and altered movement patterns**	**Clinical movement analysis**
Keywords	(Chronic knee pain OR Knee Osteoarthritis OR Patellofemoral pain syndrome) **AND** (Kinematics OR Movement OR Joint angles OR Range of motion) **AND** (Gait OR Walk OR Squat OR Jump OR Stair ascent OR Stair descent) **AND** (Movement analysis OR Motion capture OR Three-dimensional OR Inertial sensors OR IMU)	(Chronic knee pain OR Knee osteoarthritis OR Patellofemoral pain syndrome) **AND** (Direct OR Indirect OR Visual feedback OR Haptic feedback OR Biomechanical feedback OR Biofeedback) **AND** (Retraining OR Modification OR Alteration) **AND** (Kinematics OR Movements OR Kinetics OR Knee forces OR Knee moments OR Inertial sensors OR IMU)	(IMU OR Inertial measurement unit OR Sensor OR Accelerometer OR Wearable technology OR Two dimensional OR Video Camera) **AND** (Accuracy OR Validity OR Consistency OR Reliability OR Interpretation OR Description) **AND** (Kinematics OR Movement OR Joint angles OR Range of motion) **AND** (Gait OR Walk OR Squat OR Jump OR Stair ascent OR Stair descent)
Total number of references	290	316	241

Abbreviations: IMU = Inertial Measurement unit

2.6 Altered movement patterns associated with knee pain

Based on the aforementioned theories concerning motor adaptation to pain, as discussed in this chapter, alterations in motor behaviours involving movement patterns may arise as a protective response to pain, and potentially persist for long periods causing further pain and reduced physical function. Identifying any unnecessary altered movement patterns associated with knee pain may help with the rehabilitation process, by reducing load and enhancing joint movement and function (Hodges and Tucker 2011). Therefore, reviewing the literature concerning movement alterations presented in individuals with knee pain during functional activities is needed.

Numerous previous studies analysed functional activities when attempting to identify the form of altered movement patterns adopted by individuals with knee pain (Bolink et al. 2012; Nakagawa et al. 2012; Ismailidis et al. 2020; van der Straaten et al. 2020). Kinematic variables have been assessed by applying different movement analysis methods, such as optoelectronic 3D motion capture systems, sensor-based 3D movement analysis, and the camera-based 2D method. Only studies investigating kinematics using a movement analysis method based on portable wearable sensors were included. This was to meet the main aim of this research, which is to develop a clinical sensor-based movement analysis toolkit that is portable to be used outside a controlled laboratory environment.

2.6.1 Justification for functional activities used to assess altered movement patterns

Reportedly, individuals with chronic knee pain experience difficulties performing a range of functional activities related to daily life (ADL) (Dobson et al. 2013; Willy et al. 2019). Therefore, it is usually recommended that patients attend routine clinical settings where knee rehabilitation and lower extremity injuries are managed, to complete performance tests involving multiple activities that share similarities with daily activities and sports (Dobson et al. 2013; Button et al. 2014; Willy et al. 2019). A systematic review, evaluating the most commonly used clinical tests for assessing individuals with PFPS, reported that functional activities that involve weight-bearing stress on the patellofemoral joint (PFJ) are the best clinical diagnostic tests (Papadopoulos et al. 2015). Including tests to evaluate commonplace functional everyday tasks as the basis of physiotherapy clinical assessment and treatment for individuals with knee pain, is thus indicated.

Established guidelines and protocols for examining chronic knee conditions were reviewed, to identify recommendations regarding the use of the functional tasks in clinical practice. According to the Osteoarthritis Research Society International (OARSI) guidelines, a series of performance-based physical function tests that represent testing typical activities relevant to individuals diagnosed with knee OA, was recommended (Dobson et al. 2013). These functional tests are recommended as prospective outcome measures for future OA research as well as to aid therapeutic decision making as a complement to patient-reported measures. Moreover, the authors recommended the inclusion of a minimal core set of functional tests when evaluating this population walking, sit-to-stand (which is similar to squatting), and stair negotiation. Similarly, clinical practice guidelines designed for describing evidence-based physiotherapy practice for PFPS disorder strongly recommended using the performance of functional activities that load the PFJ with various knee flexion angles, such as squatting, and stair ascending or descending, as assessment tests (Willy et al. 2019). Also, it has been recommended to use jumping as a clinical assessment test to identify PFPS risk and evaluate the progress of an individual's treatment at various stages of their rehabilitation (Manske and Davies 2016). Although jumping is not a commonplace daily activity among individuals with chronic knee pain, it is an activity that requires more dynamic movement and faster execution speeds, and is important for young adults and those wishing to participate in sports activities (Witvrouw et al. 2000; Manske and Davies 2016; Cleather et al. 2013).

Accordingly, the following activities, namely walking (gait), double leg squat (DLS), single leg squat (SLS), vertical jump (VJ), stair ascent (SA), and stair descent (SD), were selected for this thesis. The selection of functional activities was determined by our research group, and supported by the fact that all of these activities were proven to be valid and reliable when assessed via sensor-based 3D movement analysis systems (as presented later in the current chapter, in sections 2.91 and 2.9.2). A comprehensive choice of activities involving a wide range of tasks that pose a distinct challenge to the knee for individuals with chronic knee pain, was deemed appropriate when considering the different age groups that may be affected by the condition (chronic knee pain) depending on their pain tolerance.

The remainder of this section discusses the evidence presented in the extant literature concerning the kinematic alterations associated with knee pain that arise when performing functional activities, such as gait, squats (single or double leg), jumps, and stair ascent or descent.

2.6.2 Gait kinematic alterations

Altered angular kinematics in people with knee pain, which can be collected using wearable sensors during the performance of walking tasks have been investigated in several studies, as summarised in Table 3 (Bolink et al. 2012; McCarthy et al. 2013; Rahman et al. 2015; Tadano et al. 2016; Ismailidis et al. 2020; van der Straaten et al. 2020; Ismailidis et al. 2021). These studies included samples of individuals with knee OA and used an observational study design to compare kinematic alterations with healthy controls. Only three studies have assessed angular kinematics measured at all the lower limb joints (hip, knee, and ankle) (Ismailidis et al. 2020; van der Straaten et al. 2020; Ismailidis et al. 2021) while other studies investigated knee joint kinematics only. Several kinematic alterations in individuals with knee OA at different lower limb joints and planes of movement have been identified at varied time points along the entire gait cycle (Table 3).

Recently, two studies (conducted by Ismailidis et al. (2020) and van der Straaten et al. (2020)) assessed altered movement patterns in individuals with knee OA and healthy controls, employing the Statistical Parametric Mapping (SPM). This method supports the investigation of variations between compared continuous kinematics during the entire movement cycle using waveforms (Nüesch et al. 2017). During a self-selected walking speed task, both studies found knee flexion ROM for individuals with knee OA was reduced significantly during the mid stance and early swing phases when compared with controls (Ismailidis et al. 2020; van der Straaten et al. 2020). At the hip joint, angular kinematics for individuals with OA exhibited significantly reduced extension during the stance phase in comparison to controls (Ismailidis et al. 2020). Distally, individuals with OA exhibited significantly increased ankle dorsiflexion and reduced plantarflexion during the stance and early swing phases (Ismailidis et al. 2020). In addition, significantly reduced trunk rotation was noted throughout the whole gait cycle, as was reduced pelvic internal rotation from the mid stance to the mid swing phase (van der Straaten et al. 2020).

Although both studies involved a homogenous population sample of knee OA (severe OA as all patients were scheduled for total knee replacement surgery), the OA sample was varied in terms of the compartments affected (medial, lateral, and tricompartmental). van der Straaten (2020) included a mixed affected compartment OA sample; however, it is unclear according to Ismailidis et al. (2020), which compartment was affected in the OA cohort. Medial compartment OA (medial joint loss) has been found to correlate with varus alignment, while lateral OA (lateral joint loss) is associated with valgus alignment (Sharma et al. 2001). Therefore, variations in alignment could modify the load and forces applied to the knee joint, and consequently, various altered movement patterns may be present.

The finding of reduced flexion at the knee joint during the stance and swing phases in previous studies is broadly consistent with the findings of studies that assessed discrete joint angles rather than the entire movement cycle (McCarthy et al. 2013; Rahman et al. 2015; Ismailidis et al. 2021). Conversely, Tadano et al. (2016) found no significant difference between the knee flexion angles during stance and swing phases for small groups of OA and healthy controls (10 vs 8 respectively), although they did detect significantly reduced ankle abduction during the stance phase. The findings produced by this study might be influenced by the unjustifiably small sample size, which was not determined based on a power calculation. This may lead to potential for Type II errors (false negative), whereby no statistically significant result is achieved despite the potential for one (Banerjee et al. 2009). Thus, including a large sample may have yielded different results. In addition, the two groups involved were heterogenous in terms of individual characteristics, such as age, height, and weight. Individuals with knee OA were much older (68.7 vs 22.9 years), lighter (54.2 vs 69.1 kgs) and shorter (1.52 vs 1.74 meters) than healthy free controls. In addition, the individuals with knee OA included in the cohort had mixed OA severity (ranged from mild to severe). It has been reported that differences in knee joint loading can be observed as the disease progresses (Mündermann et al. 2005; Thorp et al. 2006) and may be associated with changes in kinematics (Chang et al. 2007). Thus, the variations between individuals within and between groups may influence the study's results.

In line with the new pain adaptation theory previously discussed, reducing flexion at the knee joint during the initial stance phase of gait (weight acceptance) could be a movement alteration present in individuals with knee OA that is performed to unload the affected knee or reduce pain through increasing the thigh and leg muscle co-activation (Childs et al. 2004). Nevertheless, the combined alterations in kinematics and muscle activation may result in knee stiffening, which could in turn increase the compressive load and reduce the femoral contact area where force is applied (Childs et al. 2004). This motor adaptation is performed to reduce pain and stabilise the joint.

A significant correlation between reduced knee flexion ROM presented by knee OA individuals during the swing phase of the gait cycle, with the pain subscale for a knee injury and Osteoarthritis Outcome Score (KOOS) (rho = 0.54, P = 0.02) has been reported (van der Straaten et al. 2020). However, sustaining such alterations over a long period could result in additional pain and lead to the development of the disease (Childs et al. 2004). This might result from stiffness in the knee joint as well as reduced movement. Therefore, rehabilitation is required to target any unnecessary alterations, based on a robust movement analysis assessment.

In summary, studies using wearable sensors to investigate movement patterns have identified several kinematic alterations to the different lower limb joints in individuals with knee pain, specifically in people with OA. A common movement alteration observed across the studies was the stiffening of the knee (smaller knee flexion angle) during gait performance. Therefore, physiotherapy treatment needs to be directed based on the altered movement patterns identified. For example, strengthening exercises targeting the quadriceps muscles responsible for controlling knee flexion movement could be conducted to address reduced knee flexion if identified from a particular individual's movement pattern. Alternatively, movement feedback and education may help a person increase the range of knee flexion during walking. To achieve this, access to a portable movement analysis tool within clinics is needed.

Table 3: Summary of studies investigating kinematic variables in individuals with knee pain using a sensor-based movement analysis method during the performance of varied functional activity tasks

Study Authors	Subjects	Sensor-based Movement analysis system	Kinematic outcome measures	Functional task	Main angular kinematics findings at lower limb joints	Strengths and limitations
Ismailidis et al. 2020	- 23 unilateral KOA (Pre-operative severe) - 28 age-matched healthy controls	Sensor (RehaGait system; Hasomed, Magdeburg, Germany)	Hip, knee, and ankle ROM in the sagittal plane (within the entire movement cycle)	- Walking for 20 meters (self-selected speed)	**Differences between kinematics waveforms within whole movement cycle:** - Reduced hip extension ROM during the terminal stance (38 – 54% of movement cycle; maximum difference: 4.2°; P= 0.004). - Reduced knee flexion ROM from loading response to mid stance phase (4 – 24% of movement cycle; maximum difference: -6.8)** and at the end of terminal stance to mid swing phase (60 – 77% of movement cycle; maximum difference: -11.0°)**. - Increased ankle dorsiflexion ROM and reduced ankle plantar flexion ROM from midstance to the initial swing phase (8 – 68% of the movement cycle; maximum difference: 12.5°)**.	**Strengths:** - Sample size was determined based on power calculations. - Evaluation of kinematic variables was conducted using the Statistical Parametric Mapping (SPM). **Limitations:** - Individuals with severe knee OA was included only. - The affected knee compartment in individuals with OA was unclear (medial, lateral, or mixed).
Ismailidis et al. 2021	- 22 unilateral KOA (Pre-operative severe) - 46 age-matched	Sensor (RehaGait system; Hasomed, Magdeburg, Germany)	Discrete hip, knee and ankle angles and ROM in the sagittal plane during stance and swing phases.	- Walking for 20 meters (self-selected speed)	**Differences between discrete kinematics:** **Comparison between knee OA and control groups** - Reduced maximum hip extension during stance (maximum difference: -1.8°)*. - Reduced maximum knee flexion during stance phase (maximum difference: -5.2°)** and swing phase (maximum difference: -8.8°)**.	**Strengths:** - Sample size was determined based on power calculations. **Limitations:** - Individuals with severe knee OA was included only.

	healthy controls				- Reduced knee flexion ROM during load acceptance (maximum difference: -3.6°; P = 0.003), terminal stance (maximum difference: -4.4°; P = 0.002) and swing (maximum difference: - 7.9°)**. - Increased maximum dorsiflexion (maximum difference: 5.6°)**. - Increased dorsiflexion ROM during stance (maximum difference: 4.7°)**. - Reduced maximum plantar flexion during push off (maximum difference: -4.6◦; P = 0.009). **Comparison between affected and non-affected sides of OA** - Reduced maximum knee flexion during stance (maximum difference: -4.8◦; P = 0.002) swing phases (-6.1◦; P = 0.009) in affected compared to non-affected. - Reduced knee flexion at initial contact (maximum difference: -2.2°)** in affected compared to non-affected.	
Tadano et al. 2016	- 10 bilateral KOA (mixed severity - more affected "severe" and less affected "mild")	Sensors (H-Gait system; Development Code, Laboratory of Biomechanical Design, Hokkaido University,	Discrete hip, knee, and ankle angles in the sagittal and frontal planes during stance and swing phases	- Walking for 7 meters (self-selected speed)	**Differences between discrete kinematics:** - Reduced ankle abduction in the stance phase between mild and severe OA (difference: 9.3° and 14.6°** respectively) compared to control group. - No significant difference in knee flexion at maximum and minimum angles during stance and swing phases between both OA groups and control. - No significant difference in knee flexion ROM between both OA groups and control.	**Limitations:** - Unjustified small sample size. - OA and control groups were not matched in terms of age, height, body mass, and BMI. - Individuals with knee OA were varied (mixed severity), with no categorisation.

	- 8 healthy controls	Sapporo, Japan)				
Rahman et al. 2015	- 29 KOA (Pre-operative) - 29 age and gender-matched healthy controls	Sensors (GaitSmart; Dynamic Metrics Limited, UK)	- Discrete knee ROM in the sagittal plane - Discrete thigh and shank ROM in the sagittal and frontal plane	- Walking for 20 meters in non-laboratory environment	**Discrete kinematics of knee OA group compared to control group:** - Reduced knee flexion ROM during stance phase (difference: 13.8°)**, and swing phase (difference: 20.1°)**. - Reduced thigh and shank sagittal ROM (difference: 7.2° and 15°, respectively)**. - Reduced shank frontal ROM (difference: 4.8°)**.	**Strengths:** - OA and control groups were matched in terms of age and gender. - Gait kinematic assessment was conducted outside a controlled laboratory setting (out-patient clinical setting). **Limitations:** - Unjustified sample size. - OA and control groups were not matched in terms of BMI.
McCarthy et al. 2013	- 23 KOA in medial compartment (Pre-operative) - 21 age-matched	Sensors (GaitWALK system, Florida, USA)	Discrete knee ROM in the sagittal plane	- Walking for 20 meters (self-selected speed)	**Differences between discrete kinematics:** - Reduced knee flexion ROM during stance phase (difference: 7.7°)**, and swing phase (difference: 6.4°)**.	**Strengths:** - OA and control groups were matched in terms of age. - Participants were recruited from varied settings in two countries (Israel and UK). **Limitations:**

	healthy controls					- Unjustified sample size. - OA and control groups were not matched in terms of BMI.
van der Straaten et al. 2020	- 19 unilateral KOA (severe) - 12 healthy controls	Sensors (MVN BIOMECH Awinda; Xsens Technologies, Enschede, The Netherlands)	Trunk, hip, knee, and ankle ROM in the sagittal, frontal, and transverse planes (within the entire movement cycle)	- Walking for 10 meters (self-selected speed) - Stair ascent - Stair descent - Single leg squat - Sit to stand	**Differences between kinematics waveforms within whole movement cycle:** - Reduced knee flexion during stance phase (0 - 33% of movement cycle)**, and swing phase (49 - 92% of movement cycle)**. - Reduced trunk rotation during the entire cycle (0 - 100% of movement cycle)**. - Reduced pelvic internal rotation during late stance phase and to early swing phase (39 - 80% of movement cycle)**. - Reduced knee flexion (15 - 41% of movement cycle)**. - Reduced knee flexion (12 - 72% of movement cycle)**. - Reduced knee flexion (39 – 59% of movement cycle)**. - No significant difference found at any of the joints in the three planes of movement.	**Strengths:** - Evaluation of kinematic variables was conducted using the Statistical Parametric Mapping (SPM). **Limitations:** - Unjustified small sample size. - OA and control groups were not matched in terms of age. - Individuals with severe knee OA was included only. - The affected knee compartment in individuals with OA was unclear (medial, lateral, or mixed). - For stair ascend and descend tasks, only 4 steps were assessed with no information about the steps' height.
Bolink et al. 2012	- 20 KOA (severe)	Sensors (Inertia-Link;	Discrete trunk ROM in the sagittal,		**Differences between discrete kinematics:**	**Limitations:**

	- 30 healthy controls	MicroStrain Inertia-Link., Vermont, USA)	frontal and transverse planes	- Walking for 20 meters (self-selected speed) - Sit to stand - Step up	- Reduced trunk lean (abduction/adduction) (difference: 3.5°)**. - Increased trunk flexion (difference: 1.5°)**. - Increased lateral trunk lean (difference: 2.1°)**. - Increased trunk flexion (difference: 6.7°)**.	- The sensor used for assessing trunk kinematics was placed at the pelvis, which might lead to underestimation. - The number of participants involved in both groups was significantly differed (20 OA vs 30 healthy). - It is unclear whether the OA and control groups were matched in terms of height and body mass.
Nakagawa et al. 2012	- 40 PFPS (20 males and 20 females) - 40 healthy controls (20 males and 20 females)	Sensors (miniBIRD; Ascension Technology Corporation, Burlington, Vermont, USA) with MotionMonitor software (Innovative Sports Training, Inc, Chicago, USA)	Discrete ipsilateral trunk lean, contralateral pelvic drop, hip adduction and internal rotation, and knee abduction ROM	- SLS with > 60° knee flexion (Speed standardised as 2 seconds squat and 2 seconds return)	- Increased ipsilateral trunk lean ROM (difference: 2.6°)*. - Increased contralateral pelvic drop ROM (difference: 2.9°)*. - Increased hip adduction ROM (difference: 4°)*. - Increased knee abduction ROM (difference: 3.4°)*. - No significant difference in hip internal rotation ROM.	**Strengths:** - Sample size was determined based on power calculations. - OA and control groups were matched in terms of age and gender. - Inclusion criteria of individuals with PFPS were representable with literature and guidelines. - Performance of SLS was standardised across participants (squat depth ≥ 60°) at a consistent speed. **Limitations:** - OA and control groups were not matched in terms of height and body mass.

						- Gluteal muscle strengthening tests were done prior to movement assessment of squat task.
Nakagawa et al. 2015	- 30 PFPS (20 males and 10 females) - 30 healthy controls (20 males and 10 females)	Sensors (miniBIRD; Ascension Technology Corporation, Burlington, Vermont, USA) with MotionMonitor software (Innovative Sports Training, Inc, Chicago, USA)	Discrete peak ipsilateral trunk lean, hip adduction and knee abduction angles	- SLS with > 60° knee flexion (Speed standardised as 15 squats per minute)	- Increased ipsilateral trunk lean ROM (difference: 2.9°)*. - Increased hip adduction ROM (difference: 4.8°)*. Increased knee abduction ROM (difference: 3.6°)*.	**Strengths:** - OA and control groups were matched in terms of age, gender, height, and body mass. - Inclusion criteria of individuals with PFPS were representable with literature and guidelines. - Performance of SLS was standardised across participants (squat depth ≥ 60°) at a consistent speed. **Limitations:** - Gluteal muscle strengthening tests were done prior to movement assessment of squat task.
Severin et al. 2017	- 20 PFPS (10 males and 10 females) - 20 healthy controls (10 males and 10 females)	Sensors (Nanotrak; Catapult sports, Docklands, Victoria, Australia)	Discrete peak hip and knee in the sagittal and frontal planes	- DLS with arms overstretched across the body (Speed standardised as approximately	**Comparison between affected and non-affected sides of PFP** **(DLS task)** - No significant differences in any of the peak kinematic variables at the hip and knee joints in the sagittal and frontal planes.	**Strengths:** - OA and control groups were matched in terms of age, gender, height, and body mass. **Limitations:** - Unjustified small sample size.

				12 squats per minute) - SLS with arms overstretched across the body and contralateral limb flexed at 70°-90° (Speed standardised as approximately 12 squats per minute)	**(SLS task)** - Increased maximum trunk ipsilateral lean (difference: 2.9°)*. - Reduced maximum hip flexion (difference: 9.1°)*. - Reduced maximum knee abduction (difference: 2°)*. - Increased maximum shank medial rotation (difference: 5.1°)*. **Comparison (Asymmetry index score) between PFPS (affected + non-affected) and control (dominant + non- dominant) groups** **(DLS task)** - Reduced hip abduction (difference: 1.8°)*. - Reduced knee flexion (difference: 0.1°)*. Reduced knee abduction (difference: 2.6°)*. **(SLS task)** - Increased trunk ipsilateral lean (difference: 1.1°)*. - Increased hip flexion (difference: 0.7°)*. - Increased thigh Medial-Lateral (difference: 3.6°)*. - Increased knee abduction (difference: 3.4°)*. Increased shank Medial-Lateral (difference: 4.3°)*.	- Inclusion criteria of individuals with PFPS were not representable with literature and guidelines. - Performance of SLS was not standardised across participants in terms of depth and speed.

McKenzie et al. 2010	- 10 PFPS (Females) - 10 healthy controls (Females)	Sensors (Polhemus Systems; Skills Technology, Colchester, Vermont, USA)	Discrete knee ROM in the sagittal, and hip ROM in the sagittal frontal and transverse planes	- Stair ascent (self-selected speed, 5 steps each 20 cm high and 22 cm deep, for 3 minutes continuously) - Stair descent (self-selected speed, 5 steps each 20 cm high and 22 cm deep, for 3 minutes continuously)	**Differences between discrete kinematics:** **-** No significant difference for knee flexion angle at initial contact. - No significant difference for hip flexion, adduction, and internal rotation angles upon initial contact. - Increased hip adduction angle at initial contact (difference: 7.5°)**. - Increased hip internal rotation angle upon initial contact (difference: 5.9°)**. - No significant difference for hip and knee flexion angles upon initial contact.	**Strengths:** - OA and control groups were matched in terms of age and gender, height, and body mass. - Performance of stair ascent/descent was standardised and consistent across participants in terms of speed cadence. **Limitations:** - Unjustified small sample size. - Only female participants were included. - Stair depth (22 cm) was lower than the standard step depth (30.5 cm) recommended by previous literature. - Stair ascending and descending for a continuous 3 minutes.

Abbreviations: * = Statistical significance <0.005, ** = Statistical significance <0.001, ° = degree, 3D = three-dimensional, BMI = Body Mass Index, cm = Centimetres, DLS = Double leg squat, KAM = Knee adduction moment, KOA = Knee Osteoarthritis, OA = Osteoarthritis, PFPS = Patellofemoral pain syndrome, ROM = Range of motion, SLS = Single leg squat, SPM = Statistical Parametric Mapping, UK = The United Kingdom, USA = The United States of America

2.6.3 Squat kinematic alterations

Sensor-based movement analysis systems have been used for investigating kinematic alterations in individuals with knee pain during squat tasks (Table 3) (Nakagawa et al. 2012; Nakagawa et al. 2015; Severin et al. 2017; van der Straaten et al. 2020). Four studies used an observational study design to examine altered movement patterns associated with the condition of PFPS (Nakagawa et al. 2012; Nakagawa et al. 2015; Severin et al. 2017) and knee OA (van der Straaten et al. 2020).

Two studies of people with PFPS were conducted by Nakagawa et al. (2012) and Nakagawa et al. (2015), to examine differences in angular kinematics at the lower limb joints in the frontal and transverse planes during SLS (squat depth of > 60°) (Table 3). Both studies demonstrated that those individuals with PFPS were squatting with significantly greater ROM for ipsilateral trunk lean, hip adduction, and knee abduction of the affected leg compared to healthy controls (Nakagawa et al. 2012; Nakagawa et al. 2015). In addition, Nakagawa et al. (2012) identified a significant increase in contralateral pelvic drop ROM between the PFPS and control groups. The strength of these studies is that the procedures are standardised across studies with regard to squat depth (more than 60°) at a consistent speed using a metronome. Also, these studies were sufficiently powered by including the required sample size based on a power calculation. However, these studies were limited by the fact that prior to the kinematics assessment performed during the squat task, the participants had undergone gluteal muscle strengthening tests (maximal voluntary isometric contraction) using a handheld dynamometer. These tests may cause muscle fatigue and yield more kinematic alterations during a squat analysis, especially as it is unclear whether the participants were allocated adequate recovery time.

Similarly, Severin et al. (2017) compared lower limb movement patterns (peak angles) within the PFPS group (affected vs. non-affected) and asymmetry index scores (IS) between the PFPS and control groups during SLS. They reported a significant increase in peak ipsilateral trunk lean and knee abduction in the affected limb of individuals with PFPS, as compared to the non-affected limb and the control group, in agreement with the previous studies (Nakagawa et al. 2012; Nakagawa et al. 2015). However, Severin et al. (2017) also observed inconsistent results for peak hip flexion, knee abduction, and shank medial rotation angles.

These conflicting results may be explained by the fact that Severin et al. (2017) used a PFPS sample not comparable with that used by Nakagwa et al. (2012) and Nakagawa et al. (2015). In addition, Severin et al. (2017) included individuals who reported any unilateral knee pain lasting for at least 3 months in the PFPS group, without reference to the functional tasks being performed when pain is aggravated. In contrast, Nakagawa et al. (2012) and Nakagwa et al. (2015) categorised individuals based on the recommendations in previous literature and guidelines (Leibbrandt and Louw 2017; Willy et al. 2019), which defined individuals with PFPS as individuals reporting retro-patellar or anterior knee pain for a minimum of 6 weeks aggravated by a minimum of two functional tasks, such as squatting, prolonged sitting, and/or stair negotiation. Thus, potentially, the populations used in the aforementioned studies to yield different results due to the dissimilar inclusion criteria for people with PFPS. Furthermore, Severin et al. (2017) did not standardise the depth of the squat tasks unlike Nakagawa et al. (2012) and Nakagawa et al. (2015) who stated a squat depth of > 60°. Arguably, movement alterations in the hip and knee joints associated with knee pain conditions are more likely to present when the depth of the squat increases (Zawadka et al. 2020; Chan et al. 2022). Therefore, methodological limitations in this regard may produce in different results.

An increase in ipsilateral trunk lean has been suggested as compensation for hip abductor weakness, which is usually present in individuals with PFPS (Willson et al. 2008; Souza and Powers 2009; Nakagawa et al. 2012). Weakness of the hip abductors might lead to a shifting of the centre of mass medially over the hip joint centre, thus increasing the internal valgus moment and movement alterations of contralateral pelvic drop, hip adduction, and knee abduction (Nakagawa et al. 2012). Therefore, the compensatory movement of the ipsilateral trunk may help to control the biomechanical alterations in the loaded extremity during functional activities.

One study assessed lower limb joint kinematics during SLS, in all planes of movement in individuals with knee OA (van der Straaten et al. 2020). Compared to pain free healthy participants, individuals with OA exhibited significantly reduced knee flexion, particularly during maximum squat depth, whereas no significant results were found for the kinematic variables in the frontal and transverse planes (Table 3). This study included a small sample size (19 individuals with PFPS and 12 healthy controls), not justified by a power calculation. Future studies investigating lower limb joint kinematics using a large sample of individuals with knee OA during SLS are thus required.

Although no study has evaluated movement patterns during the functional task of double leg squat (DLS), two studies have analysed sit to stand (STS) to compare healthy and OA populations, as summarised in Table 3. This activity is cited as comparable to the DLS task and is considered a simple method for use in rehabilitation when seeking to progress and achieve independent squat tasks (Topp et al. 2009; Ness 2017; Buskard et al. 2019). Based on the study by Bolink et al. (2012), the only significant finding was increased contralateral trunk ROM in the frontal plane. However, there were no other movement alterations identified in the lower limb joints across the sagittal or frontal planes. A limitation of this study is that the sensor used for assessing trunk kinematics is placed at the pelvis, which might lead to underestimation (Faber et al. 2009). In order to avoid this issue, the sensor should be placed in a location between the posterior superior iliac spine and the seventh cervical spine (Faber et al. 2009). Another limitation is that the OA and control groups were not matched in terms of the number of participants recruited (20 knee OA and 30 controls). In addition, there was a lack of information regarding the participants' physical characteristics (e.g., height and body mass), even though age was matching between the OA and healthy control groups (mean age = 60 and 61 years old, respectively). Further studies are needed to evaluate lower limb kinematics using inertial sensors in individuals with OA during STS.

Alteration in the contralateral trunk lean movement adopted by individuals with knee OA could result from pain during the activity or persistent muscle weakness (Farquhar et al. 2009). This may suggest that individuals with knee OA attempt to unload the affected extremity and consequently move their trunk and shift the load towards the unaffected extremity. Unloading the affected side may produce a significant reduction in knee flexion moment (KFM) (Turcot et al. 2012), which has been significantly correlated with knee contact forces (R^2 = 0.73), particularly when associated with increased knee adduction moment (KAM) (Richards et al. 2018).

To review, varied altered movement patterns were observed in individuals with knee pain when engaged in squat tasks (DLS and SLS) and the comparable sit to stand task. Increased trunk movements in the sagittal and frontal planes are a common movement alteration adopted by individuals with knee pain when performing SLS and STS tasks. Physiotherapy treatment needs to identify and target these movement alterations based on a robust clinic-based movement analysis method.

2.6.4 Jump kinematic alterations

To the best of the researcher's knowledge, evaluation of lower limb kinematics for individuals with knee pain using sensor-based movement analysis has never been conducted during the performance of a jump task. Only limited studies have used the optoelectronic 3D motion capture system to assess the kinematics of individuals with PFPS during different jump tasks, such as drop vertical jump (DVJ) (Nunes et al. 2019; Baellow et al. 2020), jump landing (JL) (Souza and Powers 2009), single jump landing (SLJ) (Willson and Davis 2009), and single leg hopping (SLH) (Souza and Powers 2009; dos Reis et al. 2015; Alvim et al. 2019). This small number of studies could be because the jump task may be used less frequently to assess kinematics for individuals with chronic knee pain compared to those with sports-related injuries, such as ACL injury, due to the dynamic nature of the jump activity task (van der Straaten et al. 2020).

Willson and Davis (2009) assessed hip and knee kinematics (ROM) at a time defined by the initial contact of each jump until the point of maximum knee extensor moment during repetitive SLJ tasks. Their findings revealed that individuals with PFPS were jumping with a significant increase in hip adduction ROM for the affected leg ($P< 0.05$) (Willson and Davis 2009). Moreover, increased contralateral pelvic drop, hip internal rotation, and knee flexion have been observed in the affected leg of individuals with PFPS, whereas the increase was not considered statistically significant (Willson and Davis 2009). Despite the strength of the inclusion of the two matched PFPS and the control cohorts in terms of age, height, weight, and functional activity level in this study, only female participants were involved in both groups, potentially impacting the external validity of this study and the potential to generalise the findings to male individuals.

During the DVJ task, Nunes et al. (2019) and Baellow et al. (2020) assessed kinematics (ROM) at the hip, knee, and ankle joints across the three planes among PFPS and control groups during the deceleration phase. Nunes et al. (2019) reported a significant reduction in ROM for hip and knee flexion (mean difference = hip: -5.9°, knee: -6.3°, $P < 0.01$), whereas knee flexion ROM was the only kinematic variable to exhibit a significant reduction during the deceleration phase (mean difference = -2.62°, $P < 0.05$) in Baellow et al.'s (2020) study. Despite both studies (Nunes et al. 2009; Baellow et al. 2020) reporting a significant difference in the sagittal plane kinematics, the kinematics in the frontal plane did not differ significantly between the groups. The absence of a significant difference in the frontal plane kinematics, particularly in terms of hip adduction, could be explained by the limited movement of hip and knee flexion reported during deceleration. Reduced flexion in the hip and knee during landing may be an adaptation strategy adopted by individuals with PFPS in order to protect the PFJ through decreasing forces accompanied by knee flexion or when averting hip adduction and knee abduction (Dos Reis et al. 2015). A significant correlation was found between the reductions in sagittal hip and frontal knee kinematics during the performance of jumping (Nunes et al. 2019) and stair ascent (de Oliveira Silva et al. 2016). Thus, stiffening of the sagittal hip and knee movements performed by individuals with PFPS, as reported in Nunes et al.'s (2019) and Baellow et al.'s (2020) studies, might also reduce the variability of the frontal hip and knee kinematics.

A plethora of significant kinematic alterations during the SLDH task have been reported, such as increased trunk flexion and lean, anterior pelvic tilt, contralateral pelvic drop, hip adduction and internal rotation and ankle eversion, in addition to reduced trunk and pelvic rotation, hip, knee, and ankle flexion (Dos Reis et al. 2015; Alvim et al. 2019). Similarly, during the JL task, the maximum angle of the hip internal rotation was found to be greater in PFPS individuals relative to healthy controls (Souza and Powers 2009). However, all previous studies included a small sample size, resulting in the potential for a Type II error. Thus, a large sample population might produce a different conclusion. Also, only female participants were included in these studies, which may affect their external validity. It is recognised that the increased hip internal rotation reported in these previous studies may be another common altered movement pattern adopted by individuals with PFPS. This compensatory movement might have resulted from weakness in the external rotators of the hip, which is associated with the development of PFPS (Nakagawa et al. 2012; Willson and Davis 2009; Souza and Powers 2009). A correlation has also been noted between increased femoral rotation and PFJ stress when reducing the PFJ contact area (Salsich and Perman 2007; Besier et al. 2008).

In conclusion, wearable sensors have not yet been used to assess kinematics in individuals with chronic knee pain during jump tasks, whereas limited studies have used optoelectronic motion capture systems to evaluate them. Variations in kinematics at the lower limb joints in different planes have been reported across studies. Two commonly altered movement patterns exhibited by individuals with knee pain (particularly PFPS) have been identified during jump tasks, which are reduced knee flexion and increased internal rotation of the hip. These unnecessary movement alterations need to be targeted by physiotherapy clinicians using a portable movement analysis tool, in order to enhance their clinical decision making and treatments for individuals with knee pain.

2.6.5 Stair ascent and descent kinematic alterations

During stair negotiation, sensor-based movement analysis systems have been used to evaluate altered movement patterns for individuals experiencing knee pain in three studies (Table 3) (McKenzie et al. 2010; Bolink et al. 2012; van der Straaten et al. 2020). These studies used an observational study design to compare kinematic alterations identified in individuals with knee pain and healthy controls. Of these studies, two assessed kinematics in individuals with knee OA (Bolink et al. 2012; van der Straaten et al. 2020), while PFPS kinematics were investigated in one study (McKenzie et al. 2010).

As regards OA, van der Straaten et al. (2020) assessed joint angular kinematics for 19 individuals with severe knee OA during stair ascent and descent tasks and compared them with the kinematics for both limb sides in 12 healthy individuals. The findings revealed that OA individuals were ascending and descending stairs with a significant reduction in knee flexion ROM compared to healthy controls (15 – 41% and 12 -72% of movement cycles, respectively; $P < 0.001$) (van der Straaten et al. 2020). There is a limitation in the current study with regard to the limited number of steps used (4 steps only) and the unclear information regarding the height of the steps evaluated, which may affect the study's results and comparability with other literature. Also, Bolink et al. (2012) evaluated kinematic alterations in the trunk during the step-up task and found significantly increased trunk flexion in the OA cohort compared to the control group. Information regarding the height of the step used (20 cm) and instructing the speed of the participant (self-selected speed) has been clearly mentioned.

The findings in the previous studies agreed with a systematic review of meta-analyses that reviewed eleven studies using varied movement analysis methods to identify the altered biomechanical variables performed by individuals with knee OA during stair negotiation (Iijima et al. 2018). The findings of meta-analyses clarified that individuals with knee OA ascend stairs with increased trunk and hip flexion (standardised mean difference (SMD) = 0.38 and 0.34, respectively) in addition to reduced knee flexion and ankle dorsiflexion (SMD = -0.28 and -0.32, respectively) when compared to healthy controls (Iijima et al. 2018). However, no significant differences were noted between frontal kinematics in the lower limb joints between OA individuals and healthy participants (SMD range = -0.10 – 0.14) (Iijima et al. 2018). This systematic review was limited by the fact that the process of study inclusion and data extraction were conducted by a single researcher only, which may reduce its internal validity and yield more errors than conducting them using two or more researchers as recommended by Higgins et al. 2019. In addition, the quality of all the studies included in this systematic review was assessed using a modified Downs and Black scale as poor (range 1 – 3/ 6).

The altered movement patterns reported in previous studies (increased trunk and hip flexion, and reduced knee flexion kinematics) suggest a potential compensation strategy is being adopted by individuals with knee OA. This new altered movement pattern may be occurring as a result of associated quadriceps muscle weakness (Ling et al. 2007; Rudolph et al. 2007) and painful step loading during functional activity. Consequently, individuals with knee OA attempt to reduce the time taken during single leg step loading. This could be achieved by performing greater trunk flexion, which leads to the development of more forces for vertical displacement with greater maximum acceleration (Bolink et al. 2012). A relationship between increased peak trunk flexion and reduced KFM in individuals with knee OA during stair ascent may support the existence of a compensatory mechanism (Asay et al. 2009). Moreover, increased KFM, accompanied by increased KAM is a significant predictor of increased knee contact force ($R^2 = 0.73$) (Richards et al. 2018). Therefore, reducing KFM by increasing sagittal trunk kinematics could reduce knee joint loading.

With regard to PFPS, McKenzie et al. (2010) compared kinematics at hip and knee joints in individuals with PFPS and healthy controls during stair ascent and descent at a self-selected speed. The results exhibited no significant difference for the kinematic variables of knee flexion, hip flexion, adduction, and internal rotation angles at the point of initial contact (McKenzie et al. 2010). However, stair descent kinematic variables demonstrated that individuals with PFPS demonstrated more hip adduction and internal rotation upon initial contact (Table 3) (McKenzie et al. 2010). Limitations with regard to the protocol used to investigate kinematics in this study may have impacted the findings. The participants were instructed to ascend and descend stairs with a 22 cm depth continuously for three minutes. A stair depth of 22 cm is considered relatively lower than the standard step depth (30.5 cm), which is recommended by previous literature (Schwane et al. 2015). This may result in higher task demand causing muscle fatigue, which might yield additional kinematic alterations. Furthermore, although the two cohorts (PFPS and control) involved were consistent with respect to age, height, and mass ($P > 0.05$), a small number of participants were included in each group (10 participants), potentially yielding Type II error and impacting the findings.

The findings were correlated with other studies using optoelectronic motion capture systems, which reported no significant differences between PFPS and control groups for all the assessed kinematic variables in the sagittal and frontal planes (Salsich et al. 2001; Bolgla et al. 2008). However, some studies have demonstrated inconsistent results and exhibited significant differences across some kinematic variables, such as reduced maximum knee flexion, and increased hip adduction and rearfoot eversion during a stair ascent (de Oliveira Silva et al. 2015; de Oliveira Silva et al. 2016; Ferrari et al. 2018). Similarly, during stair descent, several of the kinematic variables differed significantly between groups, such as the increased maximum hip internal rotation (Grenholm et al. 2009) and the reduced knee abduction ROM (Richards et al. 2018).

Overall, limited studies have assessed kinematics in individuals with knee pain using sensor-based movement analysis during stair ambulation. However, a broad range of kinematic alterations was associated with different knee pain conditions, such as OA and PFPS. Common altered movement patterns adopted by individuals with knee OA during stair negotiation were increased trunk flexion and reduced knee flexion. The persistence of these unnecessary movement alterations has an important rehabilitative implication, as physiotherapy clinicians need to address them based on a clinic-based objective movement analysis.

2.6.6 Section summary

Based on this review, limited research has evaluated lower limb kinematics using the sensor-based 3D movement analysis method during functional tasks of gait, squat, jump, and stair negotiation. Across all functional tasks, a wide range of varied kinematic alterations could be performed by individuals experiencing knee pain, particularly knee OA and PFPS. Kinematic alterations could be present in the three planes of movement when undertaking the discussed functional activities. The inconsistency in altered movement patterns identified in individuals with knee pain suggests a highly personalised change in kinematics in response to knee pain (Hodges and Tucker 2011). Despite this, there were few commonly altered movement patterns identified in individuals with knee pain during functional activities. These are: reduced knee flexion, increased ipsilateral trunk lean, increased trunk flexion, and increased hip adduction and internal rotation. These alterations may play a role in reducing pain (short-term benefit), as suggested by pain adaptation theory (Hodges and Tucker 2011). However, the persistence of such alterations over a long period of time could result in reduced movement variability and increased load, which would then limit physical activity and cause further pain.

The findings for the individualised varied movement alterations presented in individuals with knee pain have a crucial rehabilitative implication, as physiotherapy practice needs to consider varied unnecessary alterations when assessing individuals with knee pain during functional activities. Additionally, physiotherapy treatment needs to be tailored based on the altered movement patterns identified in order to restore motor control. This highlights the need for the availability of portable movement analysis within clinical practice. Therefore, individualised treatment for the purpose of modifying altered movement patterns in lower limb joints identified by using feedback from the movement analysis method is discussed in the following section.

2.7 Individualised physiotherapy treatment interventions based on movement assessment

Investigating functional limitations in individuals with knee pain by assessing their movements and identifying various altered movement patterns by employing a robust portable movement analysis system can serve to optimise rehabilitation. Notably, this process could assist physiotherapy clinicians with their clinical decision making regarding the optimal treatment strategies to implement. The remainder of this section details the role of movement analysis feedback in physiotherapy treatment. Additionally, several biomechanical physiotherapy interventions and data regarding how individualised movement assessments could enhance their use and effectiveness are presented.

The effect of using biomechanical feedback provided by a movement analysis method on clinical decision making has not yet been studied in a population suffering from musculoskeletal conditions. However, movement analysis has been extensively evaluated in the literature concerning children with cerebral palsy (Cook et al. 2003; Lofterød et al. 2007; Wren et al. 2011). A randomised controlled trial (RCT) conducted by Wren et al. (2011) divided 178 children with cerebral palsy into a gait report cohort, for whom the orthopaedic surgeon received reports comprising biomechanical data, and a control group for which there was no biomechanical feedback report. Wren et al. (2011) reported statistically significant differences between the number of surgical procedures conducted for children in the gait report cohort compared to the control cohort ($p < 0.05$). This was based on agreement between the recommendations concerning gait analysis and the original plan for conducted procedures. Therefore, it has been concluded that the recommendations in the gait analysis data reinforced the original plan for surgical procedures when they confirmed suspicions, or altered the original surgical plan when they differed (Wren et al. 2011). This study may, however, have been limited by the small number of referring orthopaedic surgeons involved (4 surgeons). In addition, gait analysis was conducted in a single gait analysis laboratory and the interpretation was made by one physician. These factors might impact the generalisability of the findings reported in this study (Wren et al. 2011). Nonetheless, the findings in Wren et al. (2011) corresponded to the findings in other studies with less robust designs (Cook et al. 2003; Lofterød et al. 2007). These studies lacked a comparator group, which may have limited their findings, as it was unclear whether the changes to clinical decision making were affected by gait assessment (Cook et al. 2003; Lofterød et al. 2007).

In the field of musculoskeletal physiotherapy, several biomechanical interventions have been proposed to modify the kinematic alterations associated with knee pain, and consequently to improve knee symptoms and functionality. Examples of these interventions are strengthening programmes, neuromuscular training, knee taping, orthotic devices, and movement retraining strategies (Powers et al. 2008; Bennell et al. 2010; Thorp et al. 2010; Pagani et al. 2012; Arazpour et al. 2013; Rodrigues et al. 2013; Baldon et al. 2014; Hickey et al. 2016; Dessery et al. 2017; Hanada et al. 2018; Tsai et al. 2020; Ye et al. 2020). These interventions may have benefitted from the availability of a portable movement analysis method within clinical practice, which could provide feedback about the patient's movements when performing different activities, to ensure efficient treatment personalisation. For example, the effectiveness of using a knee brace in the treatment of medial knee OA (reducing knee forces) is significantly correlated with varus malalignment in the affected knee joint ($p < 0.05$) (Gaasbeek et al. 2007). This may indicate that the effect of the knee brace on reducing the knee forces responsible for OA progression, such as KAM (Miyazaki et al. 2002; Amin et al. 2004), might be more prominent in knee OA individuals with a varus deformity (Gaasbeek et al. 2007).

Moreover, Kobsar et al. (2015) examined the successful treatment rate for a 6-week intervention involving hip targeted strengthening exercises based on baseline gait kinematics and self-reported outcome measures relating pain and function. The authors found that knee OA individuals who demonstrated an increased hip adduction angle during loading response in the gait task at baseline, accompanied by lower scores on the daily living subscale (ADL) on the KOOS questionnaire, responded best to the hip strengthening intervention (Kobsar et al. 2015). Thus, these examples supported the benefits of individual kinematic assessment to aid treatment selection and enhance its efficiency.

Another biomechanical treatment strategy used for modifying the altered movement patterns associated with knee pain is movement retraining. This individualised treatment strategy is dependent largely on feedback information given using movement analysis methods to correct faulty patterns, and is discussed in the subsection below.

2.7.1 Movement retraining and motor skill learning

This subsection concerns the role of feedback in individualised biomechanical physiotherapy interventions. The focus here is on movement retraining interventions used to manage altered movement patterns, with a focus on feedback and motor learning in the literature to date. Reviewing the literature will help identify an evidence base for developing the new movement analysis feedback toolkit and guide its design.

Movement retraining involves enhancing the ability to acquire a new movement pattern in a permanent manner through optimising specific functional components (altering biomechanical variables) (Charlton et al. 2021). This can be achieved by motor skill learning, which is defined as "a set of processes associated with practice or experience leading to relatively permanent changes in the capability for skilled movement" (Schmidt and Lee 2019, p. 23). More clearly, the success associated with movement retraining relies completely on motor learning and new movement patterns constantly acquired in real-world contexts (Charlton et al. 2021). This success is also related to a central characteristic of motor learning, which is permanence (Schmidt and Lee 2019). The permanent characteristics of motor learning differentiate it from motor performance (modification in skill execution during practice or experience) (Charlton et al. 2021). It is imperative to evaluate the magnitude of learning, and differentiate between changes that result from motor skill performance, and the more permanent modifications that accompany learning.

Motor learning can be measured by employing three varied assessments; retention, skill transfer, and multi-tasking (Schmidt and Lee 2019). Retention assessment can be performed with a similar practice condition (functional task, time, and environment) but without providing feedback (Schmidt and Lee 2019). The persistence of an acquired movement pattern over time suggests motor learning has been achieved (Charlton et al. 2021). It has been recommended that retention assessment be performed over a long period of time (follow up) to ensure more complete motor learning (Charlton et al. 2021). Another aspect of motor learning assessment measured is skill transfer. This assessment is designed to assess the generalisability of a skill, to determine if it could be applied in varied contexts (Schmidt and Lee 2019). The final assessment test is multi-tasking. This test could be achieved by performing two or more tasks simultaneously. Conducting the two tasks successfully without a significant regression in performance suggests the task can then be learned (Rémy et al. 2010). These assessment tests will be discussed in line with movement retraining studies using feedback from individuals experiencing knee pain in the next subsection.

2.7.2 Movement retraining on modifying altered movement patterns

Understanding the effect of movement retraining, as provided by individualised feedback on modifying kinematics will help to support the rationale for the necessary movement analysis feedback toolkit, which will be developed in this PhD thesis. Also, identifying and investigating the varied feedback methods used may assist in the development and design of the tool in terms of identifying the best feedback method to use.

Limited studies have evaluated the effect of gait retraining for individuals with knee pain using feedback on diverse kinematic variables, such as foot progression angle (Shull et al. 2013a; Shull et al. 2013b; Hunt and Takacs 2014; Hunt et al. 2014; Charlton et al. 2019; Booij et al. 2020), hip adduction angle (Noehren et al. 2011; Willy et al. 2012), and foot strike position (Roper et al. 2016) (Table 4). All these studies have exhibited significant improvements in terms of the kinematic variables assessed after feedback retraining programmes when compared to baseline assessments. However, the majority of these studies have been limited by the fact that they employ a single arm experimental pre-post design, aside from one study that involved an RCT (Roper et al. 2016). The pre-post study design has a major limitation in terms of the lack of control group, which could avoid comparability and affect internal validity. Thus, it is encouraged that future studies will investigate the effect of retraining interventions using feedback involving a more robust study design, such as an RCT.

A well-designed RCT conducted by Roper et al. (2016) divided 16 PFPS individuals into an intervention group that received eight sessions of a retraining programme with feedback and a control group that received retraining with no feedback on how to modify gait by altering the foot strike position. Roper et al. (2016) found statistically significant differences in some knee and ankle kinematic variables post-retraining programme and at 1-month of follow-up when compared to baseline measures ($P < 0.05$), while the control group had no significant differences for the same variables (Table 4). Despite the strength of the rigorous design of this study (RCT) and the excellent randomisation process, blinding of PFPS individuals to the intervention was lacking, which may have led to performance bias. Also, skill transfer tests have not been performed to confirm the transferability of improved kinematics to other tasks.

In order to evaluate the occurrence of successful motor learning, all the studies assessed the magnitude of motor learning using retention assessments. However, the time when the retention assessment was conducted has not been reported in three studies (Shull et al. 2013a; Hunt and Takacs 2014; Hunt et al. 2014). Therefore, it is unclear whether the altered kinematics are a result of enhanced motor skill performance during practice, or if they have permanently changed to form acquired new movement patterns. Four studies have evaluated the retention of kinematic changes at 1 month (Noehren et al. 2011; Willy et al. 2012; Shull et al. 2013b; Roper et al. 2016), and 3 months of follow up (Willy et al. 2012). For instance, Noehren et al. (2011) and Willy et al. (2012) assessed the impact of 8 sessions of instrumented gait retraining using combined visual and verbal feedback on hip adduction angle in individuals with PFPS (Table 4). Both studies demonstrated statistically significant post-retraining reduced maximum hip adduction and contralateral pelvic drop angles (Noehren et al. 2011; Willy et al. 2012). These reductions were retained at 1-month of follow-up (Noehren et al. 2011; Willy et al. 2012) and at 3-months (Willy et al. 2012).

The persistence of learned movement patterns during the retention assessments in the previous studies suggests that motor learning has been achieved. However, the retention assessment trials conducted in previous studies were performed in the same highly controlled laboratory environment as the optoelectronic 3D motion capture system used may be challenging to implement in the context of a real-world environment. It has been recommended that enhancing measures of movement learning is undertaken to perform assessments in a real-world environment (Charlton et al. 2021). Therefore, it is unclear whether the trained modifications assessed in controlled laboratory settings can be translated to real-world settings. This suggests a need for portable 3D movement analysis within clinical settings.

Skill transfer assessment has been conducted in two studies (Noehren et al. 2011; Willy et al. 2012). The kinematic alteration of the reduced maximum hip adduction angle during gait has been found to be translated to SLS tasks at the end of training and after 1 month of follow-up (Noehren et al. 2011; Willy et al. 2012) and to the step descent task at the end of training after 1 and 3 months of follow-up (Willy et al. 2012). The generalisability of the new movement pattern acquired by gait retraining and feedback confirms that learning has occurred. It is noteworthy that multi-tasking assessment has not been used across knee pain studies to evaluate motor learning.

To conclude, movement retraining using individualised feedback appears to be effective for permanently modifying altered movement patterns in individuals suffering chronic knee pain. This provides insight that the individualised feedback provided during retraining sessions plays an important role in motor learning. This is vital in terms of physiotherapy treatment, as individualised treatment based on structured feedback about individuals' movements can correct movement alterations that may cause pain and reduce function. Therefore, it is vital to further explore feedback in terms of the information provided, including structure, methods, and timing.

Table 4: Summary of study characteristics and outcomes for studies investigating movement retraining interventions based on feedback from individuals with knee pain

Author and date	Sample population	Functional task	Movement analysis method	Feedback type	Kinematics measures assessed	Main results	Strengths and limitations
Hunt and Takacs 2014	- Adults with KOA (N=15) - No controls	- Baseline and post-training assessments: Over-ground gait - Retraining: Treadmill gait (6 sessions over 10 week)	Optoelectronic 3D Motion capture system (Motion Analysis Corp., Santa Rosa, California) with Cortex software (Motion Analysis Corp., Santa Rosa, California)	Performing toe-out gait 10° using faded visual real-time feedback for foot toe-out angle	- Toe-out angle	- Increase in toe-out angle post-training intervention versus baseline (P<0.001)*.	**strengths:** - Post-training and follow-up assessment was performed. **Limitations:** - Unjustified small sample size. - Lack of control group. - Feedback was provided using a laboratory-based 3D motion capture system only. - Post-training assessments were performed at 1 week only in the same highly controlled laboratory environment. - No skill transfers assessment was conducted.
Hunt et al. 2014	- Adults with KOA (N=20)	- Baseline and post-training assessments: Over-ground gait	- Optoelectronic 3D Motion capture system (Motion Analysis Corp., Santa	Performing toe-out gait 10° using 3 visual feedback approaches: -Mirror	- Toe-out performance error - Perceived difficulty	- Reduction in toe-out performance errors for all feedback approaches post-training versus baseline (P=0.025)*.	**Strengths:** - Sample size was determined based on power calculations. **Limitations:**

	- No controls	- Retraining: Treadmill gait	Rosa, California) with Cortex software (Motion Analysis Corp., Santa Rosa, California, USA) - Mirror - 2D video camera (Sony, Toronto, Ontario, Canada)	-Raw data (video) -Real-time visual feedback provided by 3D motion capture system of foot toe-out angle		- Reduction in toe-out performance errors for real-time feedback provided by 3D motion capture system compared to mirror and video*. - No significant differences between the 3 feedback approaches for perceived difficulty (P=0.51).	- Lack of control group - Single retraining session was performed. - No follow-up and/or skill transfers assessments were conducted.
Simic et al. 2012	- Adults with KOA (N=22) - No controls	- Baseline and post-training assessments: Over-ground gait - Retraining: Over-ground gait	Optoelectronic 3D Motion capture system (Vicon; Oxford, UK) with Vicon Nexus software (Oxford, UK)	Performing lateral trunk lean gait at 3 conditions: 1) 6° 2)9° 3)12° using visual real-time feedback of trunk lean angle	- Lateral trunk lean angle	- Significant differences between the 3 trunk lean conditions in the trunk lean angle post-training versus baseline (P<0.001)*.	**Limitations:** - Unjustified sample size. - Lack of control group. - Single retraining session was performed. - Feedback was provided using a laboratory-based 3D motion capture system only. - No follow-up and/or skill transfers assessments were conducted.
Booij et al. 2020	- Adults with KOA (N=40)	- Baseline and post-training assessments and	Optoelectronic 3D Motion capture system	Performing gait under 3 conditions:	- Foot progression angle	- Increased in toe-in angle for (toe-in and medial thrust conditions) (7° and 5°	**Limitations:** - Unjustified sample size. - Lack of control group.

	- No controls	retraining: Treadmill gait	(Vicon; Oxford, UK)	1) Toe-in 2) Wider steps 3) Medial thrust using visual real-time feedback of: foot progression angle, distance between steps, and distance between knees	- Step width - Inter-knee distance	respectively) post-retraining versus baseline*. - Increased in step width for (all 3 conditions) (ranges 0.03 – 0.08 meters) post-retraining versus baseline*. - Increase in inter-knee distance for (wider step) (0.05 meters) post-retraining versus baseline*.	- Single retraining session was performed. - Feedback was provided using a laboratory-based 3D motion capture system only. - No follow-up and/or skill transfers assessments were conducted.
Charlton et al. 2019	Adults with KOA (N=15) No controls	- Baseline and post-training assessments: Over-ground gait - Retraining: Treadmill gait	Optoelectronic 3D Motion capture system (Motion Analysis Corp., Santa Rosa, California) with Cortex software (Motion Analysis Corp., Santa Rosa, California)	Performing gait with 5 conditions: - toe-in 10° - Natural - 0° - toe-out 10° - toe-out 20° using visual real-time feedback of foot progression angle	- Ankle kinematics and kinetics	- Significant differences between conditions in foot progression angles post-training versus baseline (P<0.001)*. - Increase in rearfoot inversion angle at IC for toe-in 10° compared to other conditions (P<0.001)*. - Reduction in maximum rearfoot eversion for toe-in 10° compared to other conditions (P<0.05)*. - Increase in rearfoot eversion/inversion ROM for Toe-in 10° compared to other conditions (P<0.05)*.	**Limitations:** - Unjustified sample size. - Lack of control group. - Individuals with knee OA included were high functioning with mild and moderate OA only. - Single retraining session was performed. - Gait assessments were performed in barefooted individuals - Feedback was provided using a laboratory-based 3D motion capture system only. - No follow-up and/or skill transfers assessments were conducted.

Shull et al. 2013b	- Adults with KOA (N=10) - No controls	- Baseline, post-training and follow-up assessments and retraining: Treadmill gait (6 weeks retraining)	Optoelectronic 3D Motion capture system (Vicon; Oxford, UK)	Performing personalised gait with modifications in foot progression or trunk lean (based on baseline gait assessment) using indirect haptic bandwidth faded feedback (vibration) of foot progression or trunk sway angle	- Foot progression angle - Trunk lean angle At baseline, post training, and 1- month follow- up	- All participants chose to alter the foot progression angle rather than trunk lean due to discomfort, reduced balance, and difficulty persisting. - Reduction in foot progression angles post retraining (P<0.01) and at 1-month follow-up (P<0.05) versus baseline*. - No significant differences in trunk lean angle post retraining or at 1-month follow-up versus baseline.	**Limitations:** - Unjustified small sample size. - Lack of control group. - Feedback was provided using a laboratory-based 3D motion capture system only. - Post-training and follow-up assessments were performed in the same highly controlled laboratory environment. - Follow-up assessments were performed at 1 month only. - No skill transfers assessment was conducted.
Shull et al. 2013a	- Adults with KOA (N=12) - No controls	- Baseline and post-training assessments and retraining: Treadmill gait	Optoelectronic 3D Motion capture system (Vicon; Oxford, UK)	Performing gait with toe-in using indirect haptic bandwidth feedback (vibration) of foot progression angle	- Foot progression angle - Trunk lean angle All outcomes were quantified at early stance KAM and late stance KAM	- Reduction in foot progression angle at the early and late stance peak KAM for toe-in post-training versus baseline (P<0.01)*. - No significant difference in trunk lean angle at early and late stance peak KAM for toe-in post-training versus baseline.	**Strengths:** - Sample size was determined based on power calculations. **Limitations:** - Lack of control group. - Single retraining session was performed. - Feedback was provided using a laboratory-based 3D motion capture system only.

							- No follow-up and/or skill transfers assessments were conducted.
Noehren et al. 2011	- Adults with PFPS (N=10 female runners) - No controls	- Baseline and post-training assessments: SLS (60°) followed by treadmill running - Retraining: Treadmill running (8 sessions) - Follow-up assessment (after 1 month): SLS (60°) followed by treadmill running	Optoelectronic 3D Motion capture system (Vicon; Oxford, UK) with Visual 3D software (Germantown, Maryland, USA)	Running using visual real-time faded feedback for hip adduction angle with verbal instructions to maintain reduced hip adduction	- Hip kinematics (hip adduction and internal rotation, contralateral pelvic drop, and hip abduction moment)	**Running** - Reduction in maximum hip adduction and contralateral pelvic drop during running post-training versus baseline, these reductions were maintained at 1-month follow up (P<0.05)*. **SLS** - Reduction in maximum hip adduction angle post-training versus baseline*.	**Strengths:** - Sample size was determined based on power calculations. - Follow-up and skill transfers assessments were performed **Limitations:** - Lack of control group. - Only female participants were included. - Feedback was provided using a laboratory-based 3D motion capture system only. - Follow-up and skill transfers assessments were performed at 1 month only in the same highly controlled laboratory environment.
Willy et al. 2012	- Adults with PFPS (N=10 female runners) - No controls	- Baseline and post-training assessments: treadmill running, SLS (60°), and step descent	- Optoelectronic 3D Motion capture system (Vicon; Oxford, UK) with Customized software (LabVIEW 8.0, National	Performing running using visual real-time faded feedback (mirror) with faded verbal instructions to reduce hip adduction	- Hip kinematics (hip adduction and internal rotation, contralateral pelvic drop, and hip	**Running** - Reduction in maximum hip adduction and contralateral pelvic drop during running post-training versus baseline, reduction in contralateral pelvic drop only was maintained at 1- and 3-month follow up (P<0.05)*.	**Strengths:** - Sample size was determined based on power calculations. - Follow-up and skill transfers assessments were performed. **Limitations:** - Lack of control group

		- Retraining: Treadmill running (8 sessions) - Follow-up assessment (after 1 and 3 month): treadmill running, SLS (60°), and step descent	Instruments, Austin, Texas, USA) - Mirror		abduction moment) At baseline, post training, and 1- and 3-month follow-up	- Reduction in maximum hip abduction moment during running post-training versus baseline, reduction maintained at 1-month follow up only (P<0.05)*. **SLS** - Reduction in maximum hip adduction angle post-training versus baseline; reduction was maintained at 1-month follow up only (P<0.05)*. **Step descent** - Reduction in maximum hip adduction and contralateral pelvic drop angles post- training versus baseline, reduction in hip adduction angle only was maintained at 1- and 3-month follow up (P<0.05)*.	- Only female participants were included. - Follow-up and skill transfers assessments were performed at 1 and 3 months only in the same highly controlled laboratory environment.
Roper et al. 2016	Adults with PFPS (N=16) divided into:	- Baseline and post-training assessments: Treadmill running	- Optoelectronic 3D Motion capture system (Vicon; Oxford, UK) with Vicon Nexus software (Oxford, UK)	- Intervention group: Performing running using visual feedback (mirror with faded verbal	- Knee and ankle kinematics in sagittal and frontal planes	- Reduction in knee abduction at IC post-retraining and 1-month follow-up versus baseline (P<0.05)* in intervention group, while no significant difference was found in control.	**Strengths:** - A robust study design was used (RCT). - Excellent randomisation process. - Sample size was determined based on power calculations.

	- Experimental (N=8) - Control (N=8)	- Retraining: Treadmill running (8 sessions) - Follow-up assessment: Treadmill running	- Mirror	instructions to perform forefoot strike instead of rearfoot strike) - Control group: Performing running without intervention (no modification feedback)	At baseline, post training, and 1-month follow-up	- Increase in knee flexion angles at IC post-retraining versus baseline (P<0.05)* in intervention group, while no significant difference was found in control. - Increase in ankle flexion at IC post-retraining and 1-month follow-up versus baseline (P<0.05)* in intervention group, while no significant difference was found in control. - Increase in sagittal ankle ROM post-retraining and 1-month follow-up versus baseline (P<0.05)* in intervention group, while no significant difference was found in control. - No significant differences in all kinematic variables for the control group over time.	- Follow-up assessment was performed. **Limitations:** - Lack of Blinding of individuals with PFPS to the intervention. - Follow-up assessments were performed at 1 month only in the same highly controlled laboratory environment. - Skill transfers assessment was not conducted.

Abbreviations: * = Statistical significance, 2D = two dimensional, 3D = three dimensional, KAM = Knee adduction moment, KOA = Knee Osteoarthritis, N = number, OA = Osteoarthritis, PFPS = Patellofemoral pain syndrome, RCT = Randomised Controlled Trial, ROM = Range of Motion, SLS = Single leg squat, UK = The United Kingdome, USA = The United States of America

2.7.3 Feedback

Feedback is used to guide the process of motor learning. Feedback can be derived from both intrinsic and extrinsic sources (Schmidt and Lee 2019). Intrinsic feedback refers to the proprioceptive sensory afferent, which conveys information regarding the extremity position when the movement is being conducted (Sigrist et al. 2013). External feedback is information carried out by external sources via visual, auditory, or tactile feedback modes. In rehabilitation, external feedback can be employed as an assistive treatment tool to augment internal feedback in the recovery process and enhance motor learning (as reported in the previous section) (Schmidt and Lee 2019). In addition, feedback can assist in assessing the altered movement patterns associated with knee pain (previously discussed in section 2.4), providing information about the movement to physiotherapy clinicians and patients, informing a treatment plan, and monitoring progress. Thus, further investigation regarding external feedback is needed. Factors associated with external feedback, such as information provided, timing, and modes, are discussed in turn.

2.7.3.1 Information provided by feedback

External feedback could be directed towards two categories of information, namely knowledge of performance (KoP) or knowledge of results (KoR) (van Vliet and Wulf 2006). Knowledge of results arises when feedback is used to inform a performance outcome or goal, while knowledge of performance is feedback providing information about the specific motion characteristics that lead directly to an outcome (van Vliet and Wulf 2006). For instance, gait speed is a motion characteristic that is usually assessed in individuals with knee pain to evaluate performance and progress. The speed of walking in metres per second could be KoR for observing progress. However, information regarding specific movement characteristics of gait like joint kinematics (foot progression angle, trunk lean angle, distance between knees and steps, tibia rotation angle, hip adduction angle, or forefoot strike) or kinetics (peak KAM, or patellofemoral joint forces) represented the performance of the walking task conducted. For individuals with knee pain, the evidence showed that feedback is provided to give information about biomechanical outcome measures (representing

KoP) (Shull et al. 2013a; Shull et al. 2013b; Hunt and Takacs 2014; Hunt et al. 2014; Noehren et al. 2011; Willy et al. 2012; Roper et al. 2016). KoP and KoR have not been combined or compared in the literature on knee pain, despite it having been proposed that integrating both types of information for external feedback might be advantageous in terms of neurological rehabilitation (Badets and Blandin 2004; Badets and Blandin 2005). Therefore, integrating KoR and KoP may add to the external feedback involved.

2.7.3.2 Feedback timing

Feedback timing relates to how frequently feedback needs to be provided during the course of treatment. Feedback could be given for all trial treatment sessions, parts of trials across all sessions, or in a number of sessions only. Movement skill learning can be impacted by the amount of feedback given during one or multiple visits, using feedback (Charlton et al. 2021). To the best of the researcher's knowledge, studies comparing the effect of varied feedback frequencies applied during movement retraining to alter movement patterns for individuals with knee pain have not yet been conducted. The frequency of feedback during movement retraining for individuals with knee pain varied across the studies reviewed. The majority of knee pain studies implemented high-frequency (continuous) feedback, which means that the feedback is provided in 100% of trials during each session (Simic et al. 2012; Hunt et al. 2014; Charlton et al. 2019; Booij et al. 2020). All the studies reported a significant impact of feedback gait retraining on modifying movement patterns in individuals with knee OA. However, none of these studies measured motor learning (permanence of the modified patterns) using retention, transfer skill, or multitasking. Therefore, these movement modifications may have resulted from improved motor performance, rather than learning. Reportedly, high-frequency feedback could prove advantageous as a way of greatly enhancing the performance of the trained movement pattern, whereas movement learning may be negatively impacted (Winstein and Schmidt 1990).

In contrast, faded feedback (feedback that reduces gradually over time) has been used in limited literature (Hunt and Takacs et al. 2014; Noehren et al. 2011; Willy et al. 2012; Roper et al. 2016). For instance, Hunt and Takacs (2014) implemented a ten-week treatment course involving six sessions of treadmill gait retraining for individuals with knee OA, using feedback on foot progression angle (15° toe-out angle). The amount of feedback provided was reduced over time (weeks 1 and 2 = 30 min, week 3 = 25 min, week 5 = 20 min, week 7 = 15 min, and week 9 = 10 min) (Hunt and Takacs 2014). The findings demonstrated a significant increase in the foot progression angle during post training retention (one week after the treatment course was completed during overground gait) (Hunt and Takacs 2014). Although this study had a strength, in that the 1-week short-term retention assessment used an overground gait, which represented the walking task in a real-world environment, it was not conducted over a delayed long-term period. Additionally, the lack of a control group and the unjustifiably small sample involved (n = 15) may have underpowered the study and affected the results, yielding a Type II error.

Furthermore, studies conducted by Noehren et al. (2011) and Willy et al. (2012) implemented continuous feedback across all trials during the first four retraining sessions, and then progressively reduced the volume of feedback on trials over the last four sessions. Improved hip adduction angle at post retraining 1-month and 3-month time points were presented in both studies. In addition, this improvement was translated to another unrelated task, the SLS (Noehren et al. 2011; Willy et al. 2012). The retention and translation findings suggest that faded feedback could improve motor learning.

In related feedback studies not concerning knee pain, an RCT was conducted to assess the impact of feedback timing from rehabilitative ultrasound imaging on motor performance and learning with regard to lower back muscle activity (Herbert et al. 2008). Two groups were included; a constant group, which received feedback in a continuous manner, and a variable group, which received delayed feedback after performing a number of trials (Herbert et al. 2008). The results revealed improved performance in muscle activity across both groups during the performance phase and were retained one week following the short-term retention assessment (Herbert et al. 2008). However, during the long-term retention assessment, the variable group demonstrated better performance than the constant group (Herbert et al. 2008). This could be explained by the fact that individuals may rely on the feedback given when identifying movement errors and performing modifications when feedback is given continuously (Salmon et al. 1984; Winstein and Schmidt 1990). Although this study has a rigorous design with an RCT including two comparator groups and an efficient randomisation process, it is limited by the unjustified small number of participants involved in each group (n = 15) and the dropout rate at the point of follow-up (23%). Moreover, other motor learning tests, such as skill transfer and multi-tasking, have not been conducted.

In conclusion, faded feedback timing appears to be more effective than continuous feedback as a means of improving motor learning for modified movement patterns in individuals with knee pain, based on limited experimental studies. A more robust study design, such as an RCT, is needed to compare the effect of feedback timing on motor performance and learning in individuals with knee pain.

2.7.3.3 Feedback modes

Feedback can be provided using varied external sources (e.g., visual, auditory, or haptic modes). The most common external source employed for providing feedback across the knee pain studies was the visual mode (Table 4). Visual feedback was provided in real-time based on using varied methods; mirror (Hunt et al. 2014; Willy et al. 2012; Roper et al. 2016), video camera (Hunt et al. 2014), or a 3D motion capture system providing input regarding different forms of joint kinematics displayed on a projection screen (Noehren et al. 2011; Simic et al. 2012; Hunt et al. 2014; Charlton et al. 2019; Booij et al. 2020). Conversely, feedback was haptic in nature over two studies, providing vibrations from vibrational motors that were positioned on the lateral aspect of the affected leg and the upper back to guide the patient's joint kinematics (Shull et al. 2013a; Shull et al. 2013b). Vibrations were provided when a movement performance error was detected (bandwidth feedback) based on a movement analysis system. Both studies reported a significant reduction in the foot progression angle (increased toe-in gait) following the retraining programme (Shull et al. 2013a; Shull et al. 2013b). In addition, the change in movement patterns was maintained for 1 month following the retention test (Shull et al. 2013b). The lack of a control group is considered a limitation in these studies (Shull et al. 2013a; Shull et al. 2013b). Moreover, motor learning was not measured by assessing performance over the long term or across a variety of tasks.

Regarding visual feedback studies, one study provided a comparison of three real-time visual feedback approaches (3D motion capture system, mirror, and video) and used them to guide gait retraining (by modifying the foot progression angle) for individuals with knee OA (Hunt et al. 2014). The results demonstrated that all three approaches significantly reduced the toe-out performance error in comparison to baseline. However, the toe-out performance error was significantly decreased when utilising a 3D motion capture system compared to the mirror and video camera (mean differences = 2.05° and 1.51°, respectively) (Hunt et al. 2014). Hence, the results suggested the use of real-time visual feedback for altering foot kinematics for individuals with OA provided by an optoelectronic 3D motion capture system is the superior method when compared to mirrors and videos (Hunt et al. 2014). However, visual feedback based on a laboratory-based optoelectronic 3D motion capture system may be challenging to implement in the context of a real-world environment. The main limitation of this study is the lack of a control cohort (with no feedback provided) designed to assess whether training with no feedback could improve movement patterns. Another limitation is that the study did not include learning assessment tests such as retention, transfer, and multi-tasking.

Furthermore, two studies were conducted to evaluate the effect of gait retraining on hip adduction angle in individuals with PFPS using varied visual feedback methods, such as a 3D motion capture system (Noehren et al. 2011) and a mirror (Willy et al. 2012) (Table 4). Both studies presented that retraining reduced maximum hip adduction and contralateral pelvic drop angles (Noehren et al. 2011; Willy et al. 2012). These reductions were shown to persist at 1-month (Noehren et al. 2011; Willy et al. 2012) and 3-month retention assessments (Willy et al. 2012). In addition, the reduction in maximum hip adduction angle translated to the SLS task at the end of training and after 1-month of follow-up and to the step descent task at the end of training 1- and 3-month of follow-up (Willy et al. 2012). Even though both studies employed different feedback methods, they yielded a significant effect from the feedback retraining intervention over a period of 3 months. It is noteworthy that feedback was used to target frontal hip kinematics only during the running task. Thus, using a mirror to target multiple joint kinematic variables in different planes of movement during dynamic functional activities is not deemed feasible. Consequently, the optoelectronic 3D movement analysis system is concluded to be the superior method for providing visual feedback when assessing kinematics in comparison to the mirror approach, despite its limited use within the context of clinical practice. Interestingly, movement analysis systems based on small devices such as inertial sensors have not been used as a method for delivering visual feedback in the literature on knee pain. Thus, a clinically portable 3D movement analysis method is required to provide feedback on kinematics.

Overall, according to the limited knee pain studies reviewed, the methodological limitations of the visual feedback provided by the mirror and video methods indicate that movement feedback given by laboratory-based optoelectronic 3D motion capture systems is the most effective method. However, these systems may be challenging to implement in the context of a real-world environment (clinical settings). Therefore, a robust clinic-based 3D movement analysis is needed.

2.7.4 Section summary

Individualised physiotherapy treatment interventions based on feedback regarding movement assessment could improve rehabilitation for individuals experiencing knee pain. This could be attained by helping clinicians with their clinical decision making regarding the most effective treatment intervention applied. Using individualised feedback about kinematics for retraining individuals with knee pain to perform functional activities with movement modifications seems to be a promising treatment method based on the limited body of evidence. Therefore, this suggests a need for clinically portable movement analysis methods that could be used to provide feedback information about movements.

Various methods of feedback, in terms of the information offered, delivery frequency and timing, and modes, have been used in the literature. This could assist with designing the toolkit developed in this PhD thesis by informing the best application of feedback.

Faded feedback might be more effective for enhancing motor learning and modifying movement patterns in individuals with knee pain than continuous feedback, according to several experimental studies that are limited in quality in terms of design. Furthermore, the visual feedback provided by laboratory-based optoelectronic 3D motion capture is a superior method for assessing movement in individuals with knee pain when compared to other methods, such as the use of a mirror or video. However, implementing such a movement analysis system within clinical settings is challenging. A practical movement analysis method is therefore required to provide visual feedback clarifying the individual's movement patterns in a real-world environment.

2.8 Movement analysis

Clinical movement analysis is considered an essential component when assessing individuals' joint kinematics during the performance of different functional activities within physiotherapy clinical settings. It is valuable for guiding clinicians' clinical decision making, and when managing and preventing musculoskeletal injuries, by identifying alterations in movement patterns as reported in previous sections (Kobsar et al. 2015; Watari et al. 2016). Consequently, this could lead to individualised treatment, providing the most effective rehabilitation programme to target each individual's precise needs (Gaasbeek et al. 2007; Kobsar et al. 2015). Therefore, there is a requirement to provide physiotherapy clinicians with access to movement analysis systems to accurately facilitate kinematics assessment within the real-world environment (clinical practice).

The movement analysis methods employed for quantifying kinematics data range from simple visual observation to camera-based video recordings, and more complex optoelectronic 3D systems. The most common objective method employed when assessing complex lower limb movement patterns is laboratory-based optoelectronic 3D motion capture systems (Ford et al. 2003; Boling and Padua 2013; Nakagawa et al. 2013; Jones et al. 2014). These systems are considered the gold standard for evaluating movement kinematics and kinetics in all planes of movement when performing functional tasks (Sigward et al. 2011; Munro et al. 2012). However, a key limitation of the use of such 3D systems is the lack of portability and ease of use of this technology in clinical settings (Dingenen et al. 2014; Schurr et al. 2017). This may limit the widespread application of movement analysis systems in the context of common clinical practice. Further, observed limitations include the complexity of the set-up, the need for advanced user training, the high cost of equipment, and the time required to collect and analyse the data provided by the system (Schurr et al. 2017). Therefore, an objective portable clinical movement analysis method that does not rely on expensive equipment is needed. The following sections discuss the alternative movement analysis methods used to facilitate movement analysis within clinical settings.

2.8.1 Clinical-based movement analysis methods

2.8.1.1 Two-dimensional (2D) movement analysis methods

2D movement analysis may be an inherent solution with which to address the aforementioned limitations that arise when employing laboratory-based optoelectronic 3D motion capture systems in clinical practice in terms of portability, training and time required, and cost-effectiveness (Schurr et al. 2017). This method only requires video cameras and video player goniometer software to provide angular joints' kinematics (Schurr et al. 2017). Camera-based 2D movement analysis has been used to measure the angular kinematics of lower limb joints in the sagittal and frontal planes for varied populations, including healthy and musculoskeletal diseased individuals (Alahmari et al. 2020; Kingston et al. 2020; Mousavi et al. 2020; Neal et al. 2020). Furthermore, several studies have found that the 2D method might be useful for quantifying joint kinematics during a variety of functional activities, such as squatting, jumping, hopping, and running (Willson and Davis 2008; Belyea et al. 2015; Krause et al. 2015; Herrington et al. 2017; Alahmari et al. 2020; Neal et al. 2020). The validity and reliability of applying a 2D movement analysis method are discussed in the next section.

2.8.1.1.1 Validity and reliability of camera-based 2D movement analysis methods

A limited number of previous studies evaluated the validity and reliability of the 2D movement analysis method for measuring angular lower limb joint kinematics in the sagittal and frontal planes, in order to assess individuals with knee pain (Willson and Davis 2008; Scholtes and Salsich 2017; Kingston et al. 2020; Neal et al. 2020). This section discusses these studies in turn.

Regarding the validity of lower limb angular kinematics in the frontal plane, Willson and Davis (2008) and Scholtes and Salsich (2017) compared the correlations in the measurements of hip and knee frontal plane kinematics obtained by a 2D movement analysis system with a gold-standard optoelectronic 3D motion capture system, during a SLS task involving individuals with PFPS. The quantifying of the 2D joint angular kinematics was based on a well-justified data processing method that involved the visual identification of the markers placed in various anatomical positions of interest, in order to draw lines between them and achieve consistent angles. The results demonstrated the presence of a weak correlation when quantifying the knee abduction angle (Pearson correlation coefficients r = 0.21 and 0.03, respectively) (Willson and Davis 2008; Scholtes and Salsich 2017), and a strong correlation in the hip adduction angle (r = 0.83) (Scholtes and Salsich 2017). Despite the well-justified sample sizes involved, these studies were limited by the fact that only female participants were included, and only SLS tasks were evaluated in a controlled laboratory environment. Therefore, the generalisability of the findings to males and to additional, more dynamic tasks outside the laboratory environment may be limited.

The correlation findings for the frontal kinematics at the lower limb joints aligned with the findings of two prior studies conducted with healthy participants during multidirectional landing tasks (Alahmari et al. 2020) and SLS (Schurr et al. 2017). Alahmari et al. (2020) reported a strong correlation between 2D and 3D systems when quantifying frontal hip kinematics (r = 0.70 – 0.90), and a weak correlation when quantifying frontal knee angle (r = 0.17 - 0.42) across all landing tasks (Alahmari et al. 2020). Although this study evaluated kinematics when performing a number of landing tasks, only the frontal angular kinematics at the hip and knee were assessed. Therefore, the findings of this study were not sufficiently comprehensive to evaluate other lower limb joints, such as the pelvic and ankle joints, or sagittal plane kinematics. In addition, Alahamri et al. (2020) standardised the distance between the start point and the force platform available for each participant to jump and land within. This may reduce the generalisability of the findings, as in clinical practice standardised pre-determined distances are not used.

It should be noted that although all of the previous studies employed a similar statistical methodology (Pearson product correlation coefficients) to calculate the correlation of the 2D and 3D kinematic variables, their agreement was not quantified. Quantifying agreement is crucial for demonstrating how much the two movement analysis systems differ (Peat et al. 2020). This can be achieved by combining the correlational statistical methods with the recommended Bland-Altman plots that can determine the average mean differences, and the acceptable limits of agreement (LoAs) (Peat et al. 2020).

In contrast, the study by Schurr et al. (2017) evaluated both the correlation and the agreement of the frontal angular kinematics at the lower limb joints obtained by 2D and 3D movement analysis systems, reporting a significant poor correlation between the frontal angles at the hip, knee, and ankle joints (r = 0.28, 0.03, and 0.39, respectively). These correlation findings were supported by Bland-Altman plots that revealed large average mean differences and a wide LoAs for the frontal kinematics at the hip (-8.72°; LoAs -21.90° to 4.45°), knee (-6.62°; LoAs -29.83° to 16.59°), and ankle (3.03°; LoAs -7.96° to 14.02°). However, the study was limited as the 2D video analysis used had a considerably slower frame rate than the frame rate used by the 3D system (60 Hz vs. 144 Hz). The lower frame rate of 2D systems can reduce video quality and increase parallax error (Alahmari et al. 2020; Neal et al. 2020). The differences in the two frame rates of the 2D and 3D systems can thus impact the accurate selection of the same exact frame of interest used for digitising the joint angles. Therefore, low-cost 2D video analysis systems may be limited, due to this slow frame rate.

Only one study to date has compared the high frame rates of a 2D movement analysis system using smartphone cameras (240 Hz) with a gold-standard optoelectronic 3D motion capture system when quantifying peak angular kinematics in individuals with PFPS (Neal et al. 2020). The findings reported exhibited poor correlation between the 2D and 3D systems for the outcome measures of peak knee flexion (Interclass Correlation Coefficients ICC = 0.42, 95% CI ranged from -0.10 to 0.75) and peak hip adduction (ICC = 0.06, 95% CI ranged from -0.35 to 0.47) (Neal et al. 2020). This study had several limitations, such as only including a single functional activity task (overground gait) and evaluating limited kinematic measures (peak hip adduction and knee flexion only). Moreover, data processing, which involves visually identifying the anatomical position of interest and quantifying joint angular kinematics, was conducted using a marker-less method using a relatively small touch-screen tablet (10.2-inch screen size). These marker-less methods and small screens may reduce clear observation and identification of the bony landmarks for mapping of consistent angles (Mousavi et al. 2020; Kingston et al. 2020; Schurr et al. 2017). Therefore, further evaluations of 2D movement analysis systems with high frame rates are required.

In contrast, two studies demonstrated strong correlations for knee frontal kinematics provided by 2D and 3D movement analysis during a standardised SLS (≤ 60°) ($r = 0.79$ and 0.78, respectively) (Gwynne and Curran 2014; Herrington et al. 2017). The conflict in findings could be explained by the fact that hip and knee kinematics are not purely in the frontal plane, and include some degree of rotational movement (Ageberg et al. 2010; Malfait et al. 2014), which are unquantifiable using the 2D movement analysis. Thus, the frontal joint angles obtained by the 2D system may not be a true representation of the 3D angles, as they might be influenced by an out-of-plane error resulting from the combined rotational movements (Jones et al. 2014). Furthermore, it has been found that the combination of movements across the frontal and transverse planes at hip and knee joints is increased when knee flexion increases (beyond 40°) (Cheng and Pearcy 1999). Hence, the standardised squat depth (≤ 60°) used in the current two studies may reduce the combination of rotational movements and frontal ones, and thus ensure a stronger correlation was achieved. It is therefore worth concluding that the limitation of the 2D movement analysis concerns its feasibility to assess movement in the transverse plane may impact its frontal plane measurements and therefore accuracy when used in a clinical setting.

The correlation and agreement between different 3D and 2D movement analysis methods in sagittal plane kinematics was also investigated by previous studies (Krause et al. 2015; Schurr et al. 2017; Mousavi et al. 2020). The studies by Krause et al. (2015) and Mousavi et al. (2017) examined the correlation and agreement between a 2D video camera tool (Coach's Eye application) and an optoelectronic 3D motion capture system (Vicon) when quantifying the hip, knee, and ankle angles during DLS and running, respectively. Specifically, Krause et al. (2015) evaluated the agreement using the Bland and Altman plots with 95% LoAs that revealed agreement in the average mean difference between the two analysis methods at the knee (5°; LOAs -17.6° to 7.6°) and the ankle (3.1°; LOAs -14.6° to 8.3°), but not at the hip (39.8°; LOAs -10.3° to 69.3°).

However, Mousavi et al. (2020) reported the presence of a fair to good correlation using the ICC (ICC ranges from 0.51 to 0.74). Although the number of participants involved in the latter study was rationalised based on power calculations, it had the limitation of only involving female participants who were rearfoot strikers, which may have affected the generalisability of the findings to males and/or non-rearfoot strikers.

The aforementioned correlational and agreement findings for the sagittal kinematics were consistent with those of the study conducted by Schurr et al. (2017), which reported the presence of moderate to strong correlations between the joint angles for the hip, knee, and ankle, provided by the 3D optoelectronic and 2D (Kinovea) movement analysis systems during SLS (r = 0.93, 0.86, and 0.51, respectively). These correlation findings were supported by Bland-Altman plots that exhibited agreement in the average mean difference and LoAs for the sagittal angular kinematics at the hip (2.60°; LoAs -15.48° to 20.68°), knee (0.74°; LoAs -9.70° to 11.19°), and ankle (3.12°; LoAs -8.89° to 15.14°).

In terms of reliability, multiple aspects have been examined in the literature, such as between-session, within-session, and inter- and intra-rater reliability. For between-sessions reliability, Kingston et al. (2020) evaluated the agreement between 2D frontal angular kinematics at trunk, hip, and knee obtained by one rater over two measurement sessions during SLS, DVJ, and SLDH in female participants with PFPS. The findings revealed that frontal angular kinematics proved reliable between sessions during the functional tasks (ranging from good to excellent reliability, ICC = 0.70 – 0.91) (Kingston et al. 2020). The strength of this study is that three functional activities were included, which may support the transferability of the reliability findings to other functional activities (Kingston et al. 2020). This result was supported by a number of reliability studies on healthy participants (Mizner et al. 2012; Munro et al. 2012; Gwynne and Curran 2014; Herrington et al. 2017; Werner et al. 2019). A good to excellent between-sessions reliability for 2D hip and knee frontal plane angle during all activities (ICC = 0.72 – 0.96), with standard error for measurement scores (SEM), has been reported, ranging from 1.4° to 3.82° (Mizner et al. 2012; Munro et al. 2012; Gwynne and Curran 2014; Herrington et al. 2017; Werner et al. 2019). In contrast, there were conflicting findings presenting moderate agreement in the frontal hip angle kinematic (ICC = 0.65, SEM = 1.8°) (Neal et al. 2020). This reduced reliability could be explained by the fact that a marker-less 2D movement analysis method has been used in this study (previously discussed), which may reduce standardisation and increase the variability of measurements.

Similarly, several studies assessed between-session agreement for 2D sagittal plane kinematics and found it to range from moderate to excellent (ICC = 0.54 – 0.99), with SEM ranging from 0.4° to 3.46° (Krause et al. 2015; Reinking et al. 2018; Mousavi et al. 2020). A limitation that might affect between-session reliability findings across all the studies is that during the second movement analysis measurement session, 3D movement analysis was not conducted, consequently, subtle differences in the participant's conduct might occur over the two sessions.

In terms of within-session reliability, several studies have been undertaken to assess hip and knee frontal kinematics provided by the video-based 2D method during SLS, DVJ, and SLL tasks twice in the same session (Stensrud et al. 2011; Munro et al. 2012; Gwynne and Curran 2014; Herrington et al. 2017; Scholtes and Salsich 2017). These findings have exhibited moderate to excellent within-session reliability throughout (ICC = 0.59 – 0.95). Additionally, during a running task, one study examined the within-session reliability of the sagittal plane lower limb kinematics obtained by 2D movement analysis, and reported a good to excellent agreement (ICC = 0.80 – 0.91), with SEM ranging from 0.99° to 1.90° (Mousavi et al. 2020).

Regarding inter-rater reliability, the agreement between lower limb angular kinematics in the sagittal and frontal planes as measured by two raters has been assessed in several studies during a variety of functional tasks. Reinking et al. (2018) evaluated the agreement between six raters with differing levels of experience (2 experienced and 4 inexperienced) in 2D video analysis for quantifying sagittal and frontal angular kinematics during a running task. Reinking et al. (2018) noted good to excellent reliability in the experienced raters group (ICC = 0.84 – 0.98) and in the inexperienced raters group (ICC = 0.79 – 0.98). Inter-rater reliability for lower limb sagittal kinematics when running has also been found to be excellent (ICC = 0.91 – 0.94, with SEM ranging from 0.68° to 1.60°) (Mousavi et al. 2020). The findings from these studies were supported by the findings of other researchers who have assessed 2D frontal kinematics, and found excellent reliability during SLS and SLL tasks (Scholtes and Salsich 2017; Herrington et al. 2017) and good reliability during DVJ (Mizner et al. 2012).

Limitations in the aforementioned reliability studies have been identified. First, almost all the studies have failed to mention if the rater was blinded to his/her own results or the other raters' results, or if the order of the 2D video recordings varied, apart from the Mousavi et al. (2020) study. Therefore, bias may potentially affect the findings of these studies. Furthermore, it is noteworthy that the majority of the studies included only a sample of healthy participants. The exceptions were three studies by Kingston et al. (2020), Neal et al. (2020), and Scholtes and Salsich (2017) involving individuals with PFPS. Thus, the generalisability of existing findings to other knee conditions that might be associated with a variety of movement alterations at different planes may be limited.

2.8.2 Section summary

This section reviewed a clinical camera-based 2D movement analysis method as an alternative to the gold-standard optoelectronic 3D motion capture systems. A limited number of previous studies assessed the validity and reliability of 2D movement analysis in individuals experiencing chronic knee pain. According to these studies, and others concerning healthy individuals, video-based 2D movement analysis may be a reliable tool. However, its validity, particularly for frontal plane kinematics, produced inconsistent results, and lacked generalisability to other, more dynamic, tasks outside the laboratory-controlled environment. Furthermore, several limitations were identified, in terms of the use of 2D video analysis regarding its inability to assess dynamic complex movements in the transverse plane, the reduced frame rate that is generally used, and the subjectivity associated with the data processing. Due its controversial validity and associated limitations, the use of 2D video analysis in clinical settings remains ambiguous and requires further examination. There is therefore a need for a robust movement analysis method that can quantify kinematics in all planes of movement during dynamic complex activities, within clinical settings.

2.9 Inertial measurement sensors

The limitations of optoelectronic 3D and 2D movement analysis methods have been demonstrated in the previous sections, highlighting a demand for additional technologies and methods to assess movements effectively and accurately in the context of clinical practice. The development of the technology of inertial measurement units (IMUs) is an important advancement in this field and is one that allows joint movements to be objectively evaluated during dynamic activities (Aminian 2006; Fong and Chan 2010). Compared with a laboratory-based optoelectronic motion capture system, IMUs are cost-effective, portable, easily applicable, and smaller in size, which makes them a more viable alternative (Cuesta-Vargas et al. 2010). The advantages of inertial sensors against optoelectronic systems allow for the evaluation of kinematics with larger groups of patients within a less standardised clinical environment. Similarly, compared with the 2D motion analysis method, IMU sensors can quantify joint angles in all three planes of movement, including the transverse plane during complex dynamic tasks (Cuesta-Vargas et al. 2010). The aforesaid issue of using markers with the optoelectronic 3D and camera-based 2D motion analysis methods can be avoided with sensors, since using the sensor-based motion analysis system does not require the application of markers. Moreover, inertial sensors can be applied to different body parts (upper limbs, back, and lower limbs) to measure specific movements repeatedly, providing quantitative data in addition to a three-dimensional body map (avatar) (Kobsar and Ferber 2018).

Inertial measurement sensors are increasingly being utilised to analyse lower limb kinematics objectively (van der Straaten et al. 2018). Each inertial measurement sensor comprises two essential components; the 3-axis gyroscope, and the 3-axis accelerometer, in addition to the 3-axis magnetometer in some cases (Shull et al. 2014). Accelerometers, gyroscopes, and magnetometers are used to measure acceleration, angular or rotational velocities, and magnetic fields, respectively (Shull et al. 2014). By using a sensor fusion technique, signals provided by accelerometers, gyroscopes, and magnetometers are integrated, and an accurate estimate of the position and orientation of each body segment is then created (Luinge et al. 1999; Mayagoitia et al. 2002). Integrating position and orientation data estimated from several inertial sensors linked to varied body segments, joint kinematics data involving angles and spatio-temporal parameters can be identified directly from these sensors.

The aforementioned benefits of inertial sensors for quantifying kinematics, compared to other clinical movement analysis methods, suggest the need to take further steps and test them in a real-world environment (clinics). However, prior to applying this promising alternative in clinical practice, it is vital to review the literature relating to the validity and reliability of the inertial sensors as a way to quantify joint kinematics during different functional activity tasks. The validity and reliability of sensors will be discussed in the next section.

2.9.1 Validity of sensor-based movement analysis method

Several previous studies assessed the validity of the movement analysis provided by inertial sensors as a tool for quantifying the angular kinematics of lower limb joints during various functional tasks (Favre et al. 2008; Jakob et al. 2013; Laudanski et al. 2013; Zhang et al. 2013; Palermo et al. 2014; Lebel et al. 2017; Robert-Lachaine et al. 2017; Al-Amri et al. 2018; Karatsidis et al. 2018; Teufl et al. 2018; van der Straaten et al. 2019; Shuai et al. 2021).

For the gait task, Teufl et al. (2018) evaluated the validity of IMUs compared with an optoelectronic 3D motion capture system for measuring angular kinematics at the lower limb joints in the three planes of movement in 28 healthy participants. The findings of the coefficient for multiple correlation (CMC) presented an excellent correlation between the kinematics in the sagittal plane (CMC = 0.99 – 1), and a good to excellent correlation for the frontal and transverse kinematics (CMC = 0.88 – 0.99) (Teufl et al. 2018). These correlation findings were supported by the root mean squared error (RMSE) and range of motion error (ROME) scores, which were less than 2.40° and 1.6°, respectively, for the kinematics measures at all joints (Teufl et al. 2018). Furthermore, the Bland-Altman plots were performed and revealed small average mean difference values (ranging from -0.3° to 0.9°) and a narrow LoAs for all of the kinematics in all planes (Teufl et al. 2018). This study was strengthened by its use of rigid marker clusters placed directly on sensors, in order to quantify the angular kinematics via an optoelectronic system. The use of these types of markers and this method may minimise the error between the two systems, due to soft tissue artefacts, and thus improve the accuracy of the correlation and agreement findings. Specifically, the amount of soft tissue artefacts was applied to both systems equally. However, a limitation regarding the size of the sample included was identified, since the number of participants was small and was not rationalised, which may yield a Type II error.

Another validation study, conducted by Karatsidis et al. (2018), reported an excellent correlation between the two systems for all of the sagittal kinematics at the hip, knee, and ankle joints (CMC = 0.95 – 0.99), with RSME values of less than 5.7°. However, the kinematics in the frontal and transverse planes were revealed to have a lower agreement (CMC = 0.68 – 0.91), and a higher RSME (4.1° – 9.7°). Nevertheless, the study was limited by its unjustified small sample size (11 participants), which may have limited the accuracy of its findings. In addition, information regarding how the systems collected the kinematics simultaneously was lacking. However, the validity findings for the sensor-based 3D kinematics in the sagittal plane agreed with other validation studies involving gait tasks (good to excellent agreement, CMC = 0.71 – 1.00) with acceptable RMSE scores for almost all of the kinematic measurements (< 7°) (Favre et al. 2008; Zhang et al. 2013; Palermo et al. 2014; Lebel et al. 2017; Al-Amri et al. 2018; Shuai et al. 2021).

For the squat tasks, Shuai et al. (2021) assessed the validity of a sensor-based movement analysis system against the gold standard optoelectronic 3D motion capture system when quantifying the angular kinematics at the hip, knee, and ankle joints in the three planes of movement during DLS and SLS tasks. The findings exhibited an excellent correlation for all of the joints in the sagittal plane (CMC > 0.81), and a moderate to excellent correlation in the frontal and transverse planes (CMC > 0.62). The RSME values ranged from 4.69° to 10.78°. However, the credibility of the findings may have been limited by the unjustified small sample size (20 participants), which may yield a Type II error. Also, the findings may have been affected by the skin movement artefact, as the sensor placed on the sacrum, and the marker located in the centre of the posterior superior iliac spine may have slightly shifted during the large ROM of the squat tasks. Nevertheless, the findings of the study were consistent with other, similar studies in the extant literature (Robert-Lachaine et al. 2017; Al-Amri et al. 2018; Teufl et al. 2018). The sensor-based movement analysis system therefore possesses a good to excellent correlation for all joints in the three planes of movement (CMC > 0.71), with small RSME scores (< 7°), particularly for the sagittal and frontal kinematics (Robert-Lachaine et al. 2017; Al-Amri et al. 2018; Teufl et al. 2018).

For the jump task, a limited number of previous studies evaluated the validity of the sensor-based movement analysis for measuring angular kinematics at the lower limb joints in the three planes of movement (Jakob et al. 2013; Al-Amri et al. 2018; Teufl et al. 2018; Shuai et al. 2021). The sagittal kinematics produced revealed excellent agreement between the sensors and the optoelectronic motion capture system (CMC > 0.90) (Jakob et al. 2013; Al-Amri et al. 2018; Teufl et al. 2018; Shuai et al. 2021), while the lower limb kinematics in the frontal and transverse planes presented a good to excellent agreement (Teufl et al. 2018; Shuai et al. 2021).

For the stair negotiation tasks, Zhang et al. (2013) reported an excellent correlation between the angular kinematics at the hip, knee, and ankle joints in the sagittal plane (CMC > 0.81), whereas a moderate to excellent correlation was found for the frontal and transverse plane kinematics (0.50 > CMC > 0.85). The ROME were smaller than 5° for all of the joint angular kinematics in all planes. However, the number of participants included in the study was small (10 participants) and not rationalised, which may have limited the accuracy of its findings. These correlational findings concurred with the findings of other studies for sagittal angular kinematics (CMC > 0.93) (Bergmann et al. 2009; Laudanski et al. 2013), and frontal and transverse kinematics (CMC > 0.61) (Laudanski et al. 2013).

Although the validation findings for the frontal and transverse kinematics during all of the functional activities assessed were good, ranging from moderate to excellent agreement (CMC = 0.50 – 0.96), they were lower relative to the findings for the sagittal kinematics reported in the majority of the existing literature (Favre et al. 2008; Zhang et al. 2013; Palermo et al. 2014; Lebel et al. 2017; Al-Amri et al. 2018; Karatsidis et al.

2018; Shuai et al. 2021). Lower validity findings for the angular kinematics in the frontal and transverse planes could be explained by the fact that the range of movements of the lower limb joints in these planes is smaller, relative to the ranges in the sagittal plane. Thus, sagittal kinematics tend to be detected and quantified more easily by the two movement analysis systems. In addition, all of the aforementioned validity studies were conducted in laboratory settings, where the environment is controlled. The findings of research conducted in such settings may not necessarily be translatable to real-world clinical settings. There is therefore a need for future studies that evaluate the validity of inertial sensors within clinical settings. Moreover, all of the studies discussed were conducted by examining healthy participant populations only. This may have affected their generalisability, since individuals with knee pain are more prone to exhibiting altered movement patterns than healthy individuals.

In summary, sensor-based movement analysis has the accuracy necessary for use in the quantification of lower limb joint kinematics, particularly in the sagittal and frontal planes, during various functional activities.

2.9.2 Reliability of sensor-based movement analysis method

Several previous studies assessed the reliability of using the movement analysis system provided by IMUs to measure the angular kinematics of the lower limb joints during gait, squat, and jump tasks (Cloete and Scheffer 2010; Nüesch et al. 2017; Teufl et al. 2018; Al-Amri et al. 2018; Poitras et al. 2019; van der Straaten et al. 2019; Shuai et al. 2021). A systematic review conducted by Poitras et al. (2019) assessed the inter- and intra-rater reliability for quantifying angular kinematics at the hip, knee, and ankle joints in all planes of movement during gait and jumping tasks. The results demonstrated a fair to excellent intra- and inter-rater reliability for all of the lower limb angular kinematics in all planes during the gait task (ICC ranging from 0.4 to 0.95), while a poor to excellent reliability was found for the jump task (ICC ranging from 0.39 to 0.99). The findings of this systematic review may have been limited by the fact that all of the studies included were only of moderate quality.

Meanwhile, van der Straaten et al. (2019) evaluated the reliability when using Xsens MVN sensors (Xsens Technologies, Enschede, The Netherlands) between sessions, and raters to quantify the lower limb kinematics in all planes, during the SLS and the STS, which is comparable to the DLS. The results revealed that all of the reliability findings (within-session, between-session, and between-raters) in the sagittal plane during both tasks concerned were fair to excellent (ICC ranging from 0.52 to 0.96). In the transverse plane, a fair to excellent reliability was found across all of the reliability findings during the STS task (ICC ranging from 0.51 to 0.97), and it was poor to excellent (ICC range 0.20 to 0.84) during the SLS task. For the frontal plane, all of the reliability findings demonstrated a fair to excellent reliability across all of the lower limb joints during both tasks (ICC ranging from 0.53 to 0.87), except the within-session reliability at the ankle joint during SLS, which produced a poor to fair reliability (ICC ranging from 0.37 to 0.41), and the between-sessions and between-raters reliability for the hip kinematics during the STS task, which produced a poor reliability (ICC ranging from 0.00 to 0.14). A key strength of this study was the detailed instructions provided to its participants regarding the performance of different functional tasks, in order to standardise the performance of the activity tasks between the trials tested. Standardising the performance across the trials and sessions may have improved the comparability of the findings. However, the small size of the sample included, and the lack of a rationale for the number of participants involved, may have limited the study's findings.

Moreover, Al-Amri et al. (2018) demonstrated that a sensor-based movement analysis system possesses excellent between-sessions reliability (same rater) for sagittal kinematics at all lower limb joints during gait, squat, and jump tasks (ICC > 0.75), whereas joint kinematics in the frontal and transverse planes exhibited fair to excellent between-sessions reliability (ICC = 0.40 – 1.00). Furthermore, there was fair to excellent within-session (two raters) reliability for kinematics in all planes during walking and squatting (ICC > 0.60), but within-session reliability proved lower for jumping kinematics in the transverse plane (ranging from poor to excellent reliability) (Al-Amri et al. 2018). Despite the advantages of assessing within- and between-session reliability during three varied functional activities, and the well-justified sample size included, only healthy participants were included, which may limit the generalisability of the findings. In addition, a lack of standardising of the participant's performance of activity tasks was identified, as the participants were not given any instructions about how to perform them, which may have affected the consistency of the trials.

The inter-rater reliability findings for the sensor-based 3D kinematics in all planes of movement were in line with other studies involving gait, DLS, SLS, and VJ tasks (Cloete and Scheffer 2010; Nüesch et al. 2017; Teufl et al. 2018; Shuai et al. 2021). The findings exhibited excellent agreement for lower limb kinematics in the sagittal plane (Cloete and Scheffer 2010; Nüesch et al. 2017; Teufl et al. 2018; Shuai et al. 2021), and a fair to excellent agreement in the frontal and transverse planes (Cloete and Scheffer 2010; Teufl et al. 2018; Shuai et al. 2021). The lower reliability results for frontal and transverse angular kinematics, when compared to those in the sagittal plane, might be explained by the greater range of movement presented across the planes, as discussed previously in the validation studies (section 2.9.1).

Similarly to the validity studies, there were two issues regarding the transferability and generalisability of the findings of the reliability studies. Firstly, all of the reliability studies were conducted using a healthy sample. Secondly, all of the reliability studies to date were conducted in laboratory settings, where the environment is controlled. There is therefore a need to evaluate the reliability of sensor-based movement analysis in populations with knee pain, within clinical settings.

In conclusion, movement analysis systems using IMU sensors may have the consistency necessary for use in the quantification of lower limb joint kinematics in different planes of movement, during various dynamic functional activities.

2.9.3 Section summary

The technology of inertial measurement sensors has several advantages, compared with that of optoelectronic motion capture systems, such as the portability, size, and space requirements. In addition, sensor-based movement analysis systems are broadly valid and reliable, in terms of measuring movement across all planes during various activities. Based on these findings, the movement analysis provided by IMU sensors can be alternated with the gold-standard optoelectronic 3D motion capture in clinical settings. This informed the design of the movement analysis feedback toolkit intended to be developed, specifically by considering the use of inertial sensors as a means of offering feedback. However, before using it in a clinical setting, it is crucial to identify how the kinematic data provided by the sensor-based 3D movement analysis can be reported and interpreted by physiotherapy clinicians, in order to enhance their treatment of individuals with knee pain. This issue is discussed in detail in the next section.

2.10 Reporting and interpreting kinematic data provided by 3D movement analysis

Using IMU sensors to analyse and provide feedback regarding individuals' movements can generate a huge volume of kinematic data, based on the vast array of data assessed at multiple joints, in different planes, during functional tasks (Benedetti et al. 2017). The large volume of kinematic data is therefore a key challenge, in terms of affording clinical access to, and use of, kinematic data. It is therefore recommended that all kinematic findings are formulated in a user-friendly format that includes a range of outputs that summarise the key data effectively, and present it in a straightforward manner (Baker 2013). This can yield greater value, in terms of promoting the clinical utility of kinematic data among physiotherapy clinicians, and when providing patients with access to their kinematic assessments (Baker 2013). In order to achieve this, a movement analysis feedback report in a graphical waveform format that represents the kinematic and/or kinetic data at multiple lower limb joints and planes for the patient's limbs, both the affected and non-affected sides, compared with normative data of asymptomatic individuals during the entire movement cycle is required. The graphical representation of the kinematic variables during the entire movement cycle in a waveform format facilitates a visual analysis of an individual's movement performance throughout a task that can assist clinicians with their clinical decision-making (Baker 2013).

The interpretation of angular kinematic data presented in waveform format is based on two elements: the identification of the presence of altered movement patterns, and descriptions of the altered patterns identified (Skaggs et al. 2000). Physiotherapy clinicians (users) are required to possess skills in both of these aspects, in order to confirm a robust and consistent interpretation, and thus inform robust and consistent clinical decision making (Skaggs et al. 2000). However, arguably, the interpretation of the kinematic findings can be subjective in nature, and consequently, the treatment planning and recommendations based on them can be linked to variability or sub-optimal care at the clinical level (Skaggs et al. 2000). It is thus unclear how clinicians can interpret kinematic data in an accurate and consistent manner. Therefore, the extant literature regarding the reporting and interpretation of kinematic data was reviewed, and is discussed in this section.

Several previous studies investigated raters' agreement in interpreting the biomechanical data obtained by various movement analysis methods, during gait (Brunnekreef et al., 2005; Nieuwenhuys et al. 2017; Wang et al. 2019). The study conducted by Nieuwenhuys et al. (2017) assessed the agreement between and within two cohorts of raters (experienced and unexperienced) for interpreting the kinematic and kinetic gait data provided by an optoelectronic 3D gait analysis for 82 children with spastic cerebral palsy. The interpretation process involved the identification of the presence of various gait alterations by stating 'Yes' or 'No' on a list of movement alterations presented during the different gait phases (Nieuwenhuys et al. 2017). The agreement results revealed a substantial to almost perfect agreement for all of the kinematic data for the pelvis, hip, knee, and ankle joints (within-rater Kappa = 0.64 - 0.91; between-rater Kappa = 0.63 - 0.86), apart from the knee kinematics during the stance phase, which showed a moderate agreement (Kappa = 0.49). The study was strengthened by its inclusion of the necessary sample size, based on power calculations, and its involvement of raters with various levels of experience. However, the agreement in identifying the presence of gait alterations was evaluated by the study without considering how the alterations were qualitatively described.

Similarly, Wang et al. (2019) assessed the agreement among seven experienced orthopaedic surgeons when interpreting 3D gait biomechanical data (kinematics, kinetics, electromyography, and video) for a sample of 15 children with gait abnormalities. The raters were instructed to interpret the data by identifying the existence of gait alterations and stating 'Yes' or 'No' on a list of gait problems, without describing them (Wang et al. 2019). The results exhibited a moderate agreement among the raters (averaged Kappa = 0.55). However, the study was limited by the fact that it only included raters who were experienced orthopaedic surgeons. Moreover, the biomechanical data analysed and interpreted was obtained from a limited number of participating children, and may therefore not have been representative of various gait alterations.

It should be worth noting that the aforementioned studies evaluated the raters' interpretation of the kinematic data based on identifying the presence of gait alterations. This was achieved by presenting 3D movement analysis data stating 'Yes' or 'No' only on a list of specific gait problems (Wang et al. 2019), and a list of specific movement alterations that occurred during various gait phases (Nieuwenhuys et al. 2017). However, the way in which these kinematic alterations was qualitatively reported and described by the raters was not investigated. Moreover, none of the aforementioned studies were conducted with a sample with knee pathologies and/or during other functional tasks, such as squatting, jumping, or stair negotiation. There is therefore a need for future studies that investigate these aspects of the interpretation of the movement alterations performed by individuals with knee pain, during various tasks. Despite these gaps in current knowledge, these studies suggested that standardising the way in which raters interpret the data obtained may enhance their agreement, yielding more consistent results. It is thus crucial that future studies consider the issue of standardisation.

Meanwhile, Brunnekreef et al. (2005) evaluated the agreement within and between experienced and inexperienced raters when analysing 2D video recordings to identify the movement alterations present in 30 individuals with orthopaedic impairments. The interpretation of the video recordings was conducted by 10 raters, using a standardised gait analysis template with 12 items for movement patterns at the trunk, arm, pelvis, hip, knee, and ankle, throughout the gait cycle. The agreement results revealed a moderate between- and within-rater agreement (between the experienced raters of ICC = 0.42, between the inexperienced raters of ICC = 0.40, within the experienced raters of ICC = 0.63, and within the inexperienced raters of ICC = 0.57). It was noted that the agreement findings may have been affected by the form of the kinematic data used, as analysing 2D video recordings requires a clear observation of movements in different planes that it is considered to be challenging for raters to identify visually. For instance, Brunnekreef et al. (2005) found that there was a lower between-rater agreement for the template's items that were considered to be difficult to identify, such as pelvic alterations in the transverse plane, compared with other items with an easier set of alterations at the knee in the sagittal plane (ICC ranges = 0.19 – 0.33 vs 0.58 – 0.60, respectively). As a result, the visual observation of 2D video recordings may be inaccurate and inconsistent for evaluating the movement patterns throughout the entire gait cycle, and thus quantitative assessment based on a more robust 3D movement analysis would be crucial. This finding was consistent with that of other previous studies (discussed in Section 2.8.1.1.1), regarding the limitations associated with the use of 2D video analysis for quantifying that kinematics at different planes of movement.

2.10.1 Section summary

A limited number of previous studies assessed the interpretation of the kinematic data provided by movement analysis methods for a varied pathological sample of interest during gait tasks. There is therefore a need to investigate clinicians' interpretations of the movement alterations performed by individuals with knee pain during various functional tasks. Also, both aspects of the interpretation, namely the identification of the presence of movement alterations, and the description of the alterations identified, should be investigated. Despite their limitations, these studies suggested that access to a clear, consistent, and comprehensive method may improve the consistency of users' interpretation of biomechanical data (Brunnekreef et al., 2005; Nieuwenhuys et al. 2017; Wang et al. 2019). It is thus necessary to standardise the mode of reporting and interpreting the altered movement patterns identified across movement analysis reports, as this will deliver significant advantages for the clinical movement analysis community (Baker 2006). Considering this in the development of SMAFT had the potential to enhance its design and delivery within clinical practice.

2.11 Literature review summary

A reduction in physical activity is the main characteristic of individuals with knee pain, due to activity-related pain (Dunlop et al. 2011; Wallis et al. 2013; Hurley et al. 2015). Over time, such individuals may gradually lose their ability to perform their main daily functional activities (Vos et al. 2020). This reduction in functional level for individuals with knee pain can impact their physiotherapy treatment negatively, and reduce its effectiveness (NICE 2022). One of the key factors that can cause a reduction in the level of functional capability is the movement alterations performed by individuals in response to pain, as suggested by the pain adaptation theory (Hodges and Tucker 2011). These unnecessary alterations may sustain over time, due to the reduced movement variability and increased load, causing further pain, and reducing physical function (Hodges and Tucker 2011; Merkle et al. 2020).

A review of the extant literature in this field identified the presence of a wide range of altered movement patterns in individuals with knee pain (McKenzie et al. 2010; Bolink et al. 2012; Nakagawa et al. 2012; McCarthy et al. 2013; Nakagawa et al. 2015; Rahman et al. 2015; Tadano et al. 2016; Severin et al. 2017; Ismailidis et al. 2020; van der Straaten et al. 2020; Ismailidis et al. 2021). These alterations were identified in the three planes of movement during various functional activities, such as gait, DLS, SLS, VJ, SA, and SD. Although there were few common altered movement patterns, the inconsistency in the altered movement patterns identified in individuals with knee pain concurred with the pain adaptation theory, suggesting a highly personalised change to kinematics in response to knee pain (Hodges and Tucker 2011). These findings suggested that physiotherapy practice should consider the unnecessary movement alterations present during the performance of various functional activities, and individualise treatment accordingly.

Using individualised kinematic feedback for the movement assessment of individuals with knee pain could benefit their rehabilitation. This might be achieved by assisting physiotherapy clinicians with their clinical decision making regarding the most effective treatment intervention to use (Gaasbeek et al. 2007; Kobsar et al. 2015; Hickey et al. 2016; Dessery et al. 2017; Hanada et al. 2018; Tsai et al. 2020; Ye et al. 2020).

Furthermore, movement retraining for individuals with knee pain, based on kinematic feedback whilst performing functional activities, appears to be a promising treatment intervention (Noehren et al. 2011; Willy et al. 2012; Simic et al. 2012; Shull et al. 2013a; Shull et al. 2013b; Hunt and Takacs 2014; Roper et al. 2016; Charlton et al. 2019; Booij et al. 2020). Despite this effect, there is a current gap in literature in this regard, as it has not been evaluated within a real-world environment, such as clinical practice, as all of the existing studies were conducted in controlled laboratory settings. Moreover, the review of the existing literature suggested that the visual feedback provided by optoelectronic 3D motion capture is the superior method for assessing movement and retraining individuals with knee pain (Willy et al. 2012; Hunt et al. 2014). However, it is challenging to implement in clinical practice, due to its lack of portability and ease of use (Dingenen et al. 2014; Schurr et al. 2017). These current gaps indicated a need for a robust portable movement analysis method that could be used to provide feedback information about movement in clinical settings.

One option that might be used for providing visual feedback in clinical settings, as an alternative to the gold-standard optoelectronic 3D motion capture, is to use the camera-based 2D movement analysis method (Gwynne and Curran 2014; Krause et al. 2015; Herrington et al. 2017; Schurr et al. 2017; Mousavi et al. 2020). However, the findings of the previous literature indicated that 2D movement analysis is controversial, due to its inconsistent validation findings, particularly for frontal plane kinematics. Also, 2D movement analysis is associated with several limitations, such as the inability to evaluate dynamic complex movements in the transverse plane, its limited frame rates, and the subjectivity associated with the data processing, all of which may limit its clinical use.

The technology of inertial measurement sensors is an option for an alternative approach. Compared with the optoelectronic 3D motion capture system, inertial sensors are portable, easily applicable, and smaller in size (Cuesta-Vargas et al. 2010). Previous studies investigated the validity and reliability of sensor-based movement analysis, and found that it possesses adequate accuracy and consistency for quantifying kinematics in all planes, during different functional tasks (Laudanski et al. 2013; Zhang et al. 2013; Al-Amri et al. 2018; Karatsidis et al. 2018; Teufl et al. 2018; van der Straaten et al. 2019; Shuai et al. 2021). This indicated that the sensor-based movement analysis method is the most suitable method to use in clinical settings as an alternative to the gold-standard motion capture systems. This informed the design of the movement analysis feedback toolkit intended to be developed, which considered the use of inertial sensors as a means of offering feedback. However, sensor-based movement analysis can generate a huge volume of kinematic data that can limit its clinical access and use, in terms of reporting and interpreting the data (Benedetti et al. 2017). Hence, there is a need for a kinematic report that presents the kinematic data at different joints and planes of movement, and for different activity tasks, during the entire movement cycle, in a user-friendly format (Baker 2013).

It has been argued that the interpretation of the kinematic data provided by 3D movement analysis may be subjective in nature, which can cause variability in clinical decision making (Skaggs et al. 2000). The review of the extant literature regarding the clinical interpretation of kinematic findings indicated that there is currently a gap in the field of knowledge, as this has not been evaluated in populations with knee pain, during various functional activities. According to previous studies conducted with children with cerebral palsy during gait tasks, standardising the means of interpretation may enhance users' accuracy and consistency in interpreting kinematic data (Nieuwenhuys et al. 2017; Wang et al. 2019). There is therefore a need to evaluate users' interpretation of the kinematic findings provided by a sensor-based movement analysis method, during a range of functional activities, in individuals with knee pain. This may help to standardise the means of interpreting kinematic data among users. It is therefore crucial to consider this suggestion before implementing a movement analysis method within clinical practice.

The findings of the literature reviewed in this chapter identified the rationale and evidence base for developing a clinic-based movement analysis feedback toolkit, as recommended by the MRC framework (Skivington et al. 2021). Moreover, the literature review provided guidance for the design of the toolkit, which involves inertial sensors, a kinematic report, and a reporting framework. This has the potential to optimise physiotherapy practice by informing clinical decision making and individualising treatment plans for individuals with knee pain.

2.12 Thesis Aim

The overall aim of this thesis is to further develop and evaluate the acceptability of a sensor-based movement analysis feedback toolkit (SMAFT) for clinical practice using an iterative process. This toolkit can be used when assessing and treating individuals with knee pain.

A report for displaying kinematic data from inertial sensors was developed in a previous study (K.N.) (more details about the development of the kinematic waveform report will be presented later in chapter 3, section 3.2). In this PhD, a framework for interpreting the kinematic waveforms was designed; this is known as the standardised reporting template (Phase I). The kinematic report was used alongside the standardised reporting framework to create a preliminary version of SMAFT. SMAFT was then used in an acceptability study (Phase II).

2.12.1 Objectives

1) To create a standardised reporting framework to improve clinicians' accuracy and consistency when interpreting the kinematic data provided by 3D movement analysis (phase 1).
2) To explore the acceptability of SMAFT from the perspective of its users (individuals with knee pain and their treating physiotherapy clinicians) when used for individuals with knee pain within the physiotherapy clinical practice of a University Health Board (UHB) (phase 2).

Chapter 3. Phase I: Development of the sensor-based movement analysis feedback toolkit (SMAFT)

3.1 Introduction

The previous literature review chapter provided evidence supporting the importance of developing a portable movement analysis toolkit within the context of clinical practice, affording individualised feedback concerning the altered movement patterns presenting in individuals with knee pain. Therefore, this chapter details the first phase of the thesis, addressing the development of SMAFT. This phase involves a developmental study, and was in part informed by a project conducted by a PhD student examining the development of SMAFT. In this phase, the study investigated whether kinematics data outcomes obtained via the sensor-based movement analysis can be interpreted by physiotherapy clinicians in an accurate and consistent manner, leading to the development of a standardised reporting framework. The results of the study will be linked to developing a movement analysis feedback toolkit for individuals with knee pain, consequently to inform the second phase (acceptability of SMAFT within clinical practice) and future studies.

3.2 Previous works on the development of SMAFT

Providing a summary of previous works conducted prior to the development SMAFT is crucial to provide a comprehensive view of what has been done and inform the next stages in the development. Several studies were conducted by the lead researcher of this thesis (M.F.) and one PhD student (K.N.) within our research group, in order to develop a movement analysis feedback toolkit, provided by inertial portable sensors. Table 5 presents the stages of the development of SMAFT, including a summary of all the studies conducted. In the first stage, the validity and reliability of the sensor-based movement analysis system were evaluated by a PhD student (K.N.) during various functional tasks (gait, squatting, and jumping) (Al-Amri et al. 2018; this study was discussed in Chapter 2, sections 2.9.1 and 2.9.2). This study concluded that the sensor-based movement analysis system had sufficient accuracy and consistency to quantify the angular kinematics of the lower limb joints in different planes. When combining the findings with those of the literature review conducted for this thesis, it was determined that the use of the inertial sensors as a mean to provide kinematic data in the potential movement analysis toolkit was justified.

In addition, a comparison between a sensor-based 3D movement analysis and a camera-based 2D video analysis for quantifying lower limb joint angular kinematics during DLS, SLS, and SLDH tasks was conducted by the lead researcher (M.F.) (Table 5 and Appendix B). This was conducted to compare the use of a sensor-based movement analysis with a 2D video analysis, in order to determine whether it had a place in clinical settings. In addition, this study was conducted for training purposes, specifically for the lead researcher (M.F.) to practice the data collection and analysis using the kinematic data provided by the IMU sensors. The study suggested the two systems were not comparable as a means of quantifying joint angular kinematics in the sagittal and frontal planes. This poor correlation and agreement could be explained by limitations associated with the use of a 2D video analysis, and can be eliminated using a sensor-based movement analysis (Table 5 and Appendix B). However, due to the huge volume of angular kinematic data obtained by the sensor-based movement analysis system, including data derived from different joints in several planes of movement when performing functional activities, this study suggested a need to collect and present the kinematic data in a user-friendly report (Baker 2013).

An immediate, and attainable movement analysis report was therefore developed. This was intended to facilitate the use of a sensor-based 3D system by its users (physiotherapy clinicians and individuals with knee pain), and to provide them with access to kinematic assessment. This report was developed by our research group, in adherence with the recommendations reported by Baker (2013). A custom-written code based on MATLAB software (MATLAB version 9.6.0.1150989 (R2019a) Update 4) was developed to generate the report (Nicholas et al. 2018; Davies et al. 2021). The report was designed to display the kinematic data (temporo-spatial and joint angle waveforms) obtained from the inertial sensors for the joints in the lower limbs, namely the hip, knee, and ankle, as well as in the sagittal and frontal planes, during different functional tasks, including gait, DLS, SLS, VJ, SA, and SD. The inclusion of these functional activities was justified in the current chapter, see section 2.6.1).

The kinematic report created by K.N. includes the following information for each individual:

- The individual's details, including the side of the knee joint affected, and the date and location of the movement analysis session (first page) (Figure 3a);
- A summary of the performance measures, including the temporo-spatial measures for gait, the squat duration for the double leg squat, and the step duration for the stair ascent (second page) (Figure 3b);
- Graphs present the average joint angle waveforms for the hip, knee, and ankle joints in the sagittal and frontal planes, during the movement cycle. Each graph presents the waveform for both the affected and unaffected sides (subsequent pages) (Figure 3c).

However, this report did not interpret the kinematic waveforms for users, so physiotherapy clinicians and patients can make their own interpretation of the kinematic findings presented in the report, and use this to guide their clinical decision making, to inform treatment planning, and to monitor progress. In my research, I designed a template to support users in reporting and interpreting the movement patterns presented within the pre-developed kinematic waveform report (Phase I). In Phase II of my research, I combined the sensor-based kinematic report created by K.N. with the standardised reporting framework created by me to form SMAFT.

In the second stage, two exploratory qualitative studies were conducted by K.N. In the first study, physiotherapists were interviewed to explore their opinion of the sensors-based kinematic waveform report, and its potential acceptability within physiotherapy practice for anterior cruciate ligament (ACL) rehabilitation (Nicholas et al. 2019). In the second study, the acceptability of using the sensors-based kinematic waveform report to patients undergoing rehabilitation following anterior cruciate ligament reconstruction (ACLR) was examined. Neither of these studies included the standardised reporting framework created by me. The studies by K.N. found that the kinematic waveform reports were usable by clinicians and patients, as they helped to educate, inform, and motivate them. This was informed by the quantifiable kinematic data presented in a visualised format. However, some recommendations and suggestions were indicated. The recommendations for the kinematic waveform report were as follows:

- Stick figures to illustrate the movement required to perform each functional activity task should be integrated into the kinematic waveform graphs. This will help physiotherapists identify the time event when the altered movement patterns occur along the entire movement cycle.
- Consistency plots should be included to illustrate the joint angle waveforms for all of the movement trials performed before they are averaged.

It was also found that the physiotherapists involved were not consistent in the way they described the movement patterns displayed in the kinematic waveforms. It was thus unclear at this stage whether the physiotherapy clinicians were able to interpret the kinematic data provided in the feedback report in an accurate and consistent manner. Therefore, there is a need for a template to assist the clinicians interpret the kinematic data. This was done by myself in Phase I of this PhD thesis. The intended impact of this work was that the standardised reporting framework would be used alongside the sensor-based kinematic waveform report to create SMAFT.

Moreover, although the sensor-based kinematic report was considered acceptable by the patient participants, there was a need to adapt it to the knee pain context. Hence, it was necessary to investigate the acceptability of it by individuals with knee pain, and their physiotherapy clinicians, within a real-world context (clinical practice). This was conducted by the lead researcher (M.F.) using an exploratory mixed-methods case study design, which will be presented in chapter 4 (Phase II) of the current thesis.

In conclusion, the previous research in this field, and the preparatory study conducted for this PhD, were vital for the development of SMAFT. However, further research and investigation was required regarding clinicians' interpretation of kinematic waveform data (Phase I of this PhD thesis). It was crucial that this be conducted before using SMAFT for the population with knee pain, and before testing it within the context of clinical practice (Phase II of this PhD thesis).

Table 5: The stages involved in developing SMAFT

Stages	Studies	Author	Aims and methods	Main results and implications
Stage I	**Validity and reliability of the sensor-based movement analysis**	PhD student (K.N.) thesis (Al-Amri et al. 2018)	- The aim of this study was to investigate the reliability and validity of a sensor-based 3D movement analysis when quantifying lower limb joint angular kinematics during clinically relevant functional activities (gait, SLS, and VJ). - Two raters assessed the joint angular kinematics obtained from 26 healthy participants using optoelectronic and sensor-based 3D movement analysis systems. - The Interclass Correlation Coefficient (ICC) and a standard error of measurement were used to assess the reliability, and the coefficient of multiple correlation (CMC) and the linear fit method were used to assess the validity.	- Within- and between-rater reliability exhibited acceptable to excellent agreement across various functional tasks and planes of movement. - Sensor-based movement analysis has sufficient accuracy and consistency. - Sensor-based movement analysis can be used in a dynamic, high-speed functional task, such as jumping.
	Comparisons between using 2D video and sensor-based movement analysis	Lead researcher (M.F.) (included in the current	- The aim of this study was to examine the correlation and agreement between sensor-based 3D movement analysis and camera-based 2D video analysis when quantifying lower limb joint angular kinematics during DLS, SLS, and SLDH tasks. Also, this study was done to train the lead researcher of the current	- This study suggested that the two systems were not comparable for quantifying joint angular kinematics in the sagittal and frontal planes. - Less correlation and agreement were found for the angular kinematics in the frontal plane

	systems for assessing lower limb joint kinematics during several clinically relevant tasks	thesis, Appendix B)	thesis (M.F.) in data collection and analysis using kinematic data provided by the IMU sensors. - A convenience sample of 25 healthy volunteers was recruited, and joint angular kinematics were collected at the peak knee flexion (PKF) using the two systems. - Sensor-based 3D movement analysis: 17 wireless Xsens MTw2 IMU sensors (Xsens Technologies, Enschede, The Netherlands) were placed on the participants' body to collect kinematic data, quantified using the Xsens MVN Analyze software package (Xsens Technologies, Enschede, The Netherlands). - Camera-based 2D movement analysis: Two GoPro (GoPro Inc., California, USA; version GoPro Hero 5.1) cameras were used to record the performance of functional tasks in video episodes, and Kinovea software (version 0.8.27; Kinovea Open-Source Project, www.kinovea.org) was used to quantify the kinematic data. - The ICC test and the Bland-Altman plots were used to assess the correlation and agreement.	compared with the kinematics in the sagittal plane. - The 2D mean frontal angular kinematics at the hip and knee joints were overestimated when compared with the 3D mean angles, especially during the DLS task. - This poor correlation and agreement may have been due to the limitations associated with the use of the 2D video analysis (the inability of the 2D video analysis to quantify the transverse plane movements that could be associated with those of the frontal plane, the subjective identification of the PKF and quantification of the 2D joint angles, and the reduced 2D frame rates). These limitations could be eliminated using a sensor-based movement analysis. - Sensor-based movement analysis is suitable for use in clinical practice.

				- Physiotherapy clinicians should consider using sensors-based 3D movement analysis for quantifying angular kinematics, especially if they are seeking a more usable comprehensive movement analysis method for use in clinics that includes sagittal, frontal, and even transverse plane kinematics. - There is a need to identify how the 3D kinematic data can be presented to physiotherapy clinicians, and interpreted by them, and whether such data can impact their clinical decision making.
	Sensor-based movement analysis feedback report development	PhD student (K.N.) thesis (Nicholas et al. 2018;	- Sensor-based movement analysis provided users with a huge volume of angular kinematics data obtained by the sensor-based movement analysis system, involving data from different joints in several planes of movement when performing functional activities.	- A sensor-based kinematic waveform report was developed by our research team, according to Baker (2013). - The report represented kinematics data for joints in the lower limbs (e.g., hip, knee, and ankle) in the sagittal and frontal planes during

		Davies et al. 2021)	- The aim of this study was to develop a sensor-based movement analysis report, in order to present kinematic data in a user-friendly, immediate, and attainable format.	a variety of functional tasks (Gait, DLS, SLS, VJ, SA, and SD). - An investigation the use of the report by its users is required.
Stage II	**Acceptability of the sensor-based kinematic waveform report by physiotherapy clinicians (Study 1)**	PhD student (K.N.) thesis (Nicolas et al. 2019)	- The aim of this study was to investigate the acceptability of sensor-based kinematic waveform reports among physiotherapy clinicians. - Training sessions for physiotherapy clinicians were conducted in five physiotherapy departments and orthopaedic knee clinics within C&V UHB. The training involved introducing inertial sensors and kinematic waveform reports (contents and uses). - Kinematic data was collected from individuals who had undergone ACLR and received physiotherapy rehabilitation. The individuals performed various functional tasks in a clinical context (gait, DLS, SLS, VJ, SA, and SD). The functional task selection was based on the researcher's clinical decision making and time since ACLR surgery.	- Four key themes were identified (usability; clinical integration and decision making; behaviour change; and previous, current, and future use of the sensor-based kinematic waveform report). - The report appeared usable by the clinicians, with no major challenges in terms of its clinical usability. - Identifying individuals' altered movement patterns by clinicians may result in more personalised physiotherapy treatments. - Recommendations for the future design of the report were indicated (stick figures and consistency plots). - The interpretation of the kinematic data by physiotherapy clinicians, including the

			- Reports, representing temporo-spatial and joint angular kinematics at the hip, knee, and ankle joints in the sagittal and frontal planes, were uploaded for the physiotherapists. - Semi-structured interviews with eight of the physiotherapists who received feedback reports were conducted. - The interviews explored clinicians' opinions of the feedback report received. - A framework analysis was used to analyse the qualitative data collected.	terminology used to describe the altered movement patterns identified, varied. It was unclear in the current stage if physiotherapy clinicians would be able to interpret the kinematic data provided within the report accurately and consistently. There is therefore a need for further research, before testing SMAFT in clinical practice.
	Acceptability of the sensor-based kinematic waveform report by patients who had undergone anterior cruciate ligament	PhD student (K.N.) thesis	- The aim of this study was to investigate the acceptability of the sensor-based movement analysis and kinematic waveform report by patients who had undergone ACLR. - 12 individuals who had undergone ACLR performed various functional tasks in a clinical context (gait, DLS, SLS, VJ, SA, and SD). The functional task selection was based on the researcher's clinical decision making and time since the ACLR surgery. - Temporo-spatial and joint angular kinematic data was collected from the patients.	- Using sensor-based movement analysis and kinematic waveform report appeared acceptable to the patients who had undergone ACLR. - It was indicated that the report can be used to educate, inform, and motivate patients. - Patient positive perceptions resulted from the feature of visualisation of the kinematic findings within the report. - Patients portrayed that the report was user-friendly in terms of its format.

	reconstruction (ACLR) (Study 2)		- Reports, displaying the temporo-spatial and joint angular kinematics collected at the hip, knee, and ankle joints in the sagittal and frontal planes were shared with the patients who had undergone ACLR. - Two semi-structured interviews were conducted with each patient who had undergone ACLR (one before experiencing SMAFT and one afterwards). - The first interview explored the patients' experience with using technology for rehabilitation and the treatment they had received. - The second interview explored the patients' opinions and experience of the report. - Framework analysis was used to analyse the qualitative data collected.	- Even though SMAFT may have been deemed acceptable by the patient participants (patients who had undergone ACLR), it needs to be adapted to the knee pain context.
	Development of a standardised template for reporting kinematic waveform data	Lead researcher (M.F.)	This study is included in the current PhD thesis (Phase I) and presented later in Chapter 3	

	to inform physiotherapy decision making		
A preliminary version of SMAFT involves inertial sensors, a kinematic waveform report, and a standardised reporting framework is developed			
Stage III	**Acceptability of SMAFT by individuals with knee pain within a physiotherapy clinical practice: A mixed-methods case study design**	Lead researcher (M.F.)	This study is included in the current PhD thesis (Phase II) and presented later in Chapter 4

Abbreviations: 2D = two-dimensional, 3D = three dimensional, ACLR = anterior cruciate ligament reconstruction, C&V UHB = Cardiff and Vale University Health Board, CMC = Coefficient of Multiple Correlation, DLS = Double leg squat, ICC = Interclass Correlation Coefficient (ICC), PKF = peak knee flexion, SA = Stair ascent, SD = Stair descent, SLDH = Single leg distance hop, SLS = Single leg squat, VJ = Vertical jump

Clinical Movement Analysis Report

Patient ID: 001

Reason for treatment: Knee pain
Affected joint: Right knee

Tested on: 10/9/2019
at: St David's Hospital

[redacted]

(a)

Walk (n = 18 left and 18 right leg strides)

Stride duration	Left: 1.12 s	Right: 1.12 s
Stance time	Left: 0.65 s	Right: 0.67 s
Swing time	Left: 0.47 s	Right: 0.44 s
Stride length	Left: 1.57 m	Right: 1.57 m
Step duration	Left: 0.56 s	Right: 0.55 s
Step length	Left: 0.72 m	Right: 0.81 m
Velocity	Left: 1.33 m/s	Right: 1.33 m/s

Double-leg squat (n = 5)

Squat duration 2.32 s

Single-leg squat, affected leg (n = 4)

Single-leg squat duration 1.47 s

Single-leg squat, non-affected leg (n = 5)

Single-leg squat duration 1.28 s

Jump (n = 5)

Jump duration 0.90 s
Jump height 0.41 m

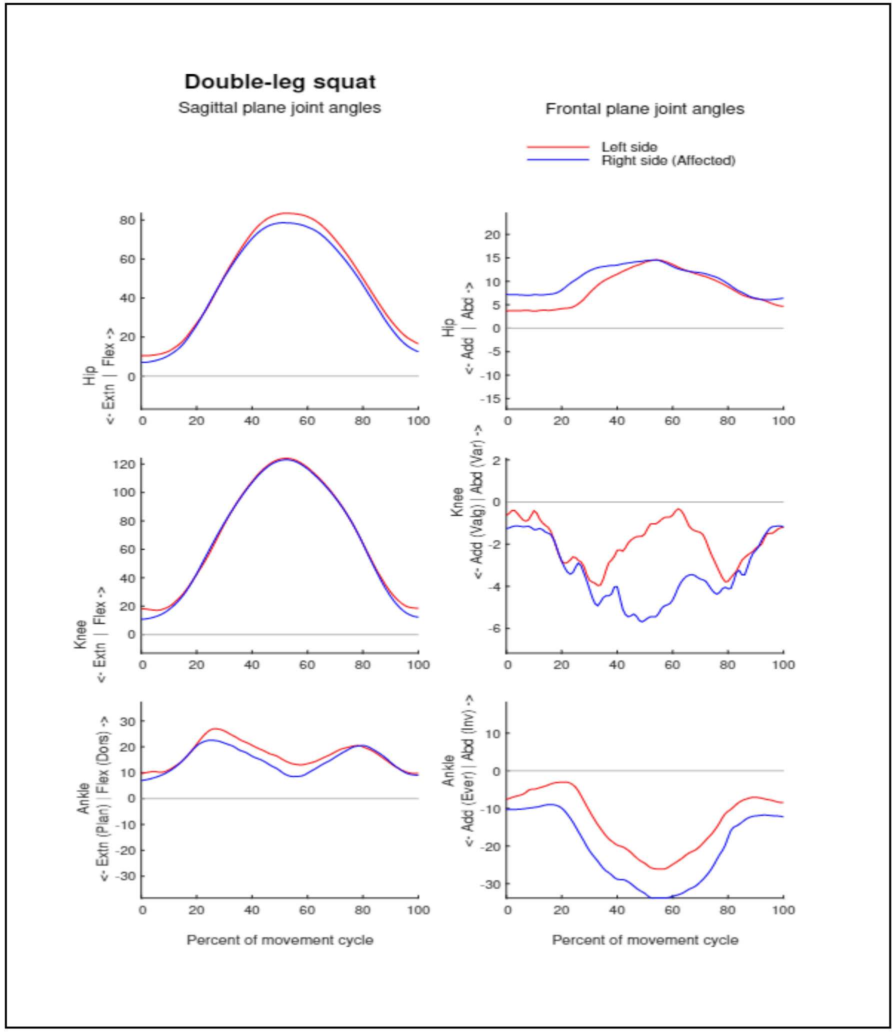
LEGEND

Left side

Right side (Affected)

(b)

Figure 3: Movement analysis report contents



(c)

Figure 3: Movement analysis report contents (continuous)

3.3 Phase 1 Study 1: Development of a standardised template for reporting kinematic waveform data to inform physiotherapy decision making

3.3.1 Introduction

Reportedly, the interpretation of 3D kinematic data is subjective and can produce variability in clinical decision making, resulting in suboptimal care (Skaggs et al. 2000). Physiotherapy clinicians (users) are therefore required to have skills in two elements when interpreting 3D angular kinematic data presented in waveform format, namely: the identification of the presence of altered movement patterns and descriptions of the altered patterns identified (Skaggs et al. 2000). This is vital to achieving a robust and consistent interpretation and thus enhancing clinical decision making.

Two studies assessed users' interpretation of the kinematic data obtained by 3D movement analysis for children with cerebral palsy during gait tasks (Nieuwenhuys et al. 2017; Wang et al. 2019). Across these studies, the interpretation process involved the identification of the presence of various gait alterations by using a standardised template listing various movement alterations presented during different gait phases. The findings exhibited a moderate to almost perfect agreement among users, suggesting that standardising the way of reporting and interpreting kinematic data might improve the accuracy and consistency of the interpretation process (Nieuwenhuys et al. 2017; Wang et al. 2019). To the researcher's knowledge, users' interpretation has not been assessed in populations with knee pain, during various functional activities. Therefore, investigating users' interpretation of 3D kinematic data adopted by individuals with knee pain is needed. This can assist in standardising the means of interpreting kinematic data among users (physiotherapy clinicians) and consequently enhance their accuracy and consistency when interpreting kinematic data.

In accordance with the MRC framework used to guide the development of the potential toolkit in the current thesis, the key uncertainties regarding the use of SMAFT within clinical practice should be considered at an early stage of development (Craig et al.

2008; Skivington et al. 2021). Users' interpretation of the kinematic data generated by SMAFT should be considered at this stage of SMAFT development. Therefore, creating a standardised reporting template to improve interpretation's consistency and accuracy among physiotherapy clinicians can add to the design and delivery of SMAFT within clinical practice and thus inform the development phase of the MRC framework.

3.3.2 Aim

The aim of this study was to create a standardised reporting template to improve clinicians' accuracy and consistency when interpreting the kinematic data provided by 3D movement analysis.

This was achieved by pursuing the following objectives:

- Assess within- and between-rater agreement when identifying the presence of altered movement patterns across kinematic waveform graphs for lower limb joints (hip, knee, and ankle) in the sagittal and frontal planes during gait, DLS, and SA tasks.
- Investigate raters' written descriptions (texts) of the altered movement patterns identified.

3.3.3 Hypotheses

H1: There will be a substantial agreement (k > 0.60) between-raters when identifying the presence of altered movement patterns presented in kinematic waveform graphs.

HO1: There will be no agreement between-raters when identifying the presence of altered movement patterns presented in kinematic waveform graphs.

H2: There will be a substantial within-rater agreement (k > 0.60) when identifying the presence of altered movement patterns presented in kinematic waveform graphs.

HO2: There will be no within-rater agreement when identifying the presence of altered movement patterns presented in kinematic waveform graphs.

3.3.4 Materials and Methods

3.3.4.1 Study design

A correlational between- and within-rater agreement design was employed to assess agreement between users when identifying altered movement patterns across kinematic waveform graphs. A quantitative content analysis was then used to explore written descriptions of their interpretation of the altered movement patterns identified. These findings were integrated to develop a standardised reporting template. This study was a part of global ethics for the Versus Arthritis Biomechanics and Bioengineering Centre at Cardiff University, approved by the Wales Research Ethics Committee 3, reference number (10/MRE09/28).

3.3.4.2 Movement analysis report

Kinematic data was collected from 14 individuals who had undergone ACLR. The data was collected as part of a previous study conducted by Nicholas et al. (2019) (described in detail in Chapter 3, section 3.2). As this kinematic data was already formulated in movement analysis feedback reports, and readily available for interpretation, these reports were used in the current PhD study, due to the time frame involved.

The individuals received one movement analysis session at the physiotherapy department of one University Health Board (Nicholas et al. 2019). This cohort of individuals presented with consistent altered movement patterns in spite of physiotherapy rehabilitation, and so are at risk of recurrent injury (Button et al. 2014; Roos et al. 2014b; Roos et al. 2014a). The data was then converted into fourteen movement analysis reports using a custom-written code on MATLAB software (Matlab version 9.6.0.1150989 (R2019a) Update 4) (Davies et al. 2021), as described in detail in Chapter 3, section 3.2. All of the movement analysis reports were anonymous. There were no identifiable details in the reports.

Each movement analysis report presented 18 kinematic waveform graphs, including kinematic data for three lower limb joints (hip, knee, and ankle) in two planes of movement (sagittal and frontal), during three functional tasks (gait, DLS, and SA). Although all the feedback reports involved kinematic waveform graphs for all of the functional tasks (gait, DLS, SLS, VJ, SA, and SD) that it had been justified previously (Chapter 2, section 2.6.1), only the graphs for the gait, DLS, and SA tasks were included in the current study, and assessed by the raters. This was because describing the altered movement patterns presented in a waveform format across some of these tasks was comparable, particularly for their time events (when they occurred throughout the movement cycle). For instance, the DLS and SLS tasks were similar in nature, and involved similar phases; nevertheless, the task was performed on a single or two limbs (Robertson et al. 2008). Similarly, the DLS served as a large part of the VJ task (McGinnis 2013). It included three phases, preparatory, propulsive, and flight, with squatting involved in the first two phases (McGinnis 2013). Also, the SA and SD were comparable to some extent, as both had similar phases, but in different directions (Song et al. 2017). Therefore, assessing the waveform graphs for gait, DLS, and SA was sufficient to meet the main aim and objectives of the current PhD study, which was restricted by the limited time frame and funding.

3.3.4.3 Sampling (Raters)

A purposive sample of six raters was recruited to participate in the current agreement study. Purposive sampling was chosen as the method of sampling, since it allows the researcher to choose participants with specific characteristics to learn the most from them (Patton 1990; Denzin and Lincoln 2011). Therefore, individuals (clinicians and researchers), with different levels of clinical experience and from different biomechanics backgrounds, were invited to participate in the current study and instructed to interpret the kinematic waveform graphs presented within the fourteen movement analysis reports provided (between-user agreement).

All of the raters were required to satisfy the following inclusion/exclusion criteria:
<u>Inclusion criteria</u>

- Raters with at least one year of experience performing clinical movement analysis, including the ability to process kinematic data during various functional activities and interpret it for clinical rehabilitation purpose.
- Raters willing to undertake training on how to interpret the kinematic waveform graph prior to participating in the interpretation process (training is described in detail later in the current section).

Exclusion criteria

- Unable to read and understand English.
- Unable to give written informed consent.

The raters were identified and recruited via word of mouth. A meeting was conducted with these individuals to discuss the nature of the research and to explain the movement analysis feedback report. Throughout this meeting, the individuals were given an opportunity to ask questions. If the individuals were interested in participating in the study, they were provided with training in how to interpret the kinematic waveform graph. A training session was conducted by the lead researcher (M.F.) to introduce the feedback report and its contents, and to provide instruction in how to identify the altered movement patterns within the graphs by comparing the kinematic waveform among the injured and non-injured limbs. The raters were informed that not all of the waveforms graphs demonstrated altered movement patterns, but were left to identify whether there was an altered movement pattern themselves. No standard criteria were given aid for the identification of the presence of an altered movement pattern.

The movement analysis feedback reports, in addition to the rating sheets (Appendix C), were then sent to the rater electronically via a Cardiff University OneDrive link or physically by hand. Raters were instructed to notify the lead researcher (M.F.) upon completion of each task and were required to send the completed rating sheets back via the same OneDrive link, or physically by hand. All the completed rating sheets were collected independently by the lead researcher (M.F.). Each rater had his/her own access link and was unable to examine the interpretation sheets of other raters. The raters' confidentiality was ensured by replacing the rater's name with a unique identification number (ID), which was used to identify the rater throughout the study.

3.3.4.4 Sample size

A sample size estimation was made according to a guideline (in the form of a table) provided by Donner and Rotondi (2010). This table was used to establish the sample size needed for agreement studies with multiple raters and a binary outcome (two categories, two possible ratings for a nominal or ordinal item) (Donner and Rotondi 2010). In order to determine the minimum sample size required using the table, it is essential to pre-define the predictable Kappa coefficient value (*k0*) and the minimal acceptable value (*kL*), in addition to the expected value for the prevalence rate. According to the interpretation guideline of the Kappa coefficient, as suggested by Landis and Koch (1977), a minimum Kappa value of 0.61 is considered to deliver a substantial agreement. Table 2 in Donner and Rotondi (2010) states that based on the inclusion of five raters with a k0 value of 0.70, a kL value of 0.60, and a prevalence rate of 0.10, a minimum sample size of 207 is required to ensure with 95% confidence that a substantial level of agreement has been attained (Appendix D).

Although this guideline is considered suitable for the current agreement study with a binary outcome among multiple raters, it is limited to a maximum number of five raters (less than the number of raters required in the current study). It was noticed from the guide table that the number of raters increased as the number in the minimum sample size required decreased. Therefore, as the current study involved more raters (six), rating a sample of 252 waveform graphs is more than enough.

3.3.4.5 Data collection

Each rater was instructed to interpret two hundred and fifty-two kinematic waveform graphs (from 14 movement analysis reports provided) (between-raters agreement). The raters were only provided with details of the time elapsed between the day of operation (ACLR) and the movement analysis session for each individual, but with no other clinical details. The raters were instructed to analyse the waveform graphs by identifying the presence of altered movement patterns by comparing the angular kinematic waveforms for the injured leg versus the non-injured one. Using the provided rating sheets (Appendix C), the raters were asked to write "YES" if an altered movement pattern was present, or "NO" if absent. Then, for each waveform graph identified by altered movement patterns, the raters were instructed to describe them in writing (text).

A second round of interpretations for the assigned four raters was required after a week (within-rater agreement), in order to reduce the effect of recognition. In this interpretation round, the raters were instructed to analyse the waveform graphs by identifying the presence of altered movement patterns only without a written description.

3.3.4.6 Data analysis

3.3.4.6.1 Between- and within-rater agreement

It is vital to select the most appropriate statistical test for assessing agreement based on several factors, such as level of data measurement, the number of raters and the study design (Hallgren 2012). The first objective of the current study was to assess agreement among six raters when identifying whether altered movement patterns are presented within kinematic waveform graphs (Yes or No) (categorical data). Variables that have categories with no natural ordering are called "nominal" (as in the current case of Yes or No categories) (Agresti 2013). Several statistical methods were employed across the literature to assess between-rater agreement to analyse nominal data (Cohen 1960; Armitage et al. 1966; Armitage et al. 2002; Gwet 2008; Hallgren 2012). Each of these statistical tests is discussed in turn.

The most basic and easiest method for evaluating agreement involves calculating the observed agreement (Zapf et al. 2016). This was calculated as "the amount of observed agreement (i.e., objects that pairs of raters assigned to the same or similar categories) divided by the amount of possible agreement (i.e., objects that pairs of raters could have assigned to the same categories)" (Button et al. 2022, p. 3). However, the challenge with this approach was that it fails to determine agreements that may arise by chance (Zapf et al. 2016). More clearly, some level of agreement might be attained by chance even when the rater guesses or randomly rates for the presence of altered movement patterns or otherwise, without looking at the waveform graph.

Cohen's Kappa coefficient (k) was introduced to fix this issue and correct the expected agreement by chance (Cohen 1960). However, the original Cohen's Kappa is restricted to measuring nominal variables between two raters only. Therefore, Kappa was subsequently modified and expanded for use in calculating agreement between three or more raters. One of these Kappa-like coefficients is Light's Kappa, which was proposed by (Light 1971). Light (1971) calculated Kappa for all rater pairs and then utilised the arithmetic mean of these estimates to yield an overall index of agreement. Although the Kappa coefficient and its variants are the most common statistical methods used for quantifying agreement, their agreement statistics may be influenced by the prevalence of the condition (Fleiss 1971; Hallgren 2012). This prevalence effect may arise when raters are much more likely to assign one rating category (e.g., YES) more often than another category (e.g., NO), or when the majority of the raters' responses fall into a single category (e.g., YES) (high agreement in one category) (Hallgren 2012). Consequently, this prevalence effect could result in Kappa yielding an unrepresentative value denoting high agreement (Hallgren 2012).

Gwet (2008) suggested an alternative agreement coefficient called the "first-order agreement coefficient" or "AC1" to resolve the aforementioned Kappa's issue. It is recommended to consider this statistical method when assessing agreement and employ it as an alternative method or alongside other statistical methods (Wongpakaran et al. 2013). Thus, the assessments of between- and within-rater agreement in the current study were conducted using observed agreement (Armitage et al. 1966) and Gwet's agreement coefficient (AC1) (Gwet 2008).

Levels denoting strength of agreement were based on the scale proposed by Landis and Koch (1977), where ≤ 0 = poor agreement, 0.01 - 0.20 = slight, 0.21 - 0.40 = fair, 0.41 - 0.60 = moderate, 0.61 - 0.80 = substantial, and 0.81 - 1.0 = almost perfect. Matlab software (version 9.6.0; The MathWorks Inc., California, USA) was utilised to measure agreement between- and within-raters. The Matlab functions employed were adapted from (Girard 2018).

3.3.4.6.2 Quantitative content analysis

Content analysis is a systematic objective method used to explore patterns and frequencies in textual data (Gerbic and Stacey 2005; Bryman 2016; Krippendorff 2018). It can be achieved by objectively analysing and quantifying a large volume of textual data into a limited number of categories and themes (Stemler 2001; Bryman 2016; Krippendorff 2018). In the current study, a quantitative content analysis method was utilised to explore and quantify how raters described and interpreted altered movement patterns across kinematic waveform graphs in the form of textual information.

Content analysis can be utilised in inductive and deductive approaches (Elo and Kyngäs 2008). If there is a limited body of prior research literature on the issue in hand, or if knowledge is fragmented, the inductive method is recommended (Elo and Kyngäs 2008). In contrast, a deductive method is employed when the analysis is structured based on previous knowledge (Elo and Kyngäs 2008). As describing and interpreting altered movement patterns presented in kinematic waveform graphs have not been investigated yet, an understanding of how the users describe these movement patterns was lacking. Therefore, an inductive approach to quantitative content analysis was used in the current study. Employing this approach, the researchers immersed themselves in the data to allow new insights to emerge, and consequently, categories and codes were developed after preliminary investigations of the textual data. According to Elo and Kyngäs (2008), the process of content analysis comprises three phases; i.e., the preparation, organisation, and reporting phases. The key element of quantitative content analysis is to quantify and categorise textual data (words and phrases) into categories and themes (Weber 1990).

3.3.4.6.2.1 Data preparation and exploration

An important factor in content analysis is that the units of analysis are sufficiently accurate to enable researchers to establish findings in a consistent manner (Silverman 2015). Each unit of analysis could be an adequate word, phrase, or theme (Krippendorff

2018). In the current study, the units of analysis were defined as any word or phrase describing the altered movement patterns identified within waveform graphs.

All raters' textual data about the description of altered movement patterns presented in the waveform graphs was transferred and collected in a Word document (version 16.56; Microsoft Word). The data was then transferred to NVivo 12 software (QSR International Pty Ltd., Burlington, Massachusetts, USA) for additional management. Self-collection and processing of the data contributed to an advantage in terms of familiarisation prior to analysis.

Textual data was repeatedly read by the lead researcher (M.F.) and second reviewer (K.B.) to provide the researchers with initial insight into the content. This process of 'repeated reading' has been considered an important step to be undertaken during the beginning of analysing of any textual data (Braun and Clarke 2006; Elo and Kyngäs 2008). A meeting between the lead researcher and the second reviewer was conducted to discuss thoughts and impressions about interesting ideas presented in the raters' written descriptions of waveform graphs.

3.3.4.6.2.2 Data analysis of raters' written descriptions

Coding is the process of labelling data (Braun and Clarke 2006). Codes identify a feature of the data that the analyst finds interesting (Braun and Clarke 2006) and lend meaning to words and phrases identified (Taylor-Powell and Renner 2003). The process of coding and categorisation (highlighting the words and phrases within the textual data) was initiated independently by the lead researcher (M.F.) and the second reviewer (K.B.) of one functional task (DLS). Conducting the data analysis, particularly involving a coding process, with more than one researcher could improve the accuracy of the findings, since it allows for sharing and discussion of different perspectives and reduces bias (Lincoln and Guba 1985). In addition, regular discussion among different researchers during the analysis process affords an opportunity for researchers to test their ability to justify their choices of codes and categories.

Following the initial coding process, a meeting was conducted for the purpose of discussion and agreement. During this meeting, the researchers compared all the preliminary codes and categories developed from the textual data regarding the DLS task. The majority of the identified codes and categories were comparable among the two researchers. As a result of this meeting, it was agreed that coding should focus on four key elements that were used to describe the altered movement patterns presented in the waveform graphs (i.e., type, event, amount, and direction), but this does not mean to ignore coding any other data describing the altered movement patterns.

For the textual data relating to subsequent tasks (gait and SA), coding was conducted independently by the lead researcher (M.F.) and then checked by the second reviewer (K.B.). As a consequence of the coding process, and checking by the reviewer during this phase, there was agreement over the majority of the preliminary codes and categories developed across all tasks. Examples of preliminary codes used within each category are presented in Table 6. Also, a summary of the comments made by the second reviewer (K.B.) on the coding process during this phase is presented in Appendix E. However, there was disagreement when categorising some codes, such as 'early stance', 'late swing', and 'mid swing' into categories "Phase" and "Discrete time point". Moreover, there were overlaps in the coding process conducted by the researchers with the categories "Amount" and "Direction". For example, codes such as 'too much', 'too little', and 'slight' were categorised into the "Amount" category, and codes such as 'increased', 'reduced' and 'greater' were categorised into the "Direction" category by one researcher. By contrast, the other researcher categorised all previous code examples into the "Amount" category.

Table 6: Preliminary categories and codes used from the textual data for three tasks (gait, double leg squat and stair ascent)

Category	Codes used
Amount specified (written)	too little, slight, subtle, too much
Amount specified (numbers)	Degrees, e.g. 10 degrees
Direction	Decreased, reduced, increased, greater, minimal, lack of, less, early, rapid, late, delay in
Peak (maximum)	Peak, maximum, Max
Range of Motion (ROM)	Range of motion, ROM, range
Timing	Timing, asynchronous…, rapid…, delayed…, earlier…, late…
Cycle	Throughout cycle, during squat, across full movement cycle, throughout the whole task, throughout
Phase	Swing phase, during ascending phase, through step up phase, early descending phase, mid stance phase (For more examples of codes, see Appendix F)
Discrete Time Point (DTP)	Heel strike, at mid stance, toe off, at maximum squat depth, at left off, at vertical thrust (For more examples of codes, see Appendix F)

Abbreviations: Max = Maximum, ROM = Range of Motion

Therefore, an additional meeting was conducted to discuss these comments and disagreements with the third reviewer (M.A.A.). As a consequence of this meeting, it was decided to integrate the "Amount" and "Direction" categories with the codes identified in one category called "Amount". In addition, the following points regarding the categorisation of codes into "Phase" and "Discrete time point" were agreed upon:

- In the case of the word 'phase' being stated, a code should be categorised into the "Phase" category.
- In the case of the word 'phase' not being stated, the code should be categorised based on the combined proposition.
  - If the word or phrase were combined with the connectors (during, through, throughout, from… till…, as…), the code should be categorised into the "Phase" category.
  - If the word or phrase is combined with the connectors (at, on, in), the code should then be categorised into the "Discrete time point" category.
- If the word 'phase' is not stated nor combined with a connector, the code should be categorised into the "Phase" category.

It is also noteworthy that in some cases, raters' descriptions of the (amount) of the identified altered movement pattern were ambiguous or unspecified. This ambiguity resulted from the terminologies used, such as altered, asynchronous, and inverted waveform. For the unspecified description, the codes were categorised into a category named "Unspecified amount description". These categories were decided not to report and excluded during the final refinement phase.

Coding was reviewed, refined, and modified by the lead researcher (M.F.) based on the points agreed upon (Appendix E). A final check of the coding across all the textual data pertaining to functional tasks (gait, DLS, and SA) was completed by the second reviewer (K.B.). Once the coding process was assured, the final categories and themes were refined, named, and clearly defined. The final codes, categories, and themes were summarised (Table 7). Three themes were identified (Amount, Nature, and Timing). These themes were defined as follows (Button et al. 2022):

- Amount: Description relating to the size or magnitude of an altered movement pattern
- Nature: Description relating to the type of an altered movement pattern
- Timing: Description relating to when an altered movement pattern occurred in the movement cycle.

For each theme, a number of categories were identified. The “Amount” theme involved two categories (Qualitative description and Quantitative description). Similarly, three categories were identified for the theme “Nature” (Peak, Range of motion, and Timing). Finally, the theme “Timing” included three categories (Cycle, Phase, and Discrete time point). The definitions for all eight categories are presented in Table 7.

Following the iterative coding process, the frequency of the occurrence of codes for each category was calculated (see result section, subsection 3.3.5.5). This was conducted to meet the main aim of the current study (to develop a standardised template to aid physiotherapy clinicians’ when interpreting and reporting the kinematic data).

Table 7: Definitions of the final categories within three themes "Amount", "Nature", and "Timing" (Button et al. 2022)

Theme	Category	Definition
Amount	Qualitative description	A description in words relating to the size or magnitude of the altered movement pattern.
	Quantitative description	The size or amplitude of the altered movement pattern described in numbers.
Nature	Peak (maximum)	An alteration in the peak (maximum) on the waveform.
	Range of Motion (ROM)	An alteration in the range of motion of the waveform.
	Timing	An alteration in the timing of the waveform.
Timing	Cycle	An altered movement pattern identified as occurring throughout the entire movement cycle.
	Phase	An altered movement pattern identified as occurring during a specific phase of the movement cycle.
	Discrete Time Point	An altered movement pattern identified as occurring at a discrete time point within the movement cycle.

3.3.5 Results

3.3.5.1 Introduction

In this section, the findings for agreement within- and between-raters, with the identification of altered movement patterns across kinematic waveform graphs are presented. In addition, the quantitative content analysis results for textual data related to the description of the altered movement patterns identified by raters are presented.

3.3.5.2 Raters

Six raters met the eligibility criteria set and agreed to participate. They had different scientific backgrounds and a differing number of years in clinical and biomechanical practice. In total, five of the raters held certificates in physiotherapy (four of the physiotherapists had over 10 years of clinical experience, and one had less than five years of experience). In addition, two of them had more than 10 years of experience in clinical movement analysis, and three had less than five years of experience. Finally, one of the raters was a clinical movement scientist with more than 10 years of experience in laboratory movement analysis.

3.3.5.3 Frequency of identifying an altered movement pattern

All six raters analysed 252 kinematic waveform graphs adapted from 14 movement analysis feedback reports. The frequency of the kinematic waveform graphs presented with altered movement patterns identified by raters at each joint in each plane of movement for each functional task is presented in Table 8. The presence of altered movement patterns identified by raters is more frequent across frontal kinematics graphs for all tasks and over all joints than for those in the sagittal plane.

3.3.5.4 Between-raters agreement

Between-raters agreement values for observed agreement and Gwet's AC1 for identifying altered movement patterns across waveform graphs were presented in Table 8. Overall, the average scores of the observed agreement across all kinematics waveform graphs for all lower limb joints in both planes in all tasks presented substantial between-rater agreement (average observed agreement = 0.79; ranged from 0.61 to 1.00). Taking into consideration the possibility of the agreement by chance, the average between-raters agreement was also identified as a substantial agreement (average Gwet's AC1 = 0.64), which ranged from 0.21 'fair agreement' to 1.00 'almost perfect agreement'.

Regardless of the statistical test used, it was found that between-rater agreement values were higher for the waveform graphs in the frontal plane than those in the sagittal plane for all tasks (Table 8). As for Gwet's AC1 values, the sagittal kinematic waveform graphs over all joints and tasks exhibited a fair to substantial agreement (Gwet's AC1 = 0.21 - 0.73). On the other hand, the frontal plane kinematic graphs demonstrated a substantial to almost perfect agreement (Gwet's AC1 = 0.66 - 1.00) over all joints and tasks.

3.3.5.5 Within-rater agreement

Four of the six raters analysed the same kinematic waveform graphs (for the same tasks in the same planes and over the same joints) for a second time to assess within-rater agreement. Within-rater agreement values for observed agreement and Gwet's AC1 across all tasks were presented in Tables 9, 10, and 11. Overall, the average scores of within-rater observed agreement presented a substantial to almost perfect agreement (average observed agreement ranges 0.80 - 0.99) across all the kinematic waveform graphs over all joints, planes, and tasks. Considering the level of agreement achieved by chance, average values of Gewt's AC1 showed a substantial to almost perfect agreement for the same kinematic graphs across all joints, planes, and tasks (average Gwet's AC1 ranges 0.70 - 0.99).

Table 8: Number of times an altered movement pattern was identified as present, and between-raters agreement for the presence of an altered movement pattern across kinematics graphs for three tasks (GAIT, DLS, and SA)

Joint	Planes	Walk (GAIT)			Double leg squat (DLS)			Stair ascent (SA)		
		n	Gwet's AC1	Observed Agreement	n	Gwet's AC1	Observed Agreement	n	Gwet's AC1	Observed Agreement
Hip	Sagittal	27	0.32	0.61	35	0.53	0.76	44	0.21	0.61
	Frontal	70	0.66	0.75	81	0.92	0.93	82	0.95	0.95
Knee	Sagittal	58	0.43	0.68	42	0.73	0.90	60	0.47	0.69
	Frontal	75	0.81	0.84	81	0.92	0.93	84	1.00	1.00
Ankle	Sagittal	53	0.31	0.63	34	0.45	0.71	57	0.33	0.62
	Frontal	75	0.76	0.81	72	0.75	0.81	80	0.90	0.91
Average		59.7	0.55	0.72	57.5	0.72	0.84	67.8	0.64	0.80

Abbreviations: Gwet's AC1 = Gwet's first-order agreement coefficient, n= frequency of the presence of altered movement patterns identified by the raters across the kinematic waveform graphs for each joint and each plane

Table 9: Within-rater agreement for the presence of an altered movement pattern across the kinematic graphs for gait task

Joints	**Planes**	**Walk (GAIT)**							
		R1		R2		R3		R4	
		Gwet's AC1	Observed agreement	Gwet's AC1	Observed agreement	Gwet's AC1	Observed agreement	Gwet's AC1	Observed agreement
Hip	Sagittal	0.81	0.86	0.84	0.86	0.78	0.86	0.66	0.78
	Frontal	0.92	0.93	1.00	1.00	0.57	0.71	0.81	0.86
Knee	Sagittal	0.70	0.79	1.00	1.00	0.86	0.93	0.44	0.71
	Frontal	0.92	0.93	1.00	1.00	1.00	1.00	1.00	1.00
Ankle	Sagittal	0.28	0.57	1.00	1.00	0.86	0.93	0.29	0.64
	Frontal	1.00	1.00	1.00	1.00	0.84	0.86	1.00	1.00
Average		0.77	0.85	0.97	0.98	0.82	0.88	0.70	0.83

Abbreviations: Gwet's AC1 = Gwet's first-order agreement coefficient

Table 10: Within-rater agreement for the presence of an altered movement pattern across the kinematic graphs for double leg squat task

Joints	Planes	Double leg squat (DLS)							
		R1		R2		R3		R4	
		Gwet's AC1	Observed agreement	Gwet's AC1	Observed agreement	Gwet's AC1	Observed agreement	Gwet's AC1	Observed agreement
Hip	Sagittal	0.52	0.71	0.76	0.86	0.62	0.79	0.86	0.93
	Frontal	1.00	1.00	1.00	1.00	0.92	0.93	1.00	1.00
Knee	Sagittal	0.59	0.79	1.00	1.00	1.00	1.00	0.59	0.79
	Frontal	1.00	1.00	1.00	1.00	0.92	0.93	1.00	1.00
Ankle	Sagittal	1.00	1.00	0.89	0.93	1.00	1.00	0.86	0.93
	Frontal	1.00	1.00	1.00	1.00	0.91	0.93	0.91	1.00
Average		0.85	0.92	0.94	0.97	0.90	0.93	0.87	0.94

Abbreviations: Gwet's AC1 = Gwet's first-order agreement coefficient

Table 11: Within-rater agreement for the presence of an altered movement pattern across the kinematic graphs for stair ascent task

Joints	Planes	Stair Ascent (SA)							
		R1		R2		R3		R4	
		Gwet's AC1	Observed agreement	Gwet's AC1	Observed agreement	Gwet's AC1	Observed agreement	Gwet's AC1	Observed agreement
Hip	Sagittal	0.59	0.79	0.92	0.93	1.00	1.00	0.37	0.64
	Frontal	0.92	0.93	1.00	1.00	1.00	1.00	0.84	0.86
Knee	Sagittal	1.00	1.00	1.00	1.00	0.76	0.86	0.57	0.79
	Frontal	1.00	1.00	1.00	1.00	1.00	1.00	0.92	0.93
Ankle	Sagittal	0.81	0.86	1.00	1.00	0.32	0.64	0.29	0.64
	Frontal	1.00	1.00	1.00	1.00	1.00	1.00	0.92	0.93
Average		0.89	0.93	0.99	0.99	0.85	0.92	0.75	0.80

Abbreviations: Gwet's AC1 = Gwet's first-order agreement coefficient

3.3.5.6 Quantitative content analysis

Following the quantitative content analysis for the raters' descriptions of the identified altered movement patterns across all kinematic graphs, the number of occurrences, when the themes and their categories were reported by raters, was calculated (Table 12). The findings presented that the raters were qualitatively describing the identified altered movement patterns in a varied manner.

The theme most frequently reported on in the raters' description was the "Amount" theme (1689 times). Within this theme, the category "Qualitative description" was frequently reported (1575 times) (e.g., terms such as more or less), and the category of "Quantitative description" was reported 114 times (e.g., numbers). The quantitative description was rarely added to the most common qualitative descriptions. Combining a qualitative description with the amount of altered movement patterns (e.g., increased, decreased, too much, too little) and a quantitative description (degrees) might enhance objectivity and help to establish targets for monitoring measurable change within the scope of rehabilitation.

The second most frequently reported theme was the timing of altered movement patterns (1383 times). The most frequent category coded within the "Timing" theme was the category of "Phase" (633 times). It was noted that there are a plethora of various codes concerning the three categories under the "timing" theme (Appendix F). This was anticipated because each functional task included several phases, consequently a range of terminologies were used for describing the time event for the identified altered movement patterns.

This variation in codes was evident in the textual description of the altered movement patterns identified in the waveform graphs for the SA task. For example, the timing of the altered movement pattern was described as 'lifting leg into a step phase' or 'swing phase', and 'floor in contact with step phase' or 'stance phase'. Also, some codes for the description of timing during the SA task involved the percentage of timing when the altered movement pattern occurred across the whole movement cycle (e.g., from 30% till 60% of the SA movement cycle). Less commonly, this variety of codes was found in the description of timing for the DLS task (e.g., 'at peak knee flexion', 'at maximum squat’, ‘at deep squat position’ or ‘at full squat depth’, and ‘squatting phase’ or ‘descending phase’). Therefore, it is required to standardise the terminologies utilised in the description of the timing event's phases and at the discrete time points within the movement cycle, particularly for the SA and DLS tasks, in order to enhance consistency between users when reporting altered movement patterns.

The least frequently reported theme was the nature of altered movement patterns (968 times). For the categories within the theme of “Nature”, the number of coding times across the three categories was similar (peak: 317 times, ROM: 319 times, and timing: 332 times). It was, in addition, noted that there were a higher number of times when the nature of altered movement patterns was either not stated clearly or ambiguous.

Table 12: The number of times that each category was reported by all raters across all planes during all tasks (Button et al. 2022)

	Amount		Nature			Timing		
	Qualitative Description	Quantitative Description	Peak (Maximum)	Range of Motion (ROM)	Timing	Cycle	Phase	Discrete Time Point (DTP)
Walk (GAIT)	553	44	106	115	107	63	303	132
Double Leg Squat (DLS)	454	35	79	96	60	159	234	84
Stairs Ascent (SA)	568	35	132	108	165	96	86	171
Total	1575	114	317	319	332	318	633	387

3.3.6 Discussion

The aim of the current study was to develop a standardised template to help users robustly and consistently report kinematic waveform data. The kinematic data, obtained by a sensor-based 3D movement analysis, was formulated in a custom-made movement analysis feedback report. This was attained through two objectives. The first objective was to test within- and between-rater agreement to identify the presence of altered movement patterns within kinematic waveform graphs for lower limb joints in the sagittal and frontal planes during three tasks. The second objective was to investigate raters' written descriptions (text) of the identified altered movement patterns. To the researcher's knowledge, investigating users' interpretations of kinematics data presented in a waveform format by identifying whether altered movement patterns were present, and describing the identified altered movement patterns qualitatively has not been done in previous literature. It is, however, considered crucial to inform the potential development of SMAFT in the current thesis by enhancing the robustness and consistency of physiotherapy clinicians' interpretation of kinematic data provided by SMAFT within clinical settings.

3.3.6.1 Summary of the main findings

The results presented substantial between-rater agreement when identifying the presence of altered movement patterns for all kinematic waveform graphs across all lower limb joints, planes of movement, and activity tasks (average Gwet's AC1 = 0.64). Also, within-rater agreement ranged from substantial to almost perfect agreement in all waveform graphs over joints, planes, and activity tasks (average Gwet's AC1 ranged 0.70 - 0.99). Therefore, these findings accepted the two hypotheses that suggest a substantial agreement within and between raters when identifying the presence of altered movement patterns presented in kinematic waveform graphs will be found. These findings proposed thus consistency in decision making about the presence of altered movement patterns across waveform graphs, when different raters analysed the same waveform, and when the same rater analysed the same waveforms over time. However, the way of describing the identified altered movement patterns qualitatively varied between the raters.

3.3.6.2 Between- and within-rater agreement

Despite the substantial agreement found, it was surprising that the majority of the inconsistencies among raters, in terms of the identification of the presence of altered movement patterns, were noted for kinematic waveform graphs in the sagittal plane rather than the frontal plane. This may be explained by the fact that the kinematic waveforms for the graphs in the frontal plane seemed to be more pronounced to the rater than the waveforms in the sagittal plane. This occurred because different scales are used to display the kinematic data for different planes, which is acknowledged as a limitation in the current study. The data for the frontal plane was on a smaller scale. Consequently, raters may have found that identifying altered movement patterns for waveform graphs in the frontal plane is easier than identifying them for graphs in the sagittal plane.

3.3.6.3 Comparing findings of between- and within-rater agreement with previous literature

The results of the between- and within-rater agreement in the current study were in line with the findings of two studies that assessed agreement when identifying the presence of altered movement patterns during gait performance (Nieuwenhuys et al. 2017; Wang et al. 2019). Nieuwenhuys et al. (2017) evaluated the agreement between and within two groups of raters (experienced and unexperienced) for interpreting kinematic and kinetic data provided by an optoelectronic 3D gait analysis for a sample of children with spastic cerebral palsy. The agreement findings exhibited a substantial to almost perfect agreement for all movement patterns at the pelvic, hip, knee, and ankle joints (within-rater Kappa = 0.64 - 0.91; between-rater Kappa = 0.63 - 0.86) (Nieuwenhuys et al. 2017). Similarly, Wang et al. (2019) found moderate agreement (averaged Kappa = 0.55) among seven experienced orthopaedic surgeons, identifying potential altered gait movement patterns in fifteen children with gait disorders by interpreting 3D gait movement analysis data (kinematics, kinetics, electromyography, and video).

In the previous studies by Nieuwenhuys et al. (2017) and Wang et al. (2019), raters were instructed to identify the presence of several gait deviations by presenting 3D movement analysis data stating 'Yes' or 'No' only on a list of gait problems (Wang et al. 2019) and a list of movement alterations that occurred during varied gait phases (Nieuwenhuys et al. 2017). However, describing these gait problems and movement alterations was not conducted (Nieuwenhuys et al. 2017; Wang et al. 2019). Thus, these studies were not comparable to the current study, which left the interpretation totally open to the raters to describe, when reporting the identified altered movement patterns within the waveform graphs without restrictions. This was vital to meeting the main aim of the current study as a way to develop a standardised reporting template based on qualitative descriptions of movement alterations written by individuals with varying levels of experience in clinical rehabilitation and movement analysis.

Another study, conducted by Brunnekreef et al. (2005), assessed agreement among experienced and inexperienced raters when analysing videotaped recordings for gait movement patterns of patients with orthopaedic impairments using a standardised gait analysis template. Brunnekreef et al. (2005) reported moderate between- and within-rater agreement (between experienced raters, ICC = 0.42; between inexperienced raters, ICC = 0.40; within experienced raters, ICC = 0.63; within inexperienced raters, ICC = 0.57). The reduced between-rater agreement in Brunnekreef et al. (2005) compared with the findings for between-rater agreement in the current study (substantial agreement) may have resulted from the form of kinematic data raters were analysing. In Brunnekreef et al. (2005), the raters were interpreting kinematic data from video footage, whereas in the current study, the raters were provided with waveform graphs. The challenge with video footage is that it requires a clear observation of movements from different planes, which are sometimes difficult for raters to identify visually. For example, Brunnekreef et al. (2005) reported lower agreement between raters on items that were considered difficult to identify, such as movement alterations at the pelvis in the transverse plane, compared to an easier set of alterations at the knee in the sagittal plane (ICC ranges = 0.19 – 0.33 vs. 0.58 – 0.60 respectively). This evidence supports the use of waveform graphs in movement analysis feedback reports for use in the clinical setting over the use of videos.

3.3.6.4 Describing the identified altered movement patterns

A unique aspect of the current study was to investigate raters' written descriptions (text) of the altered movement patterns identified across the kinematic waveform graphs. When analysing these textual descriptions of the movement alterations employing a quantitative content analysis approach, three themes were identified ("Amount", "Nature", and "Timing" of the altered movement patterns). Involving these three themes in the description and the interpretation of kinematic waveform graphs was necessary to add clarity and avoid inconsistencies in clinical decision making.

A limited number of terminologies were used to describe the nature of altered movement patterns, but there were a higher number of occurrences when the type of the altered movement patterns was either unspecified or ambiguous. For instance, the raters described the altered movement patterns without clearly stating their types (e.g., decreased dorsiflexion throughout the cycle, too much adduction throughout, and increased knee abduction). It is unclear whether the nature of the altered movement pattern was related to the range of movement or the peak angle. Therefore, in order to avoid this ambiguity, it is required to assist raters in specifying the type of the altered movement pattern identified during the analysis of the reports. This could be attained by providing a list of simple words or phrases regarding the potential types of altered movement patterns to select from, especially as the number of terminologies used to describe the nature of the altered movement patterns was found to be limited. A higher agreement between raters could be achieved if raters had a list of words or phrases regarding the type of altered movement pattern to choose from, as exhibited in a study by Nieuwenhuys et al. (2017), as previously discussed.

3.3.6.5 Developing a standardised reporting template

Based on the findings of the quantitative content analysis, a standardised reporting template was developed. This template contains a number of standardised terminologies distributed into four boxes, based on three themes identified in the current study ("Amount", "Nature", and "Timing") and their categories (Figure 4). To interpret and report any of the altered movement patterns presented in a waveform graph by comparing the waveforms for the affected and non-affected limbs, the user is instructed to choose a single term from each box to best describe the altered movement pattern identified. This is followed by integrating and writing the chosen terms in the required space according to the joint and plane of movement analysed. It is recommended to train users on how to use the standardised terminologies included in the template when describing the altered movement patterns. Recommendations for training users in interpreting feedback reports by using the standardised template are presented in Table 13.

Assessing the level of agreement among users, employing this standardised reporting template in their interpretation of the kinematic waveform graphs, is essential. Therefore, this has been done and published by a number of our research team members (Zhou et al. 2021). Zhou et al. (2021) found moderate between- and within-rater agreement when interpreting altered movement patterns across waveform graphs, as conducted by three physiotherapy clinicians with limited experience in movement analysis using the template. The findings could suggest the potential use of the template for providing consistent reporting of altered movement patterns that are identified in waveform graphs, particularly among expert physiotherapy clinicians in movement analysis. Based on this, using the created reporting template by the toolkit developed in the current thesis could enhance the accuracy and consistency of its use in the next clinical trials.

As a researcher with acceptable experience in movement analysis (> 3 years), using this standardised template to interpret kinematic waveform graphs will improve the interpretation's accuracy and consistency (Nieuwenhuys et al. 2017). Thus, the template was designed and used in a case study that aims to explore the acceptability of SMAFT among users within a physiotherapy clinical practice (presented in Chapter 4).

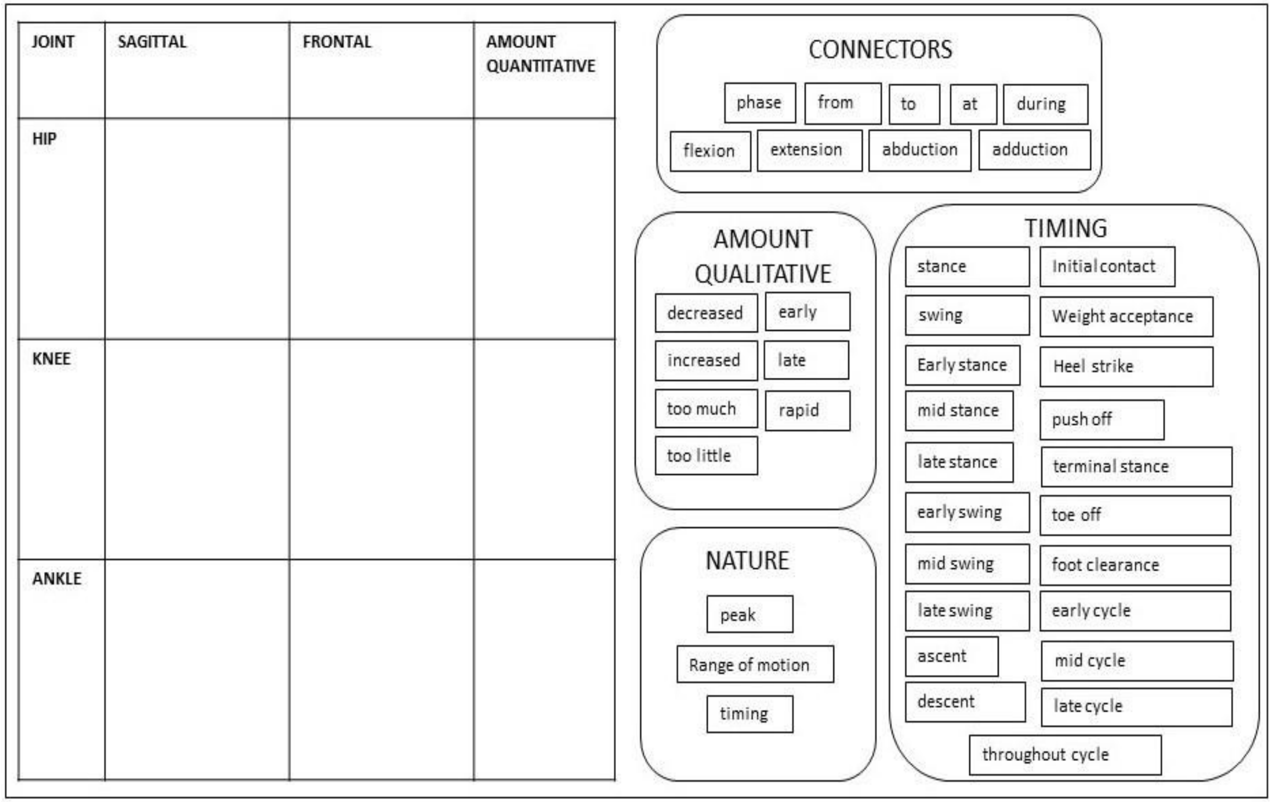


Figure 4: Developed standardised reporting template for the interpretation of kinematic waveform graphs

Table 13: Training for users to interpret kinematic waveform graphs within feedback reports using the standardised reporting template

	Users' training
Purposes of training	- Introduce a movement analysis feedback report. - Enhance the ability to identify altered movement patterns presented within kinematic waveform graphs. - Introduce the standardised reporting template. - Improve skills to adequately use the standardised reporting template.
Assessment of training success	- Monitoring users' completion of standardised reporting template.
Content of training	- Introduction of the feedback report involving its contents. - Interpreting feedback reports. - Introduction of a standardised template involving its contents (themes' boxes). - Defining the standardised terminologies included in each theme box and determining how and why to use different terminologies. - Using the standardised template to describe the identified altered movement patterns.
Methods of delivery	- Practical task. - Feedback report's interpretation guidelines. - Q&A session with the lead researcher.

3.3.6.6 Limitations

Several limitations, which may have an impact on the findings reported in the current study should be discussed. First, as was mentioned previously, the difference in scales used to show the averaged angular kinematic waveforms across the sagittal and frontal graphs may influence raters' decisions concerning the presence of the altered movement patterns across the two planes of movement. More specifically, the frontal kinematics waveforms were of a smaller scale compared to the waveforms in the sagittal plane, which may present frontal waveforms in a more pronounced form to the rater. Therefore, this should be considered in future studies.

Next, identifying altered movement patterns among raters in the current study was essential based on a comparison between the angular kinematic waveforms for the injured leg versus the non-injured one. Another way of achieving this would be to compare the kinematic data obtained to a reference for an averaged kinematic waveform adapted from a huge biomechanical database that represents normal and abnormal movement patterns during multiple functional tasks. Therefore, it would be useful to consider this in the future, and it may be added to the kinematic waveform graphs within the feedback report.

Finally, the movement analysis reports sent to the raters for the second round of interpretations were arranged in the same order as the reports sent in the first round. Even though the raters were not given any information about the case within the report, rearrangement of the reports for the second round in a randomised order may improve the robustness of the within-rater agreement findings in the current study.

3.3.6.7 Clinical implications

Using a template to help standardise the interpretation of kinematic waveform data will potentially add robustness and consistency to the clinical decision making of clinicians. Thus, variations in clinical decision making based on movement analysis data could be avoided. However, it is recommended to use the standardised template in an appropriate way to provide users with training in how to interpret angular kinematic waveforms (Zhou et al. 2021).

3.3.7 Conclusion

The aim of the current study was to create a standardised template to assist users in reporting and interpreting kinematic waveform data provided by 3D movement analysis in a robust and consistent way. This was achieved by evaluating within- and between-rater agreement to identify the presence of altered movement patterns within kinematic waveform graphs, and investigating raters' qualitative descriptions of the identified altered movement patterns. The findings of the current study found a substantial agreement between and within rater in identifying the presence of altered movement patterns over all lower limb joints, planes of movement, and tasks. However, the way of describing the identified altered movement patterns varied among raters. Therefore, a standardised template was developed. The use of this standardised template in a case study to explore the acceptability of using SMAFT within clinical practice (Chapter 4) will assist in accurately and consistently reporting kinematic alterations adapted from feedback reports.

3.4 Chapter's conclusion and clinical implications

This chapter has presented findings from an exploratory study that contributed to the development of SMAFT for this PhD thesis. The study created a standardised template that was integrated with an already developed sensor-based kinematic report in order to form SMAFT. The template was designed to help with consistently reporting and interpreting the altered movement patterns identified in waveform graphs within the kinematic reports.

Integrating the findings of this study in the current phase with the findings from other research (summarised at the beginning of the current chapter, section 3.2) facilitated the development of SMAFT in accordance with MRC guidelines (Skivington et al. 2021). This was conducted by addressing some key uncertainties about the design and content of SMAFT (Skivington et al. 2021).

Following this iterative process, SMAFT is preliminary developed. SMAFT is a portable movement analysis system, comprising inertial body-worn sensors, a feedback report based on movement analysis, and a standardised reporting template. In addition to avatar videos, which can present an individual's full body (including head, trunk, upper, and lower limbs) and demonstrate their movements during the performance of functional tasks (Figure 5). The video recordings of the avatar allow viewing an individual's movements across all joints from different views (planes of movement).

SMAFT aims to augment physiotherapy treatment as usual (TAU) and assist clinical decision making with regard to the management of the knee pain population. The range of kinematic data collected by inertial portable sensors and presented within the feedback report, and the avatar can provide clinicians with a basis for comprehensive clinical movement assessment of individuals with knee pain, which can be used to target kinematic alterations during the performance of functional tasks. The feedback report and avatar provide a visual representation of movements at multiple joints in different planes of movement, encouraging individuals' appreciation of these movement patterns. Hence, SMAFT can promote patient-centred care (Chiauzzi et al. 2015; Thornton et al. 2016; Dunphy et al. 2017) and guide clinical decision making

(Papi et al. 2015; Papi et al. 2016). Moreover, the standardised reporting template can enhance clinicians ability to accurately and consistently describe the altered movement patterns identified. In practice, physiotherapy clinicians make their own analysis and interpretation of the generated feedback report using the standardised template and avatar videos as a guide for treatment decision making based on SMAFT.

SMAFT is now ready to be tested within a real-world context. Evaluating the acceptability of any new intervention among users in clinical settings is crucial (Craig et al. 2008; Sekhon et al. 2017). Therefore, the next chapter will aim to explore users' acceptability of SMAFT (individuals with knee pain and physiotherapy clinicians) within a case study of a physiotherapy clinical practice.

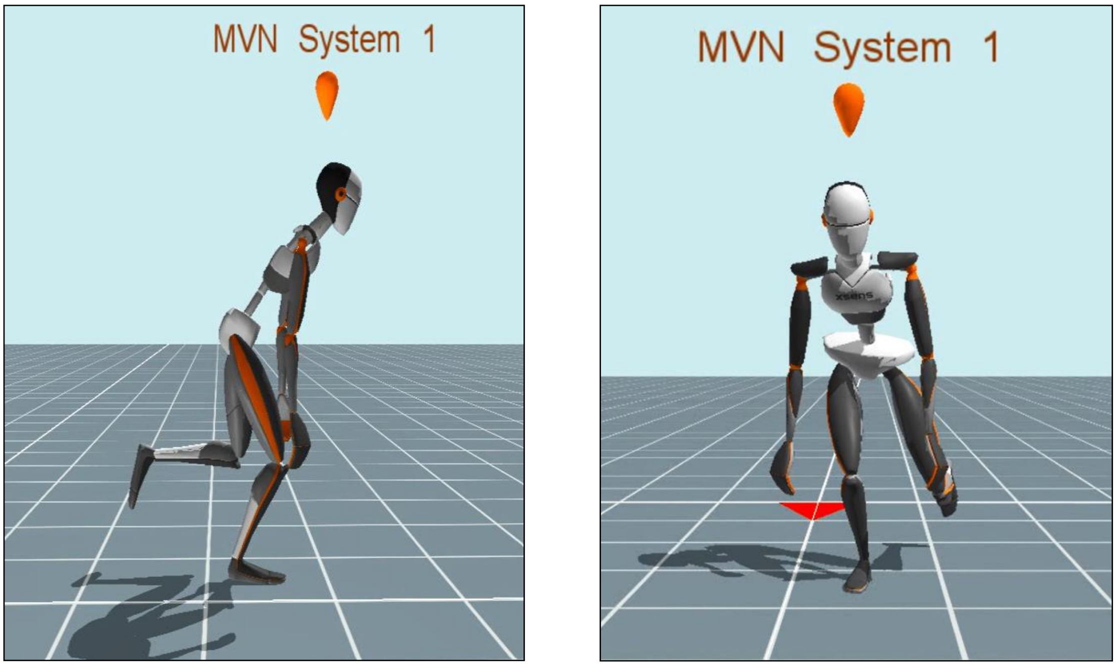


Figure 5: An example of sensor-based movement analysis avatar recordings

Chapter 4. Phase II: Acceptability of the sensor-based movement analysis feedback toolkit (SMAFT)

4.1 Introduction

Phase I of the current PhD thesis informed the development of SMAFT and concluded that SMAFT was preliminary designed and ready to be evaluated within its real-world context. This chapter details the second phase of this thesis, which addresses the key acceptability question in regards with users experience of SMAFT in clinical practice. This is achieved by conducting an exploratory study investigating the acceptability of SMAFT from the perspectives of its users (individuals with knee pain and their treating clinicians) within a case of a physiotherapy clinical practice. A theoretical framework of acceptability (TFA) is used to guide the exploration of SMAFT's acceptability in this case study (Sekhon et al. 2017). The findings set out in this chapter is vital to better understand the design and delivery of SMAFT in clinical settings and thus inform the next stage regarding the development of SMAFT.

4.2 Phase 2 Study 1: Acceptability of SMAFT used alongside physiotherapy treatment as usual in individuals with knee pain within a physiotherapy clinical practice: A mixed-methods case study design

4.2.1 Introduction

In accordance with the MRC framework used to guide the structure of this PhD thesis, acceptability should be evaluated in the early stages of development to assist in guiding decisions about the form, content, and delivery of the proposed intervention (Craig et al. 2008; Skivington et al. 2021). Acceptability is an important consideration for health technologies and interventions (Sekhon et al. 2017). The acceptability of the intervention by intervention's users is critical to its success. If an intervention is deemed acceptable, users would have a tendency to follow the intervention's suggestions and, hence, get advantages from improved clinical outcomes (Sekhon et al. 2017).

For the purposes of the current PhD thesis, acceptability was defined as "A multi-faceted construct that reflects the extent to which people delivering or receiving a healthcare intervention consider it to be appropriate, based on anticipated or experienced cognitive and emotional responses to the intervention" (Sekhon et al. 2017, p. 2). Sekhon et al. (2017) developed a Theoretical Framework of Acceptability (TFA) for healthcare interventions comprising seven component constructs (Table 14). The TFA focuses on the perspectives of those individuals who receive interventions and the individuals who deliver interventions (Sekhon et al. 2017). Acceptability can be measured over time and throughout the lifecycle of the intervention's development (pre-, during, and post-intervention) (Sekhon et al. 2017).

Table 14: Theoretical Framework of Acceptability (TFA) component constructs (Sekhon et al. 2017, p. 8)

Acceptability constructs	Definitions
Affective attitude	"How an individual feels about the intervention"
Burden	"The perceived amount of effort that is required to participate in the intervention"
Ethicality	"The extent to which the intervention has good fit with an individual's value system"
Intervention Coherence	"The extent to which the participant understands the intervention and how it works"
Opportunity costs	"The extent to which the benefits, profits, or values must be given up to engage in the intervention"
Perceived Effectiveness	"The extent to which the intervention is perceived as likely to achieve its purpose"
Self-efficacy	"The participant's confidence that they can perform the behaviour(s) required to participate in the intervention"

Arguably, TFA is beneficial when evaluating the acceptability of interventions through the MRC framework phases (development, feasibility, evaluation, and implementation) (Sekhon et al. 2017). MRC guidelines recommend for considering context and engaging key stakeholders in the early phases of development (Skivington et al. 2021). This may support further modifications to be made prior to evaluating the feasibility of SMAFT and determining how best to implement it. Therefore, the current case study focuses on exploring the acceptability of SMAFT among those users for whom it had been designed (individuals with knee pain and physiotherapy clinicians) within a real-world context (physiotherapy clinical practice), in order to further optimise development and evaluation.

This current case study was loosely aligned with the TFA, which guided semi-structured interviews with individuals with knee pain and their clinicians, focusing on the framework's constructs. In addition, the case study's findings relating to the acceptability of SMAFT will be discussed in line with TFA constructs, in order to better understand the acceptability of SMAFT and its application in physiotherapy practice within a UHB.

4.2.2 Aim

The aim of this study was to explore the acceptability of SMAFT from the perspective of its users (individuals with knee pain and their treating physiotherapy clinicians) when used alongside physiotherapy treatment as usual (TAU) within the physiotherapy clinical practice of a UHB. The study's aim and objectives are presented in Table 15.

Table 15: Study’s aim and objectives across quantitative and qualitative components

Aim	Objectives	Methodological approach and data source
To explore the acceptability of SMAFT from the perspective of its users, when used alongside physiotherapy (TAU), within the physiotherapy clinical practice of a UHB. This was achieved by integrating the findings of qualitative interviews and quantitative pain and function questionnaires, feedback reports interpretations, and clinicians’ notes	**Objective 1:** To investigate users (individuals with knee pain and their treating clinicians) acceptability for using SMAFT alongside physiotherapy (TAU) within physiotherapy clinical practice	Qualitatively analysing users’ semi-structured interviews
	Objective 2: To describe the content of kinematic altered movement patterns identified in individuals with knee pain who used SMAFT	Quantitatively interpreting movement analysis feedback reports obtained by SMAFT using the developed standardised reporting template

4.2.3 Methodology

4.2.3.1 Research design

A mixed-methods case study design was employed, and this is discussed and justified below.

4.2.3.1.1 Original plan and impact of the COVID-19 pandemic on the current acceptability study

The original plan for conducting the study presented in the current chapter was to evaluate the feasibility and acceptability of SMAFT via the development of a single-arm mixed-methods controlled feasibility trial, with a nested qualitative evaluation. The quantitative part included repeated measures of movement analysis and pain, and function questionnaires, in addition to other feasibility outcomes, such as practicality, recruitment, and retention rates. The qualitative part included an evaluation of users' experiences and their clinical acceptance. However, due to the COVID-19 pandemic, the recruitment and data collection at the University Health Board (UHB) settings were restricted. This was because of the study's requirement for direct contact between the individual and the treating clinician. Thus, the data was ultimately collected successfully from seven individuals with knee pain, over a varying number of movement analysis sessions (two individuals received the full set of three sessions, two individuals received two sessions, and three individuals received one session).

It was therefore decided that the aim and research design of the study should be modified slightly to focus only on the acceptability aspect of SMAFT within a physiotherapy clinical practice at a UHB, exploring this in depth from the users' perspectives (individuals with knee pain and their treating clinicians). The study was conducted using a mixed-methods design, similar to that intended before the pandemic. Conducting this using a mixed-methods approach within a case study, in order to explore the users' acceptability of SMAFT in depth within a real-world context, enabled the attainment of a complete and accurate definition and description of SMAFT that should precede its evaluation in clinical settings for individuals with knee pain (Yin 2017). The use of a mixed-methods case study is justified in the next sections 4.2.3.1.2 and 4.2.3.1.3.

4.2.3.1.2 Justification for use of a mixed-methods approach

In healthcare research, the mixed-methods approach has increasingly been identified as a method that is efficient for combining both qualitative and quantitative data via utilising a dominant model (O'Cathain et al. 2007). A mixed-methods approach has been defined as "the type of research in which a researcher combines elements of qualitative and quantitative research approaches. For instance, use of qualitative and quantitative viewpoints, data collection, analysis, inference techniques for the broad purpose of breadth and depth of understanding and corroboration." (Johnson et al. 2007, p. 123).

The fundamental characteristic of a mixed-methods approach is that the approach can capture a complete picture of the complexity of human experience and provide a deeper understanding of phenomena of interest (Doyle et al. 2009; Creswell and Plano Clark 2017), consequently allowing more rigorous conclusions to be achieved (Bryman 2006). Another benefit of the mixed-methods approach is its capacity to answer several questions from different perspectives in a single study (Bazeley and Kemp 2012). Inquiries can be undertaken using different approaches and then integrated to complete each other, in order to generate a comprehensive understanding and attain a single unified conclusion (Bazeley and Kemp 2012). Therefore, a mixed-methods approach was employed in the current study since it allows for a richer exploration of the acceptability of SMAFT as compared to a single method design.

The significance of reasoning when integrating quantitative and qualitative approaches within a single study has been increasingly emphasised within the mixed-methods literature (Bryman 2006). Clear identification of the rationale for combining quantitative and qualitative data through a mixed-methods approach is vital to inform the mixed-methods design (convergent parallel, explanatory sequential, exploratory sequential, and embedded) (Creswell and Plano Clark 2017). Tashakkori and Newman (2010; p. 515) determined seven purposes behind mixed-methods designs (complementarity, completeness, development, expansion, confirmation, compensation, and diversity) (Table 16).

Table 16: Purposes for the use of mixed-methods design adapted from Tashakkori and Newman (2010)

Purposes	Details
Complementarity	"To combine two different but connected answers to a research question: one achieved by a quantitative method and the other by a qualitative one"
Completeness	"To gain a greater understanding of the phenomenon under investigation by merging qualitative and quantitative findings"
Development	"To use the first phase of a study to obtain research questions, data sources or sampling frameworks for the second phase of a study"
Expansion	"As in 'development' but with the aim of elaborating on the information obtained in the first phase of a study"
Confirmation	"To determine the integrity of inferences attained from a strand of a study by means of integrated methods"
Compensation	"To compensate for the weaknesses of one method via the strengths of the other"
Diversity	"To compare and contrast divergent representations of the same phenomenon"

Quotes are taken from (Fiorini et al. 2016, p. 38)

The current mixed-methods study has two of these purposes (Tashakkori and Newman 2010), namely confirmation and completeness. Integrating the description of the content of individuals with knee pain movement analysis interpretations, pain and function levels, and treatments provided through a quantitative approach will support "confirmation" of the findings inferred from the users' interviews in the qualitative component of this study. Thus, integrating the quantitative and qualitative components will generate a more in-depth understanding of the acceptability of

SMAFT within clinical practice, as provided in this study by "completeness". Thus, according to the purposes determined for combining quantitative and qualitative data, a convergent parallel mixed-methods design is the most appropriate to achieve the aim of the current study (Tashakkori and Newman 2010; Creswell and Plano Clark 2017).

Consistent with the convergent approach (Figure 6), the quantitative and qualitative data in this study were collected concurrently, and then analysed individually and separately (Creswell and Plano Clark 2017). The findings from each component were then integrated. The quantitative data related to the individual's movement interpretations, pain and function levels, and physiotherapy treatment given, and the data from qualitative interviews regarding the users' acceptability of SMAFT, were collected concurrently. Both quantitative and qualitative components were analysed independently, and the research objectives associated with each part were addressed. Then the quantitative and qualitative data components of the data were merged to provide a comprehensive understanding and draw a robust conclusion about SMAFT's acceptability.

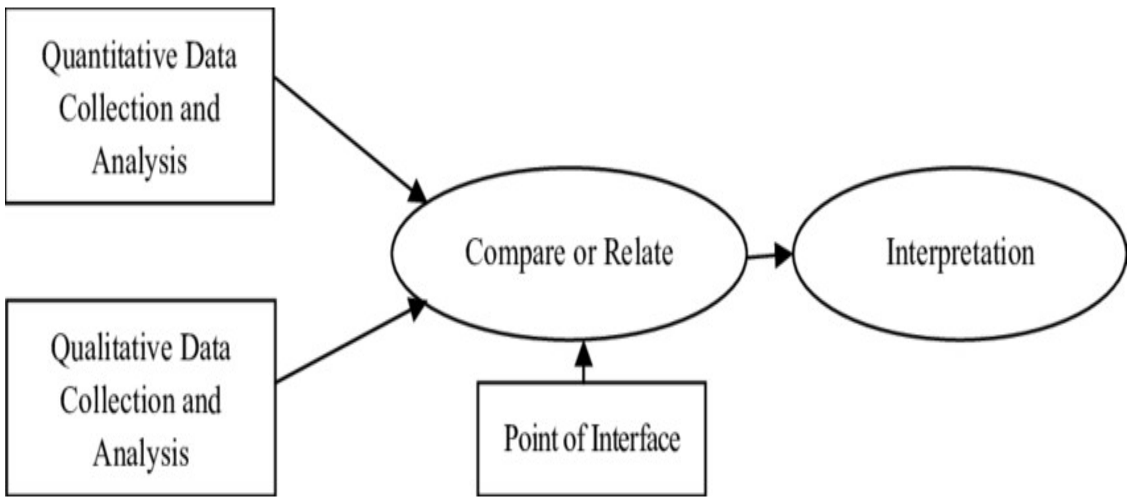


Figure 6: Convergent parallel mixed-methods design. Adapted from (Creswell and Plano Clark 2017)

4.2.3.1.3 Justification for use of a case study design

Case study designs were previously explored and defined by a number of researchers (Stake 1995; Merriam 1998). A recent, and widely accepted definition provided by Yin (2017, p. 60), described it as "An empirical method that investigates a contemporary phenomenon (the 'case') in depth and within its real-world context, especially when the boundaries between phenomenon and context may not be clearly evident". Based on this definition, a case study design can be used when the aim of a piece of research is to explore the how and why of a topic, in a situation in which the researcher has little or no control over the events involved. This situation reflected that of the current study, as its aim was to explore how using SMAFT alongside physiotherapy (TAU), within clinical practice, is accepted by its users, a matter that has not been investigated previously.

Moreover, the advantage of using a case study design was not limited to its strength and capacity to investigate the complexity of the case, but also its ability to explore it in a real-world context (Yin 2017). This can be achieved by getting close to the reality of its participants (users), in order to explore their views and behaviours (Yin 2017). The purpose of this study was to understand in detail what happened within clinical practice when using SMAFT alongside physiotherapy (TAU) that may inform its acceptability. This provided depth rather than breadth in terms of data collection, and consequently, a small sample size was deemed to be sufficient.

Also, the case study has developed in a research context as a method that can capture rich data, and provide an in-depth view of a bounded case that can involve an individual, group, organisation, or programme (Hamilton and Corbett-Whittier 2012). Rich data can be attained by integrating multiple sources of evidence and employing various forms of data collection (Yin 2017). In the current study, the use of rich data produced by multiple sources of evidence involving users' qualitative interviews, feedback reports, clinicians' notes, and pain and function questionnaires, enabled the investigation of the case in depth from different viewpoints. Thus, the inclusion of a small number of participants was appropriate.

In conclusion, the mixed methods case study design was the best alternative to the single-arm mixed methods design originally planned for the current study, which comprised a repeated measure movement analysis and qualitative interviews to determine the acceptability of SMAFT within clinical practice. This was because a mixed-methods case study design enabled the in-depth investigation of acceptability within a real-world context (clinical practice), in a single research design, by integrating multiple sources of evidence that employed various quantitative and qualitative approaches (movement analysis and interviews, respectively). Thus, the small sample size collected using the original study design, due to the restrictions of the COVID-19 pandemic, was appropriate for the current research. The next section defines the case within this research design, and determines its typology.

4.2.3.1.3.1 Define the case

Defining the 'cases' in a case study design can be challenging (Yin 2017). Baxter and Jack (2008, p. 545) proposed a strategy to help determine a case by answering a question about "what do I want to analyse?"; individual, programme, process, or organisation, and then sharing this with a colleague. In the current case study, this strategy was implemented. First, the research aim and objectives were developed and stated clearly. Then, the case was defined by considering the aim and objectives determined. Finally, the defined case was discussed with the researcher's colleagues and supervisors. Therefore, the case was defined in the current study as clinical physiotherapy service within a UHB where SMAFT was used alongside physiotherapy (TAU) for individuals with knee pain, rather than a programme, an individual, a process, or an event (Yin 2017). This case was decided because it is crucial to investigate the clinical services where the intervention is used, as recommended by the MRC framework (Skivington et al. 2021). The two key stakeholders for any intervention in clinical practice are the users (patients and clinicians) (Sekhon et al. 2017). Hence, in the current study, the users (individuals with knee pain and clinicians) of SMAFT at the clinical physiotherapy service were considered the units of analysis.

4.2.3.1.3.2 Case study design types

The case study design has been categorised by Yin (2017) into two types; single and multiple case study designs. Yin (2017) set up a useful two-by-two matrix of a case study design (Figure 7). Single and multiple cases could be considered both holistic and embedded (Yin 2017). The typology applied for this study is that of an “embedded single case study design”. The data was collected and analysed from two units of analysis (users), which were taken from a single case (physiotherapy service within a UHB) in order to inform the main aim of the current study.

According to Yin (2017), a single case study is the most suitable design to use when the case being investigated is critical, extreme or unusual, typical, revelatory, or longitudinal. As the use of SMAFT within the clinical practice was employed for the first time in this case study, this unique physiotherapy service within a UHB (case) may offer a distinct opportunity worthy of analysis. Therefore, a single case study design was chosen based on the rationale of unusual cases (Yin 2017). Multiple case designs are perceived to have a distinct advantage when compared to single case designs. The findings resulting from multiple cases are often deemed more convincing, and the study is thus considered more accurate (Yin 2017). However, the purpose of this case study was to gain in-depth exploratory information regarding using SMAFT, in the case determined (physiotherapy service), to inform its design and delivery in the next stage of development, rather than evaluating and comparing its acceptability across multiple varied physiotherapy services. Thus, a single case study design aligned with the research aim of this study.

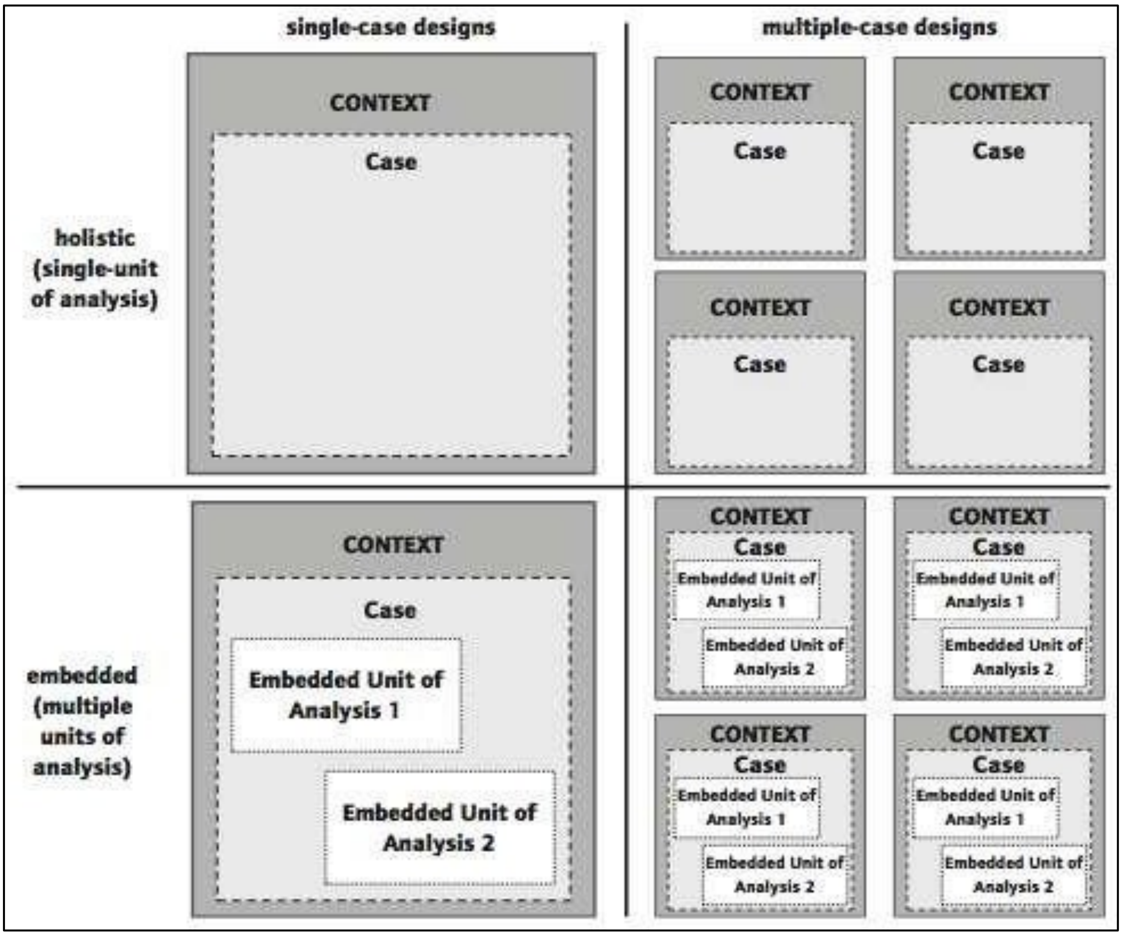


Figure 7: Types of case study design. Adapted from (Yin 2017)

4.2.4 Methods

4.2.4.1 Participants

A convenience sample of seven individuals with knee pain and their physiotherapy treating clinicians (n = 3) from the clinical physiotherapy service were recruited. All individuals were identified by a pseudonym and an identification number in the current study.

4.2.4.1.1 Individuals with knee pain

All of the individuals with knee pain met the following inclusion and exclusion criteria:

Inclusion criteria:

- Adults aged 18+ years old
- Individuals complaining of knee pain for more than three months and on most days of the previous month (Bennell et al. 2012)
- Have activity related knee joint pain
- Able to give written informed consent

Exclusion criteria:

- History of any lower limb, pelvis, or back disorder that may impair the individual's performance of functional activities during the last 6 months
- History of lower limb surgery during the last 6 months (Bennell et al. 2012)
- Any neurological or cardiovascular pathology that would influence motion (Bennell et al. 2012)

4.2.4.1.2 Physiotherapy treating clinicians

Physiotherapy clinicians were recruited to be involved in the delivery of SMAFT. Their role was to screen knee pain individuals' eligibility, obtain permission to contact them, and act as the treating physiotherapy clinician who agreed to receive and use the movement analysis feedback reports provided by SMAFT. One member of staff in each physiotherapy service within a UHB identified potential individuals, and approached them about taking part, and organised appointments.

Inclusion criteria for physiotherapy clinicians:

- Qualified physiotherapy clinicians working in musculoskeletal physiotherapy services with more than 5 years' experience in treating individuals with knee pain.

4.2.4.2 Recruitment procedures

Three NHS physiotherapy clinicians were identified and expressed an interest in participating. A meeting with these clinicians was conducted to explain SMAFT and discuss what their roles would be if they participated in the study. The clinicians were also provided with a study guideline document giving an overview of the recruitment and data collection procedures followed (Appendix G). In addition, the clinicians were given a feedback report interpretation guideline, explaining how to interpret the feedback report (Appendix H).

The potential participants diagnosed with general knee pain were screened by the clinicians, using the above-mentioned individual eligibility criteria for inclusion. If the inclusion criteria were satisfied and the potential individual was interested in taking part, their treating clinician discussed the nature of the research with them, and then provided them with the related Participant Information Sheet (PIS), a consent form (CF), and a permission to contact form (Appendix I). The individuals who expressed an interest in being involved in the study were then invited for data collection, which was timed to take place one hour before their next scheduled physiotherapy appointment. When the potential participant attended for the data collection, the lead researcher met with the individual, explained the research again briefly, and asked them if they had any questions relating to the research. The researcher then went through the consent form with the participants and requested that they sign it prior to starting the data collection process.

4.2.4.3 Sensor-based Movement Analysis Feedback Toolkit (SMAFT)

SMAFT was previously described in detail in Chapter 3, section 3.4. SMAFT is a portable movement analysis system, comprising inertial body-worn sensors, a feedback report and avatar videos based on movement analysis, and a standardised reporting template. SMAFT aims to augment physiotherapy (TAU) and assist clinical decision making with regard to the management of the knee pain population. A summary of the process of integrating SMAFT into physiotherapy (TAU) in the current study, involving the entire role of the lead researcher (M.F.), physiotherapy clinicians, and individuals with knee pain, is presented in Figure 8.

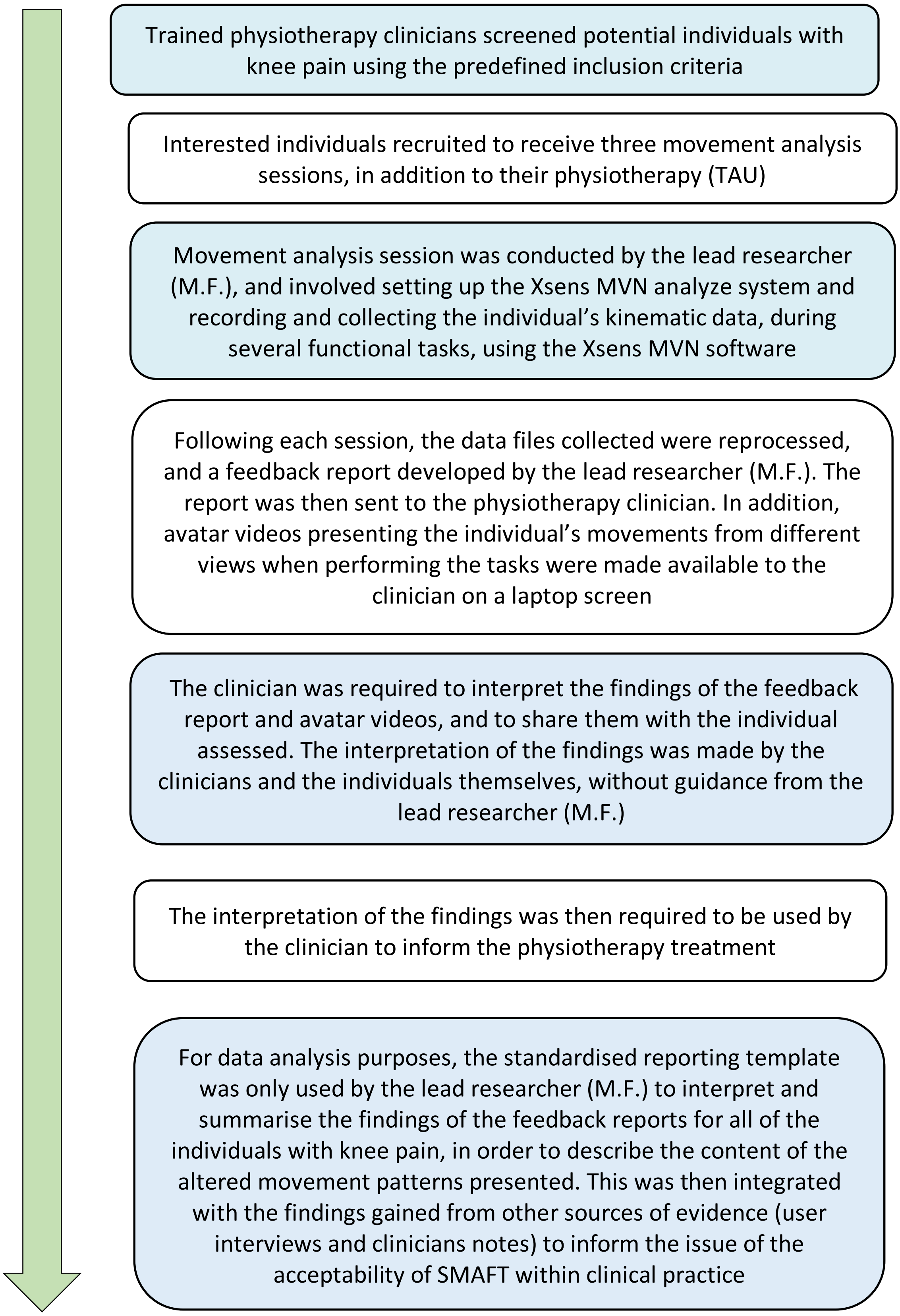


Figure 8: Summary of the process of using SMAFT, in addition to physiotherapy (TAU), within clinical practice in the current study, including the entire role of the lead researcher, the physiotherapy clinician, and the individual with knee pain

Abbreviations: SMAFT = Sensor-based Movement Analysis Feedback Toolkit, TAU = treatment as usual

4.2.4.4 Ethical considerations

This study was conducted as part of a larger study, that had ethical approval granted by the Versus Arthritis Biomechanics and Bioengineering Centre at Cardiff University, and was approved by the Wales Research Ethics Committee 3 (10/MRE09/28).

4.2.4.4.1 Ethical issues related to data collection

The participants were asked to wear fitted shorts and zip-fastened T-shirts throughout the study session. This required better placement of inertial sensors along the participant's body. Privacy for the participants and the researchers were considered by providing a private area for the participant to change their clothes.

Participant confidentiality was ensured by replacing the individual's name with a pseudonym and unique identification number (ID), which was used to identify the individual throughout the study. All of the personal data (consent forms) was retained securely on the Versus Arthritis Biomechanics and Bioengineering Centre servers. A paper copy of these forms was stored in a locked filing cabinet at a university building, which has a secure gate and doors. Also, research data, including movement analysis recordings and feedback reports were collated on a laptop. At the end of the data collection session, and whilst the lead researcher was still in the physiotherapy department the data was transferred to an encrypted drive on the Cardiff University servers (NAS drive), and then deleted from the laptop. All of the data could be retained for 15 years following completion of the study, and then deleted.

Cardiff University's Guidelines for Research Governance and the procedures for good clinical practice in the research were also followed. To the best of the researcher's knowledge, there are no known health risks concerning the proposed protocol. However, skin irritation could occur in individuals with sensitive skin, since the sensors were attached to the skin using double-sided adhesive tape. There were no direct benefits associated with participating in this study.

4.2.4.5 Quantitative data collection

4.2.4.5.1 Movement analysis session procedures

The procedures followed in the current study included three phases (preparation, calibration, and data collection). Each phase is presented separately in the following subsections.

4.2.4.5.1.1 Preparation procedures

The preparation stage began once the participant arrived in the physiotherapy department. At this stage, the participants were asked to change their clothes into shorts and a T-shirt and to take off their shoes. After that, the participant's required measurements (body mass, height, and body dimensions) were quantified.

At the beginning of each session, the anthropometric data, including shoulder height and width, arm span, hip height and width, knee height, ankle height, and foot length were measured in the standing position by a single researcher (M.F.) according to the Xsens manual guidelines (Xsens Technologies B.V. 2021). These measurements were taken using Xsens measuring tape (Xsens Technologies, Enschede, The Netherlands), and then entered into MVN software (Table 17). This data was important for creating a body configuration model in the MVN software, to allow quantification of the body segment (Roetenberg et al. 2007).

Table 17: Description of how to measure the various body measurements according to the Xsens manual guidelines (Xsens Technologies B.V. 2021)

Body measurements	Descriptions
Foot size	From the back of the heel to the front of the toe
Ankle height	From the floor to the centre of the ankle (lateral malleolus)
Knee height	From the floor to the lateral epicondyle
Hip height	From the floor to the greater trochanter
Hip width	From the left anterior superior iliac spine to the right anterior superior iliac spine
Shoulder height	From the floor to the tip of acromion
Shoulder width	From the left tip of acromion to the right tip of acromion
Arm span	From the top of left fingers to the top of the right fingers

Seventeen wireless Xsens MTw2 IMU sensors (MVN BIOMECH Awinda; Xsens Technologies, Enschede, The Netherlands) were placed on the participant's body by one researcher (M.F.) adhering to the Xsens guidelines (Xsens Technolgies B.V. 2021) (Figure 9). Each sensor has a pre-determined identification number, which could be utilised during the operation of motion capture. Therefore, it was recommended that placing sensors on the right body segment would be highly important. In addition, sensors should be placed in an appropriate position on each body segment to allow a maximum joint range of movement and ensure minimal skin motion artefacts exist.

Each participant was asked to wear a zip-fastening T-shirt over their own T-shirt, as well as a head band and gloves, to ensure reliable and easy placement of the head, shoulder and hand sensors. Elasticated Velcro straps were used to secure the sensor in position and reduce movement. The sensors were positioned between the two external layers of the strap and adhered to the Velcro in the internal layer, and distributed as follows (Figure 9):

- One on the head;

- Two on both scapula (shoulder blades);
- One on the chest (sternum);
- Two on both upper arms (on the lateral side above the elbow);
- Two on both forearms (lateral and flat on the wrist);
- Two on both hands (flat on the backside of the hands);
- One flat on the sacrum (the upper boundary of the sensor in line and centred with the right and left posterior superior iliac spine) (A 3M Tegaderm Transparent Film Roll dressing was used to keep the sacral sensor in position.);
- Two on both upper legs (in the centre between the greater trochanter and lateral epicondyle);
- Two on both lower legs (flat on the shin bone proximally and medially to the surface of the tibia); and
- Two in the middle and over the bridge of both feet

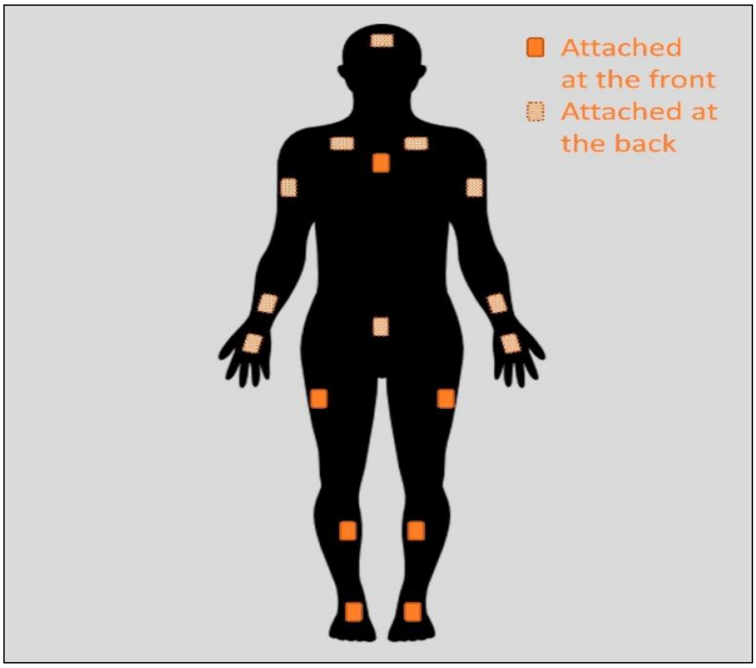


Figure 9: Full body sensors and marker placement (Adopted from Huang et al. 2020)

Key: Orange squares = sensor trackers attached at the front, Beige squares = sensor trackers attached to the back

4.2.4.5.1.2 Calibration procedures

Segment calibration is performed to coordinate sensors with aligned body segments. Generating an excellent calibration is vital to ensuring adequate, high-quality findings (Xsens Technologies B.V. 2021). Therefore, calibration procedures should be performed carefully to achieve the best results. In the current study, a thorough calibration based on the standardised instructions for the Xsens guidelines was carried out (Xsens Technologies B.V. 2021). The description of the calibration procedure is as below.

The calibration procedure involved several steps, as follows. First, the participant was instructed to stand in an upright neutral position (static N-pose) with both their arms and legs in a straight line downward, and hold this position for approximately 20 seconds. The next step was to ask the participant to walk in their normal fashion at their normal pace and return to their starting position. Finally, the participant was instructed to retain the static N-pose position until the calibration process was complete. Consequently, the MVN software revealed the quality of the calibration on screen (good, acceptable, poor, or fail) and represented the calibrated sensors. After the calibration had been applied, the participant was asked to walk around slowly and freely for approximately 30 seconds in order to warm the engine. After we ensured that the calibration procedure was working successfully by looking at the resulting quality and comparing the actual participant's with the avatar's (3D character) performance of movement, the data collection could commence.

4.2.4.5.1.3 Experimental protocol

For this study, the movement analysis was repeated three times over two months. The movement analysis sessions were scheduled as closely as possible for three weeks, six weeks, and nine weeks. The data collection appointments were scheduled to take place one hour prior to the individuals' physiotherapy treatment session for the first movement analysis data collection appointment and 30 minutes prior to the treatment session for follow up appointments. The first movement analysis data collection session was longer than the subsequent ones, because the first session required a longer preparation phase (explaining study procedures, obtaining the individual's consent to participate, and taking related body measurements). Individual's body measurements were taken during the first session and retrieved for subsequent sessions, and thus the same body configuration model was used by the Xsens MVN Analyze software. Retrieving body measurements and using the same model is important in terms of the consistency of the data collection across the movement analysis sessions.

In movement analysis sessions, kinematic data was collected by the lead researcher (M.F.) using the Xsens MVN system, while individuals with knee pain performed a variety of functional activity tasks, including gait, DLS, SLS, VJ, SA, and SD. All of these functional tasks were justified for inclusion in SMAFT (discussed previously in the literature review chapter, section 2.6.1). Sensor-based movement analysis has adequate accuracy and consistency as a way of quantifying lower limb angular kinematics in the sagittal and frontal planes during the performance of such tasks. The individuals were instructed to perform the tasks within the tolerated pain level. It was not necessary for the individuals to complete any particular task if they were unable to perform it or would have found it difficult to do so.

These functional tasks were described verbally and demonstrated to individuals by the lead researcher (M.F.). Two practice repetitions were conducted to familiarise individuals with the tasks (Phillips and van Deursen 2008). After familiarisation, the individuals were asked to perform eight trials (repetitions) of all functional tasks. Their performance of the tasks was recorded using the Xsens MVN Analyze software, controlled by the lead researcher (M.F.). The individuals were asked to perform the tasks as they would naturally, without any correction of technique given. The order of the tasks was standardised as follows: DLS, SLS, VJ, Gait, SA, and SD. The following instructions were given to individuals regarding how to perform each task:

- DLS: “Squat with both knees as deeply as you can within the limit of pain whilst maintaining balance, and then return to your starting position.”
- SLS: “Balance on one leg and bend your knee as deeply as you can within the limit of pain whilst maintaining balance, and then return to your starting position.”
- VJ: “From a standing position, bend both knees and then jump vertically as high as you can, and then return to your standing position.”
- Gait: “Walk at normal speed from the starting point until you reach the end point, and then stop.”
- SA: “Ascend a stair at normal speed, moving the right limb first from the starting point to the end point, and then stop.”
- SD: “Descend a stair at normal speed, moving the right limb first from the starting point to the end point, and then stop.”

The distance for the gait task and the number of stair steps for the SA and SD tasks were pre-determined by the lead researcher (M.F.) using two safety traffic cones based on the available space and the facilities within each physiotherapy service (ranging from 7 to 10 meters for gait and from 3 to 6 steps for SA and SD). Also, both limbs were tested during the SLS task.

For each of the functional tasks, a trial was considered to have failed if an individual lost their balance, the trial was interrupted, the Xsens software was not set to record, or the sensors dropped off or moved. If the trial failed, it was repeated. In the case of an individual being unable to perform a functional task due to knee pain, data was not collected.

To monitor the data collection trials and facilitate data analysis, a data collection sheet was used (Appendix J). For each individual, each trial was reported and marked with an (S) if successful or (F) if failed. After completion of any task, the lead researcher (M.F.) asked the individual if they experienced pain during the performance of the task and ticked (√) on the sheet when the pain was present or (×) when the pain was absent. After all tasks had been successfully completed, the sensors were removed. Then, the individuals were asked to wait in the waiting area until the time of their treatment session arrived. While waiting, the individuals were asked to complete the Numeric Pain Rating Scale (NPRS) and Knee Injury and Osteoarthritis Outcome Score (KOOS) questionnaires. The scores from these two questionnaires were used to describe the pain and function levels of the individuals with knee pain in the case study.

4.2.4.5.2 Knee Injury and Osteoarthritis Outcome Score (KOOS)

The KOOS is a valid and reliable knee-specific tool built to determine the opinions of individuals with regard to their knees and associated issues (Roos and Lohmander 2003). It was created as a supplement to the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) for utilise with individuals with knee injuries or knee osteoarthritis in a younger and more active group of individuals. KOOS claims to capture a wider range of individual-relevant functional capabilities using subscales that include leisure and daily living activities. The KOOS assesses both the short- and long-term consequences of a knee injury. It comprises 42 elements in 5 separately graded subscales; pain (9 items), other symptoms (7 items), Daily Living Function (ADL) (17 items), Sport and Recreation Function (5 items), and Quality of Life (QOL) (4 items) related to knees (Peer and Lane 2013) (Appendix K).

The KOOS scoring system involves a Likert scale of 5 points, with zero anchors (no problems) to 4 (extreme problems), with each of the five scores to be measured as the total of the included items. The ratings are converted on a scale of 0-to-100, with a score of zero indicating extreme knee problems and a score of 100 indicating no knee problems.

4.2.4.5.3 Numeric Rating Scale (NRS)

The NRS is a valid, reliable, and appropriate tool for utilising within clinical practice (Williamson and Hoggart 2005). The scale is an 11-point, 21-point, or 101-point on a scale with end points at no pain and pain as severe as it can be (worst possible pain). The NRS can be delivered in a visual or verbal format (offered visually in the current study). When viewed visually, the numbers are enclosed in boxes and referred to 11-point or 21-point scale, based on how many degrees of discrimination are given to the individual (Williamson and Hoggart 2005). In the current study, individuals were provided with a paper including some questions and a scale of 11 points (rated from 0 to 10), and were then asked to answer the following questions:

- On a scale of 0 to 10, with 0 indicating no pain and 10 indicating the worst pain imaginable, how would you grade your pain RIGHT NOW?
- On the same scale, how would you grade your USUAL level of pain during the last week?
- On the same scale, how would you grade your BEST level of pain during the last week?
- On the same scale, how would you grade your WORST level of pain during the last week?

4.2.4.5.4 Data processing and movement analysis feedback report creation

Following the collection of the kinematic data, it was reprocessed using a high-definition mode. The HD reprocessed files were then exported to provide mvnx files. The movement analysis feedback reports were then created utilising a custom-written code on MATLAB software (Matlab version 9.6.0.1150989 (R2019a) Update 4) (Nicholas et al. 2019; Davies et al. 2021) by uploading the exported mvnx files. Once the feedback report had been created (in PDF format), it was sent via email to the physiotherapy clinician (NHS email). The contents of the feedback report are presented in Chapter 3, section 3.2.

In addition, movement analysis recordings, including an avatar (3D character) of the assessed individual with knee pain (presenting their performance of functional tasks), were made available on a laptop screen for the clinician. These can be utilised in clinicians' movement assessments alongside the feedback report and shared with individuals (detailing avatar recordings presented in Chapter 3, section 3.4). The recorded trials could be played back, edited, and analysed from different views (planes of movement). The clinicians conducted their own analysis and interpretation of the feedback report and avatar recordings and utilised them as a guide to target the rehabilitation programme and monitor the individual's progress. The research team did not provide the clinician or individual with an interpretation of the report or the avatar files.

4.2.4.5.5 Standardised reporting template for interpreting altered movement patterns performed by individuals with knee pain

To analyse and interpret the kinematic waveform graphs adapted from the feedback reports, a standardised reporting template was employed. The development of the standardised reporting template was a component of the current PhD thesis (more detail about the template was presented in Chapter 3, section 3.3.6.5). Using the template, each waveform graph was interpreted by describing the altered movement patterns presented by comparing the waveforms for the affected and non-affected ones in terms of amount, nature, and timing categories. Each category included a list of terminologies to choose from and report in the relevant space on a provided table (Excel document).

For this case study, a standardised template was used by the lead researcher (M.F.) to describe the altered movement patterns presented in the waveform graphs within the feedback reports (developed after each movement analysis session for each individual with knee pain). This was conducted to interpret and summarise the findings of the feedback reports for all of the individuals with knee pain, which were integrated with the findings gained from other sources of evidence (users' interviews and clinicians' notes) to inform a comprehensive view of SMAFT's acceptability within clinical practice. Using the template enhanced the robustness and consistency of the interpretation. It was however decided not to provide the clinicians with a reporting template due to the time required to use it.

4.2.4.5.6 Clinicians' documentary notes

Documentary notes from the individuals with knee pain files were collected. These documents helped to confirm the evidence acquired from other data sources in the case study (Yin 2017). Documentary notes requested from the clinicians involved the clinician's notes, which included information about the individual's medical history, assessment, and progress reports over physiotherapy treatment sessions. The clinician's notes for each individual were collected following each treatment session by photocopying them and then storing them in a locked filing cabinet in a university building, which has a secured gate and doors. This was performed on the day of data collection.

For this case study, documents were used to describe the participating individuals with knee pain in terms of the individual's medical history, clinical examinations, physiotherapy received, and sports and functional activities performed. In addition, the clinician's notes may provide insight into the altered movement patterns identified and the physiotherapy treatments given by the treating clinicians. This information was used alongside the findings from the qualitative interviews and the quantitative movement analysis interpretations of the feedback reports to help build a picture of SMAFT and determine how it could be used alongside physiotherapy (TAU) in a future study. Textual data relating to altered movement patterns identified or treated by clinicians, in addition to data describing physiotherapy treatments given, including exercises, advice, education, or other treatment techniques, were extracted. This was done by the lead researcher (M.F.) after reviewing all the notes and extracting texts in tabular form.

4.2.4.6 Qualitative data collection

4.2.4.6.1 In-depth Interview

In-depth interviews are commonly utilised in case study research and are an invaluable source of evidence (Stake 1995; Yin 2017). In the current study, a series of semi-structured interviews were performed with the individuals with knee pain following completion of their final movement analysis sessions, and with the treating clinicians after completion of collecting data on all individuals. After the completion of the final movement analysis session, the individuals and clinicians were contacted by the lead researcher (M.F.) to recruit them and discuss the nature of the qualitative interview. The individuals and clinicians who expressed an interest in being involved in the interviews were provided with the related Participant Information Sheet (PIS), and consent form (CF) via email (Appendix L). Once the consent form had been received by the lead researcher, the participants were contacted to determine a suitable date, time, and place for them to conduct the interview.

It was intended that the interviews should take place at a convenient location and time for the participants (individuals with knee pain and clinicians); in a quiet room within the physiotherapy department, or over the phone. However, due to COVID-19, a phone interview was the only option. Phone interviews have several limitations relative to face-to-face or online interviews, such as the provision of fewer opportunities to detect non-verbal cues, build rapport, and maintain interaction (Irvine 2010; Irvine et al. 2010; Trier-Bieniek 2012). These limitations may be reduced using an online platform such as Zoom, which allows for a connection via video, audio, and phone. However, interviewing participants regarding their views about the acceptability of SMAFT in clinical practice was unlikely to be a particularly sensitive topic for participants, so the need to use non-verbal cues such as body language was not considered vital in this case. Therefore, phone interviews were not expected to negatively affect the current study. Therefore, all the interviews were conducted over the phone except for one that had already been conducted prior to the pandemic.

The interviews with the individuals with knee pain lasted approximately 20-30 minutes, and those with the clinicians approximately 35-45 minutes. All the interviews were conducted by the lead researcher (M.F.) (details relating to the interview are presented in the next subsection 4.2.4.6.2). All the interviews were recorded using a Dictaphone (Olympus Corporation, model WS-852). Audio files were transferred from the Dictaphone onto the lead researcher's personal drive on the Cardiff University servers and then deleted from the Dictaphone. This was performed on the day of the recording. Electronic audio files were retained on the drive and deleted following the completion of the study.

4.2.4.6.2 Interview topic guide

Interviews were prepared in a semi-structured format, as this delivers a flexible structure to investigate the "lived reality" of an individual's experiences (Morgan and Drury 2003) and allows the researcher to be close enough to the individual's experience of the phenomenon in question (Denzin and Lincoln 2011). It is recommended for the interviews in a case study context, that a small number of focused questions related to the issue in hand be prepared ahead to limit deviations from the topic under inquiry (Stake 1995; Rubin and Rubin 2011). Interview topic guides were therefore tailored for individuals with knee pain and physiotherapy clinicians and used during the interviews to maintain focus on the research topic and ensure appropriate phrasing of questions (Rubin and Rubin 2011).

As this case study was loosely guided by the Theoretical Framework of Acceptability (TFA), the majority of the interview questions for individuals with knee pain corresponded to the TFA constructs. More clearly, TFA constructs were considered when interviews were designed (Appendix M). Using various constructs from the (TFA) as a guide when designing the interview questions provided richer information on those specific aspects of SMAFT that related to acceptability (Sekhon et al. 2017). The interview topic guide included questions about suitability and understanding of SMAFT, perceptions of it, what participants liked and disliked about it, and the challenges identified (Appendix M). Interviews were structured to always start with introductory questions (icebreaker questions) to put the participants at ease. For instance, interviews with the individuals with knee pain began with a general question about the sports and exercises they regularly engage in. Similarly, the clinicians' interviews were begun with an introductory question about how movements are typically analysed in clinical practice.

The interview guides gave structure but were utilised flexibly (King et al. 2018). The order and phrasing of the questions sometimes varied from the interview guide. The interviewer found a balance between steering the conversation to cover crucial issues while also enabling interviewees to explore their own ideas, allowing unanticipated issues to arise. Throughout the interviews, both broad and open-ended questions were asked by the lead researcher (M.F.), to allow the participants freedom when responding to questions and conveying their experiences and opinions (Turner 2010). The participants were encouraged to answer the questions and expand on their answers in order to explore their acceptability of SMAFT. Probing was used to elicit additional detail, information, and explanation (Ritchie et al. 2014). Some examples of the prompts used were presented in the interview guides for individuals with knee pain and clinicians (Appendix M). These prompts were not used immediately when asking the questions, but were used when needed.

4.2.4.7 Data analysis

The data analysis in the current study follows a mixed-method convergent parallel design (Creswell and Plano Clark 2017). This mixed-methods design had been presented in detail previously in (Chapter 4, section 4.2.3.1.2). In the current study, the integration of both quantitative and qualitative data was done when the findings were interpreted.

4.2.4.7.1 Quantitative analysis

Descriptive statistics (mean and standard deviation) regarding individuals with knee pain demographics, the incidence of pain during the performance of functional tasks, time spent on conducting movement analysis sessions and developing feedback reports, and KOOS and NRS questionnaire scores were calculated. Also, by using a standardised reporting template for analysing feedback reports, the altered movement patterns across all individuals and movement analysis sessions were identified and summarised by counting the frequency of use. Moreover, the clinicians' notes for all the individuals with knee pain were investigated, and the altered movement patterns and treatments documented by the clinicians were summarised. This was conducted by identifying the physiotherapy treatments provided, including exercises, advice, education, or other treatment techniques used for each individual and physiotherapy treatment session. Additional related information about these treatments, including muscles targeted, applications, positions, and doses, was extracted.

4.2.4.7.2 Qualitative analysis

The individuals with knee pain and clinicians' interviews were digitally audio-recorded, anonymised, and fully transcribed verbatim into Microsoft Word documents. Microsoft Excel and Word were used to manage the data and identify the themes (described in more detail later in this section). Thematic analysis, adapted from Braun and Clarke (2006), was used to analyse the interview data. This approach was selected for its clear, and systemic approach. Following a clear systematic approach helped to provide a transparent description of the analysis process, and to provide an audit trail to confirm the credibility of later data analysis and interpretations (Lincoln and Guba 1985).

Thematic analysis is essentially a method for identifying and analysing patterns within a qualitative data set (Braun and Clarke 2006). It emphasises highlighting, examining, and reporting patterns (themes) within data (Braun and Clarke 2006) to address a research aim. Themes can be identified inductively (bottom up) or deductively (top down) (Braun and Clarke 2006). Inductive themes are identified directly from the data; whereas themes identified deductively relate to a prespecified theory achieved through coding the data into a priori coding frame. The inductive analysis approach provides a richer description of the entire data set, while the deductive approach provides a more detailed account of data that relates specifically to a priori codes (Braun and Clarke 2006). Since the case study topic (acceptability of SMAFT in clinical practice) has not yet been explored in the literature, investigating the entire data set to identify themes that are significant to the topic discussed in this case study was needed. Therefore, an inductive approach was used.

The thematic analysis comprises six phases to create established and meaningful patterns (themes) (Braun and Clarke 2006). The phases were followed iteratively rather than linearly, which included repeatedly moving back and forth throughout the phases over a period of time (Braun and Clarke 2006). These phases are: familiarisation with data; generating initial codes; searching for themes among codes; reviewing themes; defining and naming themes; and producing the final report (Braun and Clarke 2006). The process of applying the phases to this study is now described.

Phase I: Familiarisation with data

All the interviews were transcribed verbatim by a company that specialises in transcription services (Essential Secretary Ltd.) and typed out as Microsoft Word documents. In order to check precision and clarity, the transcripts were reviewed by the lead researcher (M.F.) and corrected.

Considering that it was recommended to be immersed in to become familiar with the entire body of a data set prior to starting the coding process (Braun and Clarke 2006), the lead researcher (M.F.) immersed themselves in the data while reviewing the transcripts. In addition, each interview transcript was read and re-read several times to ascertain meanings and patterns (Braun and Clarke 2006). While becoming immersed in the data, notes, thoughts, or impressions were made in order to provide the researcher with initial insights about the main issues regarding SMAFT's acceptability. At the end of this phase, awareness of interesting ideas within the data as a way to generate codes was gained by the lead researcher.

Phase II: Generating initial codes

Coding is "the process of examining and organising the information contained in each interview and the whole dataset" (Green et al. 2007, p. 548). At this first level of coding, one is seeking out special categories in the data, which will form the preliminary units of further coding (Braun and Clarke 2006). Coding is useful for reducing lots of raw data into small chunks of meaning, which is related to the topic of this case study (DeCuir-Gunby et al. 2011).

Since the analysis was performed inductively, the approach to complete coding (line-by-line coding) was utilised to code every piece of text and capture anything relating to SMAFT's acceptability. Line-by-line coding was conducted to make sure that nothing was missed during the process that would be important later in the analysis (Braun and Clarke 2013). The coding process was also based on using the participant's own words as much as possible. For instance, the identified codes 'increased individual's awareness of movements' and 'motivation to perform exercises' were derived from the participant's own words. Therefore, the thematic analysis of this case study was around the semantic level (data-derived) rather than the latent level (research-derived) when the analysis extended beyond what the participant had said (Braun and Clarke 2013).

Coding was conducted by the lead researcher (M.F.) and two supervisors (K.B. and K.H.) for one transcript for individuals with knee pain and clinicians, and initial codes were identified. A meeting was then conducted to generate discussion and develop an agreement. During the meeting, the researchers went through each assigned transcript, and all the initial codes identified were compared and checked for agreement. As a learning and development exercise; involving more than one researcher in analysing the data provided an opportunity for the lead researcher to share their thoughts and ideas and examine their ability to justify how the data was coded. This was also done to enhance the credibility of the findings (Lincoln and Guba 1985), allowing the researcher to take into account different perspectives with the potential to eliminate bias during the coding process. In addition, discussions around the initial codes, categories, and themes generated may have afforded an opportunity to refine, merge, or remove them further (when needed).

When the lead researcher and supervisors compared the codes they had identified, the majority were found to be comparable in terms of identifying the same issues despite being named slightly differently (e.g., 'used for tailoring treatment' vs. 'personalising treatment'). Furthermore, it was discussed that some code names were more general and needed to be modified to be more specific (e.g., 'using the tool across all NHS settings’ to ‘positive perception about rolling out/spreading the tool’, and ‘how the tool works’ to ‘identify compensation strategies objectively’). Some codes had also been recently generated whilst reviewing the transcripts during the meetings (e.g., ‘understanding process of movement analysis session’).

For the remaining transcripts, the coding was performed independently by the lead researcher (M.F.). The coding process was performed in a consistent manner through all the individuals with knee pain and clinicians’ transcripts, with full and equal attention being given to each transcript (Braun and Clarke 2006). Codes were identified using Microsoft Word, highlighting relevant texts within each transcript, and generating notes in the comment boxes (codes). All the codes identified alongside their text extracts were exported to a Microsoft Excel worksheet, generating a column with line numbers for the extracts taken. An example of the initial codes identified from the transcripts for individuals with knee pain and clinicians, with the associated quotations, can be seen in Appendix N. The coded extracts identified for one transcript for individuals and clinicians were reviewed by one supervisor (K.H.). This was done to ensure the codes were allocated properly by the lead researcher and reflected the raw data (Fereday and Muir-Cochrane 2006). Furthermore, regular discussions with the two supervisors (K.B. and K.H.) regarding the coding process and thematic analysis were performed in order to lend some objectivity to the analytical process being followed.

One hundred and eighty-eight initial codes were identified across all the individuals and clinicians’ transcripts and collected in a table in a Microsoft Word document (Appendix O). As the codes were categorised by looking across the codes and their extracts, it was observed that the meaning of several of the codes identified corresponded; however, their names differed slightly. These codes were therefore collapsed, and refined codes were generated (Appendix P). For instance, the codes ‘Limited time for analysing feedback report and sharing findings at the same session' and ‘Findings of feedback report were not discussed with individual at the same session because of time shortage' had the same meaning. Hence, ‘Findings of feedback report were not discussed with individual at the same session because of time shortage' was removed, and ‘Limited time for analysing feedback report and sharing findings at the same session' was selected as the new name for the code. Through this process, the lead researcher was able to refine the codes and reduce their number.

Phase III: Searching for themes among codes

During this phase, collating and sorting all the refined codes involving all the coded extracts into potential themes was undertaken. A theme typically captures something significant about the data in relation to the research aim and exhibits patterns within the data set (Braun and Clarke 2006). Codes were analysed and allocated into groups according to their similarities, to form an overreaching category (Braun and Clarke 2006). Clustering of codes into initial categories was done by the lead researcher (Appendix Q).

For example, from the lead researcher’s perspective, the refined codes ‘Identifying altered movement patterns objectively’, ‘Increased clinician’s understanding of movements’, ‘Inform clinician’s decision’, ‘Tailoring treatment’, and ‘Monitoring progress’ described how using SMAFT alongside physiotherapy (TAU) can enhance physiotherapy assessments and treatments. All of these codes were thus grouped under the initial category of ‘Add more depth to physiotherapy treatment and assessment’. In addition, through the process of reviewing the initial categories identified and their relevant extracts, some categories had no rich data to support them, which involved only very short extracts with a lack of explanations. Therefore, these categories were removed (e.g., ‘Implementing the movement analysis tool in clinical practice’, and ‘Using a movement analysis tool outside the clinic’). A diary was documented (in comment boxes) to establish an audit trail in order to assist with keeping track of any changes that occurred throughout the analysis phases.

Initial categories were then collected and sorted into potential themes based on their relevance. This was performed by using a table involving all the refined codes and their extracts, applying a colour code next to each individual cell on the table, and assigning it to its potential thematic area (Appendices R and S) (Bree and Gallagher 2016). Furthermore, an initial thematic map was used to help identify the link between categories and themes by visualising them and creatively thinking about how the different parts fit together (Appendix T).

Collating and sorting all the codes into themes and categories, and creating the preliminary thematic maps was a process conducted by the lead researcher (M.F.) and reviewed by the research supervisors (K.B. and K.H.). A meeting was conducted for the purpose of discussion and agreement. At the end of this phase, every single potential theme and its categories and codes were reviewed to provide insight into its significance (Braun and Clarke 2006).

Phase IV: Reviewing themes

During this phase, data from within the initial categories and themes was reviewed for significant coherence, and links identified between themes (Braun and Clarke 2006). The process of refining preliminary themes was performed at two levels. First, all the collected extracts covered by one theme were reviewed to ensure that they fit appropriately and form a coherent pattern (Braun and Clarke 2006). For instance, the theme of 'Understanding process of movement analysis session' was removed because there was a lack of rich data to support it. The underlying category and codes were too diverse to form a coherent pattern.

Once the first point was assured, the second level of the refinement process was performed. At this level, the themes were examined in terms of their relationship to the whole data set (Braun and Clarke 2006). For example, the two categories of 'Challenges and features of avatar videos' and 'Challenges prior session (recruitment)', which were located under the 'Miscellaneous theme' were examined to establish any relationship to other categories and themes. However, these categories did not fit with the categories covered by other themes, and at the same time, they were not rich enough to form the themes themselves. Therefore, it was decided to remove them both.

Furthermore, the code extracts involved within the initial theme of 'Changing perceptions of movement analysis feedback tool over time' were found to overlap substantially with other categories and themes, such as 'Practicality of movement analysis session' and 'Perceived impact of using movement analysis tool and its mechanisms'. Therefore, the theme 'Changing perceptions of movement analysis feedback tool over time' was removed.

Phase V: Defining and naming themes

Throughout this phase, an iterative process was conducted to refine and check all the themes, sub-themes, categories, and codes against each other (Braun and Clarke 2006). Each theme was defined clearly and identified so as to be fitted into the broader overall story of the data set in relation to the research aim. In addition, the titles of the themes and sub-themes were revised.

Regular meetings during this phase were conducted with the research supervisors (K.B. and K.H.) to explain the themes and identify how the underlying data could be integrated to create a pattern and link themes together. As a result of the discussion in the meeting, the supervisors highlighted that the themes of 'Perceived impact of the movement analysis feedback tool' and 'Mechanism of perceived tool benefits' appear to be strongly linked and concern the same topic. Therefore, they were merged into one theme named 'Perceived benefits of sensor-based movement analysis feedback toolkit'. In addition, the sub-themes 'Timing of movement analysis session', 'Frequency and spread of movement analysis sessions', 'Flow of movement analysis sessions', and 'Person should run movement analysis session' were grouped under a new sub-theme, named 'Organisation of movement analysis sessions'. Similarly, it was advised to group the sub-themes relating to the exercises included, equipment used, and calibration challenges under a single sub-theme named 'Contents and procedures of the movement analysis sessions'. This was advised and conducted to reduce the quantity of the categories covered under the theme of 'Practicality of movement analysis session'. In addition, this affords more description and context to assist with naming the sub-theme.

At the end of this phase, a final satisfactory thematic map was developed (Braun and Clarke 2006) (Appendix W).

4.2.5 Case Study Results

4.2.5.1 Introduction

This section presents the mixed-methods case study findings. As this case study was analysed using a mixed-methods convergent parallel design (Creswell and Plano Clark 2017), presenting the findings will be conducted in two stages. In the first stage, the quantitative findings regarding the incidence of pain, and KOOS and NRS questionnaires will be shown. In addition, the findings on the content of the altered movement patterns produced by individuals with knee pain will be presented, and the research objective **(To describe the content of kinematic altered movement patterns identified in individuals with knee pain who used SMAFT)** thereby met. Also, other quantitative findings of the altered movement patterns identified and the treatments given by clinicians will be shown. Then, the findings from the qualitative interviews will be presented, and the research objective **(To investigate users acceptability for using SMAFT alongside physiotherapy (TAU) within physiotherapy clinical practice)** will be addressed.

In the second stage, the findings from the quantitative and qualitative data will be merged and compared, and the research's main aim **(To explore the acceptability of SMAFT from the perspective of its users, when used alongside physiotherapy (TAU), within a physiotherapy clinical practice of a UHB)** will be answered.

4.2.5.2 Physiotherapy treating clinicians

Three qualified physiotherapy clinicians (clinician 1, clinician 2, and clinician 3) working in musculoskeletal service of physiotherapy within a UHB and experienced in treating individuals with knee pain (more than 5 years' experience) were involved in this study. Clinicians' experiences with movement analysis in clinical practice varied. Two clinicians (clinician 1 and 2) had experience interpreting movement analysis feedback reports for research purposes; however, clinician 1 had more experience using sensor-based movement analysis. Due to the onset of the COVID-19 pandemic and the rapidly changing work environment, clinician 3 declined to participate in the follow-up interview.

4.2.5.3 Individuals with knee pain recruitment and dropout

A flowchart regarding individuals' recruitment and the dropout rate is presented in Figure 10. A total of eighteen individuals diagnosed with knee pain were identified by the treating clinicians. Of these eighteen individuals, five did not meet the study's inclusion criteria. Three individuals were excluded due to a history of ligamentous injuries in the last 12 months, and two had a history of lower extremity surgery in the last 12 months. Thirteen individuals were therefore eligible to take part in this study and were provided with the PIS. Of these thirteen individuals, only seven consented. Of those that did not give consent, three individuals did not respond after signing a permission to contact form, one individual was not interested in being involved, and two individuals were not committed to the study's attendance requirements (attending the movement analysis session an hour earlier than the regular physiotherapy treatment session on the same day).

Thus, seven individuals with knee pain consented. Two individuals completed the proposed full set of three sensor-based movement analysis sessions. However, two individuals did not complete them (individual 6 and 7) due to the impact of the COVID-19 pandemic, one individual was discharged by his/her treating clinician (Individual 4), and two individuals did not attend their appointments (DNA) (individual 2 and 3). Of the seven individuals that participated in this study, five individuals completed the follow up semi-structured interviews. The other two individuals were provided by the PIS for the qualitative interview but did not respond.

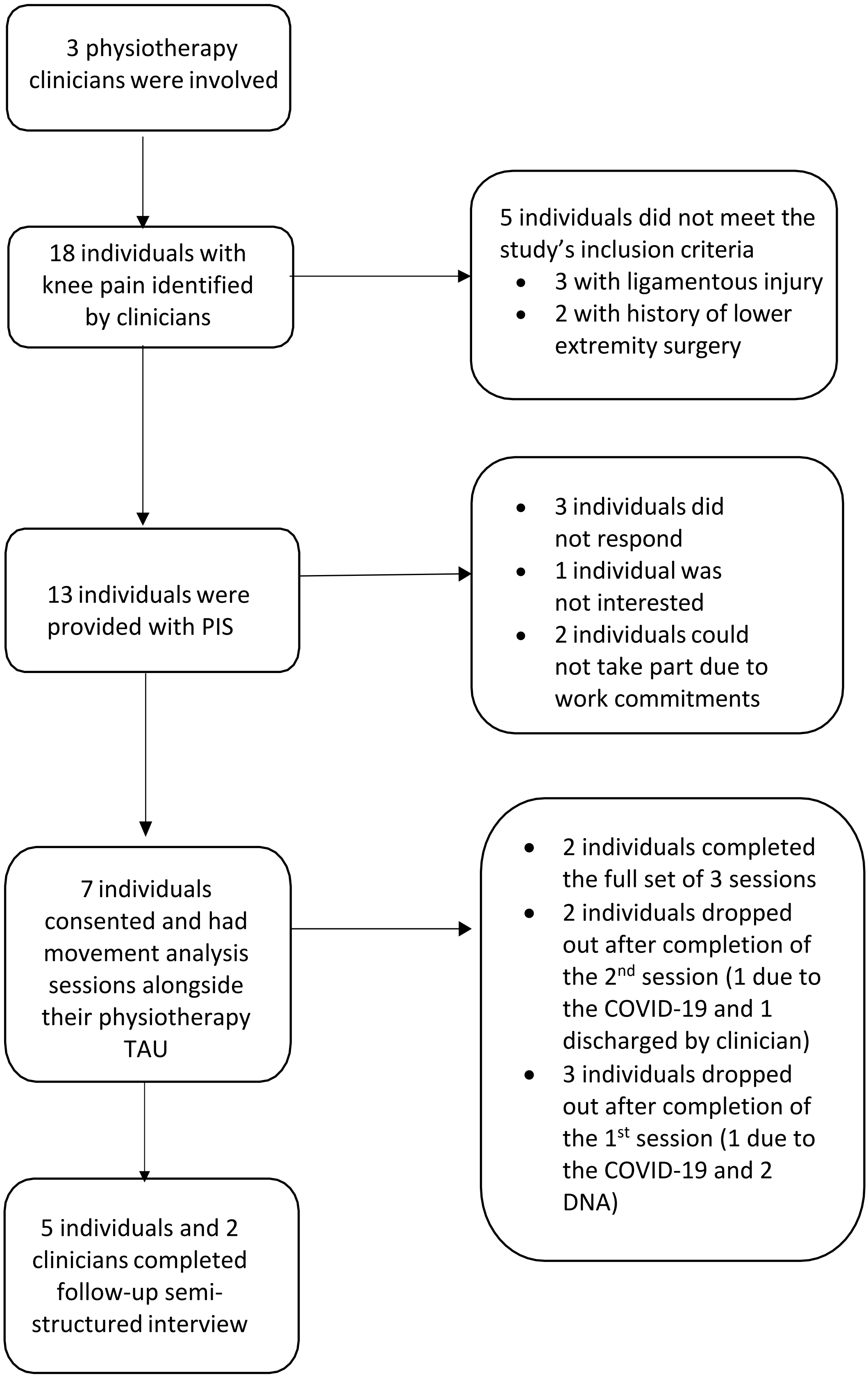


Figure 10: Recruitment and drop out of individuals with knee pain

4.2.5.4 Time spent on conducting movement analysis sessions, data reprocessing, and report development

The time spent conducting the movement analysis sessions, data reprocessing, and developing feedback reports is detailed in Table 18. The first movement analysis session required longer than the subsequent sessions to explain the relevant procedures to individuals, gain their consent, and take body measurements. The time taken to conduct the first movement analysis session was between 39 and 49 minutes (mean = 42.57 min, SD = 3.85). The subsequent movement analysis sessions lasted between 22 and 37 minutes (mean = 28.83 min, SD = 5.74). Following the completion of each movement analysis session, the kinematic data collected was reprocessed to create a feedback report. Across all the movement analysis sessions, the time taken to reprocess the data was between 17 and 36 minutes (mean = 25.08 min, SD = 6.02). Due to the time taken for reprocessing the data during the first eight sessions conducted across the five individuals, it was decided to reprocess the data using a real-time (Automatic) mode instead of a high-definition (HD) mode. Thus, the time taken to reprocess the data during the last five movement analysis sessions for all three individuals was reduced (Table 18). The time taken to develop the movement analysis reports ranged from 5 to 8 minutes (mean = 6.46 min, SD = 0.78).

Table 18: Time taken to conduct movement analysis sessions, data processing and report development

Individual numbers and pseudonym	Session	Time taken (minutes)				
		1st movement analysis session	Subsequent movement analysis sessions	HD data reprocessing	Normal data reprocessing	Report development
1: George	1st	40	-	24	-	7
	2nd	-	37	30	-	7
	3rd	-	31	27	-	6
2: Dora	1st	43	-	28	-	7
3: David	1st	40	-	31	-	7
	2nd	-	25	30	-	6
4: Nell	1st	49	-	27	-	8
5: Nancy	1st	39	-	36	-	7
	2nd	-	22	-	19	5
	3rd	-	25	-	20	6
6: Joe	1st	41	-	-	17	6
	2nd	-	33	-	19	6
7: Clare	1st	46	-	-	18	6
Mean		42.57	28.83	29.13	18.6	6.46
SD		3.69	5.74	6.02	1.14	0.78

Abbreviations: HD = High-definition, SD = Standard Deviation

4.2.5.5 Stage I: Quantitative results

Descriptive statistics regarding individuals with knee pain demographics, incidences of pain during the performance of functional tasks, KOOS and NRS scores will be presented. Furthermore, a description of each individual will be given, including information about the individual's characteristics, nature of their work, and sports and functional activities regularly performed. The findings derived from the interpretations of the feedback report developed (altered movement pattern contents) for each individual across movement analysis sessions will also be presented. Then, a summary of the altered movement patterns identified in all individuals will be presented. Moreover, a summary of physiotherapy treatments given and altered movement patterns observed by the treating clinicians for all individuals will be shown.

4.2.5.5.1 Individuals with knee pain demographics

The individuals with knee pain demographics are shown in Table 19. Seven individuals (4 males and 3 females), aged between 18 and 69 years (mean = 35.57 years, SD = 16.46), with a mix of right and left affected knee pain (5 right and 2 left), participated in the current study and received movement analysis sessions alongside their physiotherapy (TAU). Based on their Body Mass Index (BMI) scores, all individuals were categorised as being between the normal and overweight categories (ranged 21.8 – 29.9, mean = 25.71, SD = 3.25). Five individuals were seen by one clinician (clinician 1), one was seen by (clinician 2) and one was seen by (clinician 3).

Table 19: Individuals with knee pain demographics

Participant numbers and pseudonym	Age (years)	Gender	Height (cm)	Mass (Kg)	BMI score	Dominant leg	Affected knee side	Treating clinician
1: George	32	M	190	108	29.9	Right	Right	Clinician 1
2: Dora	34	F	167	61.8	22.2	Right	Right	Clinician 1
3: David	18	M	176	78.6	25.4	Left	Right	Clinician 1
4: Nell	31	M	196	83.7	21.8	Right	Right	Clinician 1
5: Nancy	24	F	166	82.4	29.9	Right	Right	Clinician 1
6: Joe	41	M	163	66	24.8	Right	Left	Clinician 2
7: Clare	69	F	170	75	26	Right	Left	Clinician 3
Mean (SD)	35.57 (16.46)	M = 4/7 F = 3/7	175.43 (12.78)	79.64 (15.67)	25.71 (3.25)	Right = 6/7 Left = 1/7	Right = 5/7 Left = 2/7	

Abbreviations: BMI = Body Mass Index, cm = centimetres, F = Female, Kg = Kilograms, M = Male

4.2.5.5.2 Incidences of pain

The pain that individuals experienced and reported whilst performing the functional tasks during the movement analysis sessions is presented in Table 20. The functional task of the SLS (affected side) was the task during which individuals most frequently reported pain. For this task, the pain was reported in all sessions by all individuals (reported during 11 sessions out of 13), except for one individual in one session only (84.6%). DLS was the next task in which individuals reported pain, as reported during six sessions out of a total of 13 (46.2%) for six individuals. During the VJ task, the pain was reported in only four sessions (30.8%) by three individuals. Also, the pain was reported in three sessions only during the SD (23.1%) task. During the SLS for non-affected limb and SA tasks, the pain was reported in two sessions only (15.4%). The gait task was the one with the lowest incidence of pain, as it was not reported in any session by any individual (0%).

Table 20: Pain reported by individuals with knee pain during the movement analysis sessions

Participant numbers and pseudonym	Affected leg	Session	Functional tasks						
			DLS	SLS (affected)	SLS (non-effected)	Vertical Jump	Stair Ascent	Stair Descent	Gait
1: George	Right	1st	N	Y	N	N	N	N	N
		2nd	Y	N	N	N	N	N	N
		3rd	N	Y	N	N	N	N	N
2: Dora	Right	1st	N	Y	N	N	N	Y	N
3: David	Right	1st	Y	Y	N	Y	Y	Y	N
		2nd	Y	Y	N	Y	Y	Y	N
4: Nell	Right	1st	N	Y	N	N	N	N	N
5: Nancy	Right	1st	N	Y	N	N	N	N	N
		2nd	N	Y	N	N	N	N	N
		3rd	Y	Y	N	N	N	N	N
6: Joe	Left	1st	N	N	N	N	N	N	N
		2nd	Y	Y	Y	Y	N	N	N
7: Clare	Left	1st	Y	Y	Y	Y	N	N	N
Frequency of the presence of pain across sessions (percentage)			6/13 (46.2%)	11/13 (84.6%)	2/13 (15.4%)	4/13 (30.8%)	2/13 (15.4%)	3/13 (23.1%)	0/13 (0%)

Abbreviations: N= No (pain was not reported), Y= Yes (pain was reported)

4.2.5.5.3 Knee Injury and Osteoarthritis Outcome Score (KOOS)

The scores on the KOOS questionnaire across all the movement analysis sessions for all individuals are presented in Table 21. The scores on the KOOS subscales varied across the individuals' movement analysis sessions. The scores ranged from 0 to 100, with a score of zero indicating extreme knee problems and a score of 100 indicating no knee problems. The highest averaged scores reported related to the subscale of KOOS Daily Living Functions (ADL) (80.62/100), the KOOS Pain (70.08/100), and the KOOS Symptoms (69.77/100). On the other hand, the subscales with the lowest averaged scores were the KOOS Sport/Recreation (Sport/Rec) subscale (65.38/100) and the KOOS Quality of Life (QoL) subscale (54.46/100) (Table 21). By observing scores across the movement analysis session for each individual, there seemed to be a trend towards improving the physical activity function over time for all individuals (who have received more than one session), apart from one individual (Joe). However, a trend towards increasing knee problems in terms of pain, symptoms, sports, and quality of life across the movement analysis sessions for all individuals (who have received more than one session) was noticed, except for one individual (George).

Table 21: Scores for Knee Injury and Osteoarthritis Outcome Score (KOOS) questionnaire subscales across all the movement analysis sessions for all individuals with knee pain

Individual numbers and pseudonym	**Session**	**KOOS Pain**	**KOOS Symptoms**	**KOOS ADL**	**KOOS Sport/Rec**	**KOOS QOL**
1: George	1st	56	61	69	70	44
	2nd	50	56	65	57	56
	3rd	72	54	87	100	69
2: Dora	1st	53	64	76	70	38
3: David	1st	81	64	75	60	50
	2nd	56	71	79	45	31
4: Nell	1st	92	82	99	75	75
5: Nancy	1st	89	82	91	55	63
	2nd	69	75	87	45	50
	3rd	69	75	93	55	44
6: Joe	1st	83	79	85	85	69
	2nd	72	75	74	75	69
7: Clare	1st	69	68	68	60	50
Mean		70.08	69.77	80.62	65.38	54.46
±SD		13.62	9.25	10.56	15.87	13.64

Abbreviations: SD = Standard Deviation

4.2.5.5.4 Numeric Rating Scale (NRS)

The scores for the level of pain reported by the individuals in their movement analysis sessions using the NRS are presented in Table 22. The NRS subscales scores varied among the individuals and across movement analysis sessions. The average score for the level of pain reported at the same moment the individual was completing the scale (Right Now) was (1.69/10). The average level of pain (Usual) score during a period of a week as reported was (3.46/10). The average score for the (Best) level of pain reported was (1/10), while the average score for the (Worst) level of pain during the same period of time was (5.92/10). It was recognised that there seemed to be a trend of reducing pain (Usual) across the movement analysis sessions for all individuals (who received more than one session), except for one individual (Joe).

Table 22: Scores on the Numeric Rating Scale across all movement analysis sessions for all individuals with knee pain

Individual numbers and pseudonym	Session	Pain Right Now	Pain Usual	Pain Best	Pain Worst
1: George	1st	2	4	1	6
	2nd	2	3	0	6
	3rd	1	3	0	5
2: Dora	1st	1	3	0	6
3: David	1st	3	6	3	7
	2nd	4	4	3	8
4: Nell	1st	0	2	2	7
5: Nancy	1st	0	2	0	4
	2nd	1	4	0	6
	3rd	1	2	0	5
6: Joe	1st	1	3	0	5
	2nd	3	5	2	6
7: Clare	1st	3	4	2	6
Mean		1.69	3.46	1	5.92
±SD		1.25	1.20	1.22	1.04

Abbreviations: SD = Standard Deviation

4.2.5.5.5 Description of individuals with knee pain characteristics

Descriptions of the individuals with knee pain, including information about the individuals' characteristics, the nature of their work, sports and functional activities regularly performed, were retrieved from the individuals and clinicians' interviews (if conducted), clinicians' documentary notes, and data collection sheets. This will also include the findings derived from the interpretations of the feedback report developed (altered movement patterns contents) for each movement analysis session, which were achieved using the standardised reporting template by the lead researcher (M.F.). Each individual will now be described in turn.

Individual 1 (George)

George was a 32-year-old male (mass 110 Kg, height 190 cm), with right leg dominant. He presented to the clinic complaining of intermittent bilateral knee pain (Right > left) for more than three years. As the level of pain was higher on the right-side knee compared to the left-side knee, the right knee was considered the affected one and the left knee the non-affected one. He had had an arthroscopy on his right knee in 2016. The intensity of pain increased during functional activities such as walking, running, squatting, ascending stairs, and kneeling. Straps and knee braces were used to ease the pain. In terms of the nature of work and functional activities and exercises, George works in an office and sits in front of a computer for five hours daily. He goes to the gym and runs on a weekly basis. He walks ninety minutes daily to and from work. However, due to his increased pain intensity, he has stopped running and exercising at the gym.

George had three sensor-based movement analysis feedback sessions. During the trials, pain prevented the individual from performing the SLS, SA, and SD activities on the first visit. However, as the pain improved, the full set of trials for all functional tasks was completed at the second and third visits. The interpretations of the movement analysis feedback report using the standardised reporting template to identify movement alterations between limbs and over time for the performance of the functional tasks are summarised in Table 23. A variety of altered movement patterns presented in the affected limb's joints, when compared to the non-affected one, at the sagittal and frontal planes during all functional tasks. Many of these movement alterations were not consistent over time (movement analysis sessions). Across the functional tasks, two movement alterations were commonly identified; i.e., increased adduction ROM in the knee and ankle joints. Less commonly, a reduced knee flexion ROM was also presented.

Table 23: Interpretations of the movement analysis feedback reports for knee pain individual 1 (George) including altered movement patterns identified during the performance of gait, DLS, SLS, VJ, SA, and SD in the sagittal and frontal planes at the hip, knee, and ankle joints over all the movement analysis sessions

Task	Plane	Joints	Altered movement patterns		
			Session one	Session two	Session three
Gait	Sagittal	Hip	NO	NO	NO
		Knee	decreased peak flexion at mid stance	decreased peak flexion at mid stance	decreased peak flexion at mid stance
		Ankle	decreased dorsiflexion ROM during mid and late stance phase/ increased peak plantarflexion at early swing	decreased dorsiflexion ROM during mid and late stance phase	NO
	Frontal	Hip	increased abduction ROM throughout cycle	NO	increased adduction ROM during mid and late stance phase/ decreased peak abduction at early swing
		Knee	NO	increased adduction during late stance phase	NO
		Ankle	increased adduction ROM throughout cycle	increased peak adduction at late stance (toe off)	increased adduction ROM during swing phase
DLS	Sagittal	Hip	NO	NO	NO
		Knee	NO	NO	NO
		Ankle	NO	decreased peak dorsiflexion at maximum depth	NO
	Frontal	Hip	NO	increased abduction ROM from mid descent to mid ascent phase	increased abduction ROM from mid descent to mid ascent phase
		Knee	NO	increased adduction ROM from mid descent to mid ascent phase	increased adduction ROM from mid descent to mid ascent phase
		Ankle	increased adduction ROM throughout cycle	early peak abduction timing at mid descent	NO
SLS	Sagittal	Hip	increased flexion ROM throughout cycle	increased peak flexion at maximum depth	NO
		Knee	decreased peak flexion at maximum depth	NO	NO
		Ankle	decreased dorsiflexion ROM throughout cycle	NO	NO
	Frontal	Hip	increased adduction ROM throughout cycle	increased adduction ROM throughout cycle	increased adduction ROM throughout cycle

		Knee	NO	increased adduction ROM throughout cycle	increased adduction ROM from mid descent to mid ascent phase
		Ankle	increased abduction ROM throughout cycle	Increased peak abduction at maximum depth	NO
VJ	Sagittal	Hip	NO	NO	NO
		Knee	NO	NO	NO
		Ankle	decreased dorsiflexion ROM throughout cycle	NO	decreased plantarflexion ROM during flight phase and heel strike
	Frontal	Hip	increased abduction ROM throughout cycle	increased abduction ROM from maximum depth to toe off	increased abduction ROM from maximum depth to toe off
		Knee	NO	increased adduction ROM from maximum depth to toe off	increased adduction ROM during late cycle
		Ankle	increased adduction ROM throughout cycle	increased adduction ROM during toe off and flight phase	increased adduction ROM during toe off, flight phase and initial contact
SA	Sagittal	Hip	NAN	NO	NO
		Knee	NAN	decreased peak flexion at mid swing	NO
		Ankle	NAN	decreased dorsiflexion ROM during early and mid stance phase	decreased peak plantarflexion at late stance (toe off)
	Frontal	Hip	NAN	late peak adduction timing at early stance	late peak adduction timing at early stance
		Knee	NAN	increased adduction ROM during early stance phase/ decreased peak adduction at mid swing	increased adduction ROM during swing phase
		Ankle	NAN	NO	increased abduction ROM during early and mid stance phase/ increased peak adduction at late stance
SD	Sagittal	Hip	NAN	early peak flexion timing at late stance (toe off)	early peak flexion timing at late stance (toe off)
		Knee	NAN	early peak flexion timing at late stance (toe off)/ decreased peak flexion at late stance (toe off)	early peak flexion timing at late stance (toe off)/ decreased peak flexion at late stance (toe off)
		Ankle	NAN	early peak dorsiflexion timing at mid stance/early peak plantarflexion timing at late swing	early peak dorsiflexion timing at mid stance/early peak plantarflexion timing at late swing
	Frontal	Hip	NAN	early peak adduction timing at late stance	NO
		Knee	NAN	early peak adduction at early swing/ increased adduction ROM during mid stance phase	Early peak adduction at early swing/ increased adduction ROM during mid and late stance phase

		Ankle	NAN	early peak adduction timing at late swing/ increased peak adduction at late swing phase	early peak adduction timing at late swing/ increased peak adduction at late swing phase

Abbreviations: DLS= Double Leg Squat, NAN= task was not performed, NO= no movement alteration, ROM= Range of Motion, SA= Stair Ascent, SD= Stair Descent, SLS= Single Leg Squat

Individual 2 (Dora)

Dora was a 34-year-old female (mass 61.8 Kg, height 167 cm), with right leg dominant. She had complained of anterior knee pain in both knees (Right > left) since her teen age. Since the level of pain was higher in the right-side knee in comparison to the left-side knee, the right knee was considered the affected one and the left knee as the non-affected one. The pain was noticed when dancing and when inactive for a period of time. The pain was relieved by moving and being active. Dora works in event management, which requires her to drive for long hours. She attends a gym three times per week, where she does cardiovascular exercises in addition to a variety of lower limb strengthening exercises (with and without weights).

Dora had only one sensor-based movement analysis feedback session, because she did not attend the rest of her appointments. During the trials for functional activities, sharp pain prevented the individual from performing SLS on the affected limb. In terms of the content of the altered movement patterns identified using the standardised reporting template during the functional tasks, there were a number of altered movement patterns present in the affected limb's joints compared to the non-affected limb's joints at the sagittal and frontal planes (Table 24). Of these, only two movement alterations were frequently presented across the functional tasks, i.e., increased ankle adduction and reduced hip abduction ROM.

Table 24: Interpretations of the movement analysis feedback report for knee pain individual 2 (Dora), including altered movement patterns identified during the performance of gait, DLS, SLS, VJ, SA, and SD in the sagittal and frontal planes at the hip, knee, and ankle joints during the movement analysis session

Task	Plane	Joints	Altered movement patterns
			Session one
Gait	Sagittal	Hip	decreased flexion ROM during early stance and late swing phase
		Knee	decreased peak flexion at mid stance phase
		Ankle	NO
	Frontal	Hip	decreased peak abduction at early swing
		Knee	decreased peak abduction at mid swing
		Ankle	increased adduction ROM throughout cycle
DLS	Sagittal	Hip	NO
		Knee	NO
		Ankle	increased dorsiflexion ROM throughout cycle
	Frontal	Hip	decreased abduction ROM throughout cycle
		Knee	decreased abduction ROM from mid descent to mid ascent phase
		Ankle	increased adduction ROM throughout cycle
SLS	Sagittal	Hip	NAN
		Knee	NAN
		Ankle	NAN
	Frontal	Hip	NAN
		Knee	NAN
		Ankle	NAN
VJ	Sagittal	Hip	NO
		Knee	NO
		Ankle	increased dorsiflexion ROM from initial contact to maximum depth
	Frontal	Hip	decreased abduction ROM throughout cycle
		Knee	decreased abduction ROM at maximum depth
		Ankle	increased adduction ROM during toe off, flight phase, and initial contact / decreased adduction ROM at maximum depth
SA	Sagittal	Hip	decreased flexion ROM during late stance phase

		Knee	decreased flexion ROM during late stance phase
		Ankle	increased dorsiflexion ROM throughout cycle
	Frontal	Hip	NO
		Knee	NO
		Ankle	increased adduction ROM during late stance and swing phase
SD	Sagittal	Hip	NO
		Knee	decreased flexion ROM during early stance
		Ankle	decreased plantarflexion ROM during late stance phase/ increased peak plantarflexion at late swing
	Frontal	Hip	decreased abduction ROM throughout cycle
		Knee	NO
		Ankle	increased adduction ROM during late stance and swing phase

Abbreviations: DLS= Double Leg Squat, NAN= task was not performed, NO= no movement alteration, ROM= Range of Motion, SA= Stair Ascent, SD= Stair Descent, SLS= Single Leg Squat

Individual 3 (David)

David was an 18-year-old male (mass 78.6 Kg, height 176 cm), with right leg dominant. He had complained of intermittent anterior knee pain in both knees (Right > left) for more than two years. As the level of pain was higher in the right-side knee compared to the left-side knee, the right knee was viewed as the affected one and the left knee as the non-affected one. The pain was noticed when sitting for a long period of time, ascending and descending stairs, landing, running and then when walking for long distances. Rest and quadriceps muscle stretches were reported to ease the pain. In terms of his nature of work and sports, David is a college student who stands for most of the day. He plays rugby three times per week and goes to the gym for the remainder of the days. In the gym, he strengthens his lower limbs by performing different functional strengthening exercises, such as squats, lunges, hamstring curls, stationary bike rides, and bench press. The pain was interfering with his sport performed (rugby) and exercises at the gym, especially during heavy squats.

David had two movement analysis feedback sessions using the inertial sensors. The interpretations of the movement analysis feedback report using the standardised reporting template over time during all functional activity tasks are shown in Table 25. In general, varied altered movement patterns presented in the lower limb joints in the sagittal and frontal planes across the functional tasks. It was noticed that an alteration in increased knee adduction was commonly presented across three functional tasks only (DLS, SA, and SD). Although the majority of alterations were consistent over time (movement analysis sessions), some inconsistent movement alterations occurred (Table 25).

Table 25: Interpretations of the movement analysis feedback report for knee pain individual 3 (David), including altered movement patterns identified during the performance of gait, DLS, SLS, VJ, SA, and SD in the sagittal and frontal planes at the hip, knee, and ankle joints in the movement analysis sessions

Task	**Plane**	**Joints**	**Altered movement patterns**	
			Session one	**Session two**
Gait	Sagittal	Hip	NO	NO
		Knee	NO	NO
		Ankle	increased peak dorsiflexion at late stance/decreased peak plantarflexion at early swing	increased peak dorsiflexion at late stance/decreased peak plantarflexion at early swing
	Frontal	Hip	NO	NO
		Knee	NO	NO
		Ankle	decreased adduction ROM during early stance (heel strike) and late swing phase	decreased peak abduction at mid stance/ increased adduction ROM during early swing phase
DLS	Sagittal	Hip	NO	NO
		Knee	NO	NO
		Ankle	NO	NO
	Frontal	Hip	NO	increased peak abduction at maximum depth
		Knee	increased peak adduction at maximum depth	early peak adduction at maximum depth/ increased peak adduction at maximum depth
		Ankle	increased adduction ROM throughout cycle	increased adduction ROM during early descent phase
SLS	Sagittal	Hip	increased flexion ROM during descent phase	decreased peak flexion at maximum depth
		Knee	decreased peak flexion at maximum depth	decreased peak flexion at maximum depth
		Ankle	decreased peak dorsiflexion at maximum depth	decreased peak dorsiflexion at maximum depth
	Frontal	Hip	increased adduction ROM throughout cycle	decreased adduction ROM throughout cycle
		Knee	NO	NO
		Ankle	increased abduction ROM throughout cycle	decreased abduction ROM throughout cycle
VJ	Sagittal	Hip	NO	NO
		Knee	NO	decreased flexion ROM during flight phase
		Ankle	decreased plantarflexion ROM during flight phase	decreased plantarflexion ROM during flight phase
	Frontal	Hip	increased abduction ROM throughout cycle	increased abduction ROM throughout cycle

		Knee	NO	NO
		Ankle	decreased peak abduction at maximum depth	decreased peak abduction at maximum depth/ increased adduction ROM during flight phase
SA	Sagittal	Hip	decreased flexion ROM during late stance phase	increased flexion ROM during early and mid stance phase/ decreased flexion ROM during late stance phase
		Knee	decreased flexion ROM during mid and late stance phase	decreased flexion ROM during late stance phase
		Ankle	decreased dorsiflexion ROM during early and mid stance phase/ late peak plantarflexion at early swing/ decreased peak plantarflexion at late swing	decreased dorsiflexion ROM during early and mid stance phase/ late peak plantarflexion at early swing/ decreased peak plantarflexion at late swing
	Frontal	Hip	increased abduction ROM during stance phase/ increased abduction ROM during swing phase	increased abduction ROM during stance phase/ increased abduction ROM during swing phase
		Knee	increased adduction ROM during early stance phase	increased adduction ROM during early stance phase
		Ankle	NO	decreased abduction ROM during stance phase/ increased adduction ROM during early and mid swing phase
SD	Sagittal	Hip	decreased flexion ROM during early and mid stance phase and late swing phase	late peak flexion at late stance (toe off)
		Knee	decreased flexion ROM during early and mid stance phase	decreased flexion ROM during early and mid stance phase /late peak flexion at late stance (toe off)/ increased peak flexion at late stance (toe off)
		Ankle	increased plantarflexion ROM at late stance (toe off)/ decreased peak plantarflexion at late swing	late peak plantarflexion at late swing/ decreased peak plantarflexion at late swing
	Frontal	Hip	decreased adduction ROM during early and mid stance phase/ increased abduction ROM during late stance and swing phase	decreased adduction ROM during early and mid stance phase/ increased abduction ROM during late stance and swing phase
		Knee	increased adduction ROM during late stance phase	increased adduction ROM during late stance phase
		Ankle	decreased abduction ROM during early and mid stance phase/ increased adduction ROM during late stance and swing phase/ increased peak adduction at late swing	decreased abduction ROM during early and mid stance phase/ increased adduction ROM during late stance and swing phase/ increased peak adduction at late swing

Abbreviations: DLS= Double Leg Squat, NAN= task was not performed, NO= no movement alteration, ROM= Range of Motion, SA= Stair Ascent, SD= Stair Descent, SLS= Single Leg Squat

Individual 4 (Nell)

Nell was a 31-year-old male (mass 83.7 Kg, height 196 cm), right leg dominant. He presented to the clinic complaining of a gradual onset of anterior right-side knee pain for more than a year. The intensity of the pain increased during the performance of different exercises involving flexion and extension knee movements. In addition, discomfort is felt at the knee when he runs. Nell is unemployed and regularly goes to the gym on a weekly basis. However, due to the ongoing knee pain experienced, he has stopped exercising at the gym.

Nell had one movement analysis feedback session provided by inertial sensors only, since he was subsequently discharged by his treating clinician (No further requirement for physiotherapy). The interpretations of the movement analysis feedback report using the standardised reporting template to identify movement alterations between the affected and non-affected limbs and over time for the performance of functional tasks are summarised in Table 26. Overall, altered movement patterns were mostly present at the lower limb joints in the frontal plane rather than the sagittal plane during all functional tasks. Only one movement alteration was consistently identified across functional tasks, which was increased ankle adduction ROM.

Table 26: Interpretations of the movement analysis feedback report for knee pain individual 4 (Nell), including altered movement patterns identified during the performance of gait, DLS, SLS, VJ, SA, and SD in the sagittal and frontal planes at the hip, knee, and ankle joints in the movement analysis sessions

Task	Plane	Joints	Altered movement patterns
			Session one
Gait	Sagittal	Hip	NO
		Knee	NO
		Ankle	decreased peak plantarflexion at early swing
	Frontal	Hip	NO
		Knee	early peak adduction at late swing
		Ankle	increased adduction ROM during early stance and swing phase
DLS	Sagittal	Hip	NO
		Knee	NO
		Ankle	NO
	Frontal	Hip	increased abduction ROM during early and mid descent phase and mid and late ascent phase
		Knee	early peak abduction at maximum depth
		Ankle	increased adduction ROM throughout cycle
SLS	Sagittal	Hip	NO
		Knee	NO
		Ankle	NO
	Frontal	Hip	NO
		Knee	NO
		Ankle	Decreased abduction ROM throughout cycle
VJ	Sagittal	Hip	NO
		Knee	NO
		Ankle	decreased plantarflexion ROM during flight phase
	Frontal	Hip	increased abduction ROM from maximum depth to toe off
		Knee	increased abduction ROM from maximum depth to toe off
		Ankle	increased adduction ROM throughout cycle
SA	Sagittal	Hip	increased flexion ROM during early stance phase/ increased peak flexion at mid swing
		Knee	increased flexion ROM during early stance phase
		Ankle	decreased peak plantarflexion at early swing

	Frontal	Hip	increased abduction ROM during early stance phase
		Knee	NO
		Ankle	increased adduction ROM during early stance (heel strike)/ increased peak adduction at early swing
SD	Sagittal	Hip	NO
		Knee	late peak flexion at late stance (toe off)/ decreased flexion ROM during early and mid stance phase
		Ankle	late peak dorsiflexion at mid stance/ increased plantarflexion ROM during early and mid stance phase
	Frontal	Hip	late peak abduction at late stance (toe off)
		Knee	late peak abduction at late stance (toe off)
		Ankle	late peak abduction at late stance (toe off)/ decrease peak abduction at late stance (toe off)/ increased adduction ROM during mid swing phase

Abbreviations: DLS= Double Leg Squat, NAN= task was not performed, NO= no movement alteration, ROM= Range of Motion, SA= Stair Ascent, SD= Stair Descent, SLS= Single Leg Squat

Individual 5 (Nancy)

Nancy was a 24-year-old female (mass 82.4 Kg, height 166 cm), with right leg dominant. She presented at the clinic complaining of a gradual, intermittent onset of pain on the antero-lateral aspect of her right-side knee that had been occurring for more than a year. The pain was aggravated with exercises that involved running, kneeling, bending, squatting, and going up/down stairs, and relieved by sitting and changing positions. Nancy is a full-time postgraduate student. She is an active lady who enjoys running for 20-30 minutes twice a week. In addition, she attends CrossFit sessions three to four days a week, which involve weightlifting, cardiovascular training, and gymnastics. However, her training and running have been reduced due to ongoing symptoms.

Nancy had three sensor-based movement analysis feedback sessions. During the trials of functional activities, sharp pain prevented her from performing the SLS with the affected limb. In terms of the content of the altered movement patterns identified using the standardised reporting template during the functional tasks, there were a number of varied altered movement patterns identified at the affected limb’s joints compared to the non-affected limb’s joints at sagittal and frontal planes (Table 27). Most of these movement alterations occurred in the frontal plane rather than the sagittal plane, especially during the DLS, Jump and SA. It was observed that no consistent movement alterations across all functional tasks and time (movement analysis sessions) were identified.

Table 27: Interpretations of the movement analysis feedback report for knee pain individual 5 (Nancy), including altered movement patterns identified during the performance of gait, DLS, SLS, VJ, SA, and SD in the sagittal and frontal planes at the hip, knee, and ankle joints in the movement analysis sessions

Task	Plane	Joints	Altered movement patterns		
			Session one	Session two	Session three
Gait	Sagittal	Hip	NO	decreased flexion ROM during early and mid stance phase	NO
		Knee	NO	decreased peak flexion at mid stance	decreased peak flexion at mid stance
		Ankle	NO	decreased dorsiflexion ROM during mid stance phase/ decreased peak plantarflexion at early swing	decreased dorsiflexion ROM during mid stance phase
	Frontal	Hip	increased adduction ROM during mid and late stance phase/ decreased peak abduction at early swing	increased adduction ROM during mid and late stance phase/ decreased peak abduction at early swing	increased adduction ROM during mid and late stance phase/ decreased peak abduction at early swing
		Knee	NO	early peak adduction at mid swing	early peak adduction at mid swing/ increased peak adduction at mid swing
		Ankle	NO	increased adduction ROM during early stance and swing phase	increased adduction ROM throughout cycle
DLS	Sagittal	Hip	NO	NO	NO
		Knee	NO	NO	NO
		Ankle	NO	NO	NO
	Frontal	Hip	NO	increased abduction ROM from mid descent to mid ascent phase	increased abduction ROM from mid descent to mid ascent phase
		Knee	decreased peak abduction at maximum depth	decreased peak abduction at maximum depth	decreased peak abduction at maximum depth
		Ankle	decreased peak adduction at maximum depth	decreased peak adduction at maximum depth	decreased peak adduction at maximum depth
SLS	Sagittal	Hip	increased peak flexion at maximum depth	NAN	late peak flexion timing at maximum depth
		Knee	increased peak flexion at maximum depth	NAN	late peak flexion timing at maximum depth/ increased peak flexion at maximum depth

		Ankle	NO	NAN	late peak dorsiflexion timing at maximum depth/ increased peak dorsiflexion at maximum depth
	Frontal	Hip	NO	NAN	late peak adduction timing at maximum depth/ decreased peak adduction at maximum depth
		Knee	NO	NAN	decreased abduction ROM from mid descent to mid ascent phase
		Ankle	increased abduction ROM during mid ascent and mid descent phase	NAN	increased adduction ROM during early and late cycle
Jump	Sagittal	Hip	NO	NO	NO
		Knee	NO	NO	NO
		Ankle	NO	NO	NO
	Frontal	Hip	increased abduction ROM from maximum depth to toe off and from initial contact to maximum depth	increased abduction ROM from maximum depth to toe off and from initial contact to maximum depth	increased abduction ROM from maximum depth to toe off and from initial contact to maximum depth
		Knee	decreased abduction ROM from maximum depth to toe off and from initial contact to maximum depth	decreased abduction ROM from maximum depth to toe off and from initial contact to maximum depth	decreased abduction ROM from maximum depth to toe off and from initial contact to maximum depth
		Ankle	increased adduction ROM during flight phase	increased adduction ROM during toe off, flight phase, and initial contact	increased adduction ROM during toe off, flight phase, and initial contact
SA	Sagittal	Hip	NO	NO	NO
		Knee	NO	decreased flexion ROM during late stance phase	NO
		Ankle	NO	increased dorsiflexion ROM during early and mid stance phase / decreased peak plantarflexion at early swing	increased dorsiflexion ROM during early and mid stance phase / decreased peak plantarflexion at early swing
	Frontal	Hip	decreased abduction ROM throughout cycle	decreased abduction ROM throughout cycle	NO
		Knee	increased adduction ROM during swing phase	increased adduction ROM during early stance and swing phase	increased adduction ROM during swing phase
		Ankle	Increased abduction ROM during stance phase/ Decreased adduction ROM during mid and late swing phase	decreased adduction ROM during stance phase/ increased peak adduction at early swing	increased peak adduction at early swing

SD	Sagittal	Hip	increased flexion ROM during early and mid stance phase	NO	increased flexion ROM during early stance phase and mid and late swing phase
		Knee	increased flexion ROM during early stance phase	decreased flexion ROM during early and mid stance and late swing phase	decreased flexion ROM during early and mid stance and late swing phase
		Ankle	decreased dorsiflexion ROM during early stance phase/ increased peak plantarflexion at late swing	decreased dorsiflexion ROM during early and mid stance phase/ increased peak plantarflexion at late swing	increased dorsiflexion ROM during early stance phase/ decreased peak plantarflexion at late swing
	Frontal	Hip	NO	decreased abduction ROM during stance phase	NO
		Knee	increased adduction ROM during late stance phase	increased adduction ROM during late stance phase	increased adduction ROM during late stance and early swing phase
		Ankle	increased peak adduction at late swing	increased adduction ROM during late stance and swing phase/ increased peak adduction at late swing	increased adduction ROM throughout cycle

Abbreviations: DLS= Double Leg Squat, NAN= task was not performed, NO= no movement alteration, ROM= Range of Motion, SA= Stair Ascent, SD= Stair Descent, SLS= Single Leg Squat

Individual 6 (Joe)

Joe was a 41-year-old male (mass 66 Kg, height 163 cm), with right leg dominant. He complained of intermittent anterior knee pain in both knees (Right < left) that had lasted for more than two years. Since the level of pain was higher in the left-side knee in comparison to the right-side knee, the left knee was taken as the affected one, and the right knee as the non-affected one, when interpreting the waveform graphs. He reported that pain is aggravated by activities or exercises that involve knee bending, such as lunges, squats, and prolonged sitting. The pain is relieved when he stops exercising, rests, and moves his legs. Joe works an office job that requires him to sit for long hours. He is an active person who plays football two to three times per week and attends the gym three days per week. The pain was not interfering with his sports generally, or when playing football.

Joe received two movement analysis feedback sessions provided by inertial sensors only due to the COVID-19 pandemic. The full set of trials for all the functional activities (DLS, SLS, VJ, Gait, SA, and SD) in the two movement analysis sessions were completed. The interpretations of the movement analysis feedback report using the standardised reporting template over time during all functional tasks are shown in Table 28. In general, a variety of altered movement patterns presented at the lower limb joints in the sagittal and frontal planes across the functional tasks. There was only one movement alteration in the increased hip abduction that was frequently identified across all the functional tasks, except for SLS.

Table 28: Interpretations of the movement analysis feedback reports for knee pain individual 6 (Joe), including altered movement patterns identified during the performance of gait, DLS, SLS, VJ, SA, and SD in the sagittal and frontal planes at the hip, knee, and ankle joints over the two movement analysis sessions

Task	Plane	Joints	Altered movement patterns	
			Session one	Session two
Gait	Sagittal	Hip	NO	NO
		Knee	increased peak flexion at mid swing	increased peak flexion at mid swing
		Ankle	NO	NO
	Frontal	Hip	decreased adduction ROM during stance phase/ increased peak abduction at early swing	increased peak abduction at early swing
		Knee	increased peak abduction at early swing phase/ increased peak adduction at mid swing	NO
		Ankle	decreased adduction ROM during early stance (heel strike)/ decreased adduction ROM during swing phase	decreased adduction ROM during early swing phase
DLS	Sagittal	Hip	increased peak flexion at maximum depth	increased peak flexion at maximum depth
		Knee	NO	NO
		Ankle	decreased dorsiflexion ROM throughout cycle	decreased dorsiflexion ROM throughout cycle
	Frontal	Hip	increased abduction ROM throughout cycle	increased abduction ROM throughout cycle
		Knee	NO	NO
		Ankle	increased adduction ROM throughout cycle	increased adduction ROM throughout cycle
SLS	Sagittal	Hip	NO	NO
		Knee	NO	decreased peak flexion at maximum depth
		Ankle	NO	NO
	Frontal	Hip	decreased adduction ROM throughout cycle	NO
		Knee	NO	early peak adduction at maximum depth
		Ankle	Decrease abduction ROM from mid descending to mid ascending phase	NO
VJ	Sagittal	Hip	NO	NO
		Knee	NO	NO
		Ankle	decreased dorsiflexion ROM during maximum depth (early and late cycle)	decreased dorsiflexion ROM during maximum depth (early and late cycle)/ increased plantarflexion ROM during flight phase

	Frontal	Hip	increased abduction ROM throughout cycle	increased abduction ROM throughout cycle
		Knee	NO	NO
		Ankle	decreased adduction ROM during flight phase	decreased adduction ROM during flight phase
SA	Sagittal	Hip	increased flexion ROM throughout cycle	increased flexion ROM during early and mid stance phase and late swing phase
		Knee	increased flexion ROM during late stance phase	increased flexion ROM during stance phase and late swing phase
		Ankle	NO	Increase dorsiflexion ROM during early and mid stance phase
	Frontal	Hip	increased abduction ROM throughout cycle	Increase abduction ROM during stance phase
		Knee	Increased adduction ROM during early and mid stance phase	Increased adduction ROM during early and mid stance phase
		Ankle	decreased adduction ROM during early and mid swing phase	Decreased abduction ROM during late stance phase
SD	Sagittal	Hip	increased flexion ROM during late stance and swing phase	Decreased flexion ROM during early and mid stance phase
		Knee	increased peak flexion at late stance (toe off)	Decreased flexion ROM during early and mid stance phase/ increased peak flexion at late stance (toe off)
		Ankle	NO	decreased plantarflexion ROM during late stance and swing phase
	Frontal	Hip	increased abduction ROM throughout cycle	increased abduction ROM throughout cycle
		Knee	increased peak adduction at late stance (toe off)	increased peak adduction at late stance (toe off)
		Ankle	Decreased adduction ROM during late stance and swing phase	decreased adduction ROM during late stance and swing phase

Abbreviations: DLS= Double Leg Squat, NAN= task was not performed, NO= no movement alteration, ROM= Range of Motion, SA= Stair Ascent, SD= Stair Descent, SLS= Single Leg Squat

Individual 7 (Clare)

The information providing descriptions of this knee pain individual was only available from the individual's interview, and data collection sheets. Documentary notes (individual's file and clinician's notes) for this individual could not be collected because the treating clinician was diverted from the outpatient clinic due to the COVID-19 pandemic, and was unable to retrieve the notes. Therefore, some data regarding this individual's knee condition and the physiotherapy treatment received was lacking.

Clare was a 69-year-old female (mass 75 Kg, height 170 cm), right leg dominant. She presented to the clinic complaining of having suffered an intermittent onset of pain in her left-side knee for more than a year. The pain was noticed when walking on a downhill slope. Clare is a retired employee who regularly does housework such as cleaning, cooking, and gardening. She is an active lady who walks outdoors and performs a variety of training and exercises at home daily. This training includes using a stationary bike and a rowing machine, in addition to performing strengthening exercises such as straight leg raises, squats, sit to stand, and step ups.

Clare had only one sensor-based movement analysis feedback session as a result of the COVID-19 pandemic. The full set of trials for all functional activities (Gait, DLS, SLS, VJ, SA, and SD) was completed. The interpretations of the movement analysis feedback report using the standardised reporting template to identify movement alterations between affected and non-affected limbs for the functional tasks are summarised in Table 29. Overall, a number of altered movement patterns were present in both planes of movement across all tasks. However, these movement alterations were not consistent across the functional tasks.

Table 29: Interpretations of the movement analysis feedback reports for knee pain individual 7 (Clare), including altered movement patterns identified during the performance of gait, DLS, SLS, VJ, SA, and SD in the sagittal and frontal planes at the hip, knee, and ankle joints over the movement analysis session

Task	Plane	Joints	Altered movement patterns
			Session one
Gait	Sagittal	Hip	NO
		Knee	NO
		Ankle	increased plantarflexion ROM during early stance and late swing phase
	Frontal	Hip	decreased peak adduction at early swing
		Knee	NO
		Ankle	decreased adduction ROM during early stance (heel strike)/ decreased adduction ROM during swing phase
DLS	Sagittal	Hip	NO
		Knee	NO
		Ankle	increased dorsiflexion ROM throughout cycle
	Frontal	Hip	late peak adduction at maximum depth
		Knee	NO
		Ankle	NO
SLS	Sagittal	Hip	decreased peak flexion at maximum depth
		Knee	decreased peak flexion at maximum depth
		Ankle	NO
	Frontal	Hip	decreased peak adduction at maximum depth
		Knee	increased adduction ROM throughout cycle
		Ankle	NO
VJ	Sagittal	Hip	NO
		Knee	increased flexion ROM from maximum depth to toe off
		Ankle	decreased peak dorsiflexion at maximum depth/ increased plantarflexion ROM during flight phase
	Frontal	Hip	NO
		Knee	NO
		Ankle	decreased adduction ROM during flight phase
SA	Sagittal	Hip	NO

		Knee	NO
		Ankle	increased peak plantarflexion at early swing
	Frontal	Hip	increased adduction ROM throughout cycle
		Knee	increased abduction ROM during early stance phase and swing phase
		Ankle	decreased peak adduction at early swing/ increased abduction ROM during mid stance phase
SD	Sagittal	Hip	early peak flexion timing at late stance (toe off)
		Knee	early peak flexion timing at late stance (toe off)
		Ankle	early peak plantarflexion at late swing/ increased peak plantarflexion at late swing
	Frontal	Hip	increased adduction ROM during early and mid stance phase
		Knee	NO
		Ankle	decreased peak adduction at late swing

Abbreviations: DLS= Double Leg Squat, NAN= task was not performed, NO= no movement alteration, ROM= Range of Motion, SA= Stair Ascent, SD= Stair Descent, SLS= Single Leg Squat

4.2.5.5.6 Summary of the altered movement patterns identified in all individuals with knee pain

Quantitative results from the interpretations of movement analysis feedback reports for all individuals with knee pain will assist here in addressing the research objective: **To describe the content of kinematic altered movement patterns identified in individuals with knee pain who used SMAFT**. A plethora of altered movement patterns were identified across the individuals with knee pain (7 individuals) and movement analysis sessions at all lower limb joints on the affected limb side compared to the joints on the non-affected side. The individuals presented with varied altered movement patterns at the lower limb joints in the sagittal and frontal planes during different functional tasks. A summary of these movement alterations and the frequency of time each alteration was identified across all sessions and individuals is presented in Tables 30 - 35. However, few consistent altered movement patterns were identified, as described below by task.

For the gait task, the most common movement alterations identified in the **sagittal** plane across the movement analysis sessions and individuals with knee pain were reduced maximum knee flexion at mid stance, ankle dorsiflexion ROM during mid and late stance, and maximum ankle plantarflexion at early swing. In the **frontal** plane, many movement alterations were presented (Table 30). However, reduced maximum abduction during the early swing at the hip joint and increased adduction ROM during the whole cycle at the ankle were commonly performed by individuals across sessions.

Squatting tasks (DLS and SLS) were the tasks presenting least often with common movement alterations across all individuals with knee pain and sessions (Tables 31 and 32). With regard to DLS, only one alteration in the **frontal** plane was presented commonly by individuals. This altered movement pattern was the increased ankle adduction ROM throughout the squat cycle (Table 31). Similarly, the altered movement patterns performed by all individuals across sessions were varied during SLS performance. Four individuals out of seven squatted on the affected limb with reduced peak knee flexion, especially at the time point of the maximum squat depth (Table 32).

Regarding the VJ task, the majority of the movement alterations identified in the **sagittal** plane occurred in the ankle joint (6 alterations) (Table 33). However, only the alteration of reduced ankle plantarflexion ROM during the flight phase was presented commonly. In the frontal plane, a plethora of varied altered movement patterns was identified in all lower limb joints (Table 33) (16 alterations). The most common ones performed by individuals were increased abduction ROM at the hip joint and increased adduction ROM at the ankle.

During the SA task in the **sagittal** plane, individuals with knee pain commonly reduced their knee flexion ROM as they lifted their affected limb from the steps (late stance) across sessions (Table 34). During early and mid stance, the movement alteration of increased hip flexion ROM was identified in 3 individuals out of seven. In the **frontal** plane, the alterations of increased knee and ankle adduction ROM during the stance phase were commonly identified across all individuals and sessions (Table 34).

As for the SD task, only two alterations in the **sagittal** plane were frequently identified across all individuals and sessions (Table 35). The most common alteration was the reduced knee flexion ROM during the early and mid stance phases. Less commonly, three individuals out of seven increased their maximum plantarflexion ROM at the late swing. In the **frontal** plane, increased knee and ankle adduction ROM during the late stance phase were found to be the most common alterations across individuals and sessions. In addition, four individuals presented with increased ankle adduction ROM during the swing phase (Table 35).

In general, across all the functional tasks, there seemed to be a variety of altered movement patterns adopted by all individuals during all sessions, with very little consistency noted. The most frequent ones used were reduced **sagittal** knee flexion and ankle dorsiflexion ROM, particularly when individuals were loading their affected limb. These were accompanied by **frontal** alterations of increased knee and ankle adduction ROM.

Table 30: Summary of all the altered movement patterns identified in the sagittal and frontal planes at the hip, knee, and ankle joints during **Gait** task and their frequencies across all individuals with knee pain and movement analysis sessions

Plane	Joint	Altered movement patterns	Frequency across sessions	Frequency across individuals
Sagittal	Hip	decreased flexion ROM during early stance	2	2
		decreased flexion ROM during late swing phase	1	1
	Knee	decreased peak knee flexion at mid stance	6	3
		increased peak flexion at mid swing	2	1
	Ankle	decreased dorsiflexion ROM during mid and late stance phase	4	2
		increased peak dorsiflexion at late stance	2	1
		decreased peak plantarflexion at early swing	4	3
		increased plantarflexion ROM during early stance	1	1
		increased peak plantarflexion at early swing	1	1
		increased plantarflexion ROM during late swing phase	1	1
Frontal	Hip	increased abduction ROM throughout cycle	1	1
		increased peak abduction at early swing	2	1
		increased adduction ROM during mid and late stance phase	4	2
		decreased peak abduction at early swing	5	3

		decreased peak adduction at early swing decreased adduction ROM during stance phase	1 1	1 1
	Knee	increased adduction during late stance phase increased peak adduction at mid swing early peak adduction at late swing decreased peak abduction at mid swing increased peak abduction at early swing phase	1 2 3 1 1	1 2 2 1 1
	Ankle	increased adduction ROM throughout cycle increased peak adduction at late stance (toe off) increased adduction ROM during early stance increased adduction ROM during swing phase decreased adduction ROM during early stance (heel strike) decreased adduction ROM during swing phase decreased peak abduction at mid stance	3 1 3 4 3 4 1	3 1 3 4 3 3 1

Abbreviations: ROM= Range of motion

Table 31: Summary of all altered movement patterns identified in the sagittal and frontal planes at the hip, knee, and ankle joints during **DLS** task and their frequencies across all individuals with knee pain and movement analysis sessions

Plane	Joint	Altered movement patterns	Frequency across sessions	Frequency across individuals
Sagittal	Hip	increased peak flexion at maximum depth	2	1
	Knee	NO		
	Ankle	increased dorsiflexion ROM throughout cycle	2	2
		decreased dorsiflexion ROM throughout cycle	2	1
		decreased peak dorsiflexion at maximum depth	1	1
Frontal	Hip	increased abduction ROM from mid descent to mid ascent phase	4	2
		increased peak abduction at maximum depth	1	1
		increased abduction ROM throughout cycle	2	1
		increased abduction ROM during early and mid descent phase and mid and late ascent phase	1	1
		decreased abduction ROM throughout cycle	1	1
		late peak adduction at maximum depth	1	1

	Knee	increased adduction ROM from mid descent to mid ascent phase increased peak adduction at maximum depth decreased peak abduction at maximum depth decreased abduction ROM from mid descent to mid ascent phase early peak abduction at maximum depth	2 2 3 1 2	1 1 1 1 2
	Ankle	increased adduction ROM throughout cycle increased adduction ROM during early descent phase decreased peak adduction at maximum depth early peak abduction timing at mid descent	6 1 3 1	5 1 1 1

Abbreviations: ROM= Range of motion

Table 32: Summary of all altered movement patterns identified in the sagittal and frontal planes at the hip, knee, and ankle joints during **SLS** task and their frequencies across all individuals with knee pain and movement analysis sessions

Plane	Joint	Altered movement patterns	Frequency across sessions	Frequency across individuals
Sagittal	Hip	decreased peak flexion at maximum depth	2	2
		increased peak flexion at maximum depth	2	2
		increased flexion ROM throughout cycle	1	1
		increased flexion ROM during descent phase	1	1
		late peak flexion timing at maximum depth	1	1
	Knee	decreased peak flexion at maximum depth	5	4
		increased peak flexion at maximum depth	2	1
		late peak flexion timing at maximum depth	1	1
	Ankle	decreased peak dorsiflexion at maximum depth	2	1
		decreased dorsiflexion ROM throughout cycle	1	1
		late peak dorsiflexion timing at maximum depth	1	1
		increased peak dorsiflexion at maximum depth	1	1

Frontal	Hip	increased adduction ROM throughout cycle	4	2
		decreased adduction ROM throughout cycle	2	2
		decreased peak adduction at maximum depth	2	2
		late peak adduction timing at maximum depth	1	1
	Knee	increased adduction ROM throughout cycle	2	2
		increased adduction ROM from mid descent to mid ascent phase	1	1
		decreased abduction ROM from mid descent to mid ascent phase	1	1
		early peak adduction at maximum depth	1	1
	Ankle	increased abduction ROM throughout cycle	2	2
		increased peak abduction at maximum depth	1	1
		increased abduction ROM during mid ascent and mid descent phase	1	1
		decreased abduction ROM throughout cycle	2	2
		decrease abduction ROM from mid descending to mid ascending phase	1	1
		increased adduction ROM during early and late cycle	1	1

Abbreviations: ROM= Range of motion

Table 33: Summary of all altered movement patterns identified in the sagittal and frontal planes at the hip, knee, and ankle joints during **VJ** task and their frequencies across all individuals with knee pain and movement analysis sessions

Plane	Joint	Altered movement patterns	Frequency across sessions	Frequency across individuals
Sagittal	Hip	NO		
	Knee	decreased flexion ROM during flight phase	1	1
		increased flexion ROM from maximum depth to toe off	1	1
	Ankle	decreased dorsiflexion ROM during maximum depth (early and late cycle)	2	1
		decreased peak dorsiflexion at maximum depth	1	1
		decreased dorsiflexion ROM throughout cycle	1	1
		increased dorsiflexion ROM from initial contact to maximum depth	1	1
		decreased plantarflexion ROM during flight phase	4	3
		increased plantarflexion ROM during flight phase	2	2
Frontal	Hip	increased abduction ROM from maximum depth to toe off	6	3
		increased abduction ROM throughout cycle	5	3
		increased abduction ROM from initial contact to maximum depth	3	1
		decreased abduction ROM throughout cycle	1	1

	Knee	decreased abduction ROM from maximum depth to toe off decreased abduction ROM from initial contact to maximum depth decreased abduction ROM at maximum depth	3 3 1	1 1 1
		increased abduction ROM from maximum depth to toe off	1	1
		increased adduction ROM from maximum depth to toe off	1	1
		increased adduction ROM during late cycle	1	1
	Ankle	increased adduction ROM during toe off, flight phase and initial contact increased adduction ROM throughout cycle increased adduction ROM during flight phase	5 3 1	3 3 1
		decreased adduction ROM during flight phase decreased adduction ROM at maximum depth	3 1	2 1
		decreased peak abduction at maximum depth	2	1

Abbreviations: ROM= Range of motion

Table 34: Summary of all altered movement patterns identified in the sagittal and frontal planes at the hip, knee, and ankle joints during **SA** task and their frequencies across all individuals with knee pain and movement analysis sessions

Plane	Joint	Altered movement patterns	Frequency across sessions	Frequency across individuals
Sagittal	Hip	decreased flexion ROM during late stance phase	3	2
		increased flexion ROM during early and mid stance phase	3	3
		increased flexion ROM throughout cycle	1	1
		increased peak flexion at mid swing	1	1
		increased flexion ROM during late swing phase	1	1
	Knee	decreased flexion ROM during late stance phase	4	3
		decreased peak flexion at mid swing	1	1
		increased flexion ROM during stance phase and late swing phase	1	1
		increased flexion ROM during early stance phase	1	1
		increased flexion ROM during late stance phase	1	1
		increased flexion ROM during late swing phase	1	1
	Ankle	increased dorsiflexion ROM during early and mid stance phase	3	2
		increased dorsiflexion ROM throughout cycle	1	1
		decreased dorsiflexion ROM during early and mid stance phase	3	2
		decreased peak plantarflexion at late swing	2	1
		decreased peak plantarflexion at early swing	3	2
		decreased peak plantarflexion at late stance (toe off)	1	1
		increased peak plantarflexion at early swing	1	1
		late peak plantarflexion at early swing	2	1

Frontal	Hip	increased abduction ROM during stance phase	3	2
		increased abduction ROM during early stance phase	1	1
		increased abduction ROM throughout cycle	1	1
		increased abduction ROM during swing phase	1	1
		decreased abduction ROM throughout cycle	2	1
		increased adduction ROM throughout cycle	2	2
		late peak adduction timing at early stance	2	1
	Knee	increased adduction ROM during swing phase	4	2
		increased adduction ROM during early stance phase	6	4
		decreased peak adduction at mid swing	1	1
		increased abduction ROM during early stance phase and swing phase	1	1
	Ankle	increased abduction ROM during early and mid stance phase	1	1
		increased adduction ROM during stance phase	4	4
		increased peak adduction at early swing	3	2
		increased peak adduction during swing phase	1	1
		decreased adduction ROM during stance phase	1	1
		decreased adduction ROM during mid and late swing phase	3	3
		Decreased abduction ROM during late stance phase	1	1

Abbreviations: ROM= Range of motion

Table 35: Summary of all altered movement patterns identified in the sagittal and frontal planes at the hip, knee, and ankle joints during **SD** task and their frequencies across all individuals with knee pain and movement analysis sessions

Plane	Joint	Altered movement patterns	Frequency across sessions	Frequency across individuals
Sagittal	Hip	Decreased flexion ROM during early and mid stance phase	2	2
		decreased flexion ROM during late swing phase	1	1
		increased flexion ROM during early and mid stance phase	2	1
		increased flexion ROM during late stance and swing phase	1	1
		increased flexion ROM during swing phase	2	2
		early peak flexion timing at late stance (toe off)	3	2
		late peak flexion at late stance (toe off)	1	1
	Knee	decreased peak flexion at late stance (toe off)	2	1
		decreased flexion ROM during early and mid stance phase	7	5
		decreased flexion ROM during late swing phase	2	1
		increased peak flexion at late stance (toe off)	3	2
		increased flexion ROM during early stance phase	1	1
		early peak flexion timing at late stance (toe off)	3	2
		late peak flexion at late stance (toe off)	2	2

	Ankle	decreased plantarflexion ROM during late stance phase	2	2
		decreased peak plantarflexion at late swing	3	2
		decreased plantarflexion ROM during swing phase	1	1
		decreased dorsiflexion ROM during early and mid stance phase	2	1
		increased peak plantarflexion at late swing	4	3
		increased plantarflexion ROM during early and mid stance phase	1	1
		increased plantarflexion ROM at late stance (toe off)	1	1
		increased dorsiflexion ROM during early stance phase	1	1
		early peak dorsiflexion timing at mid stance	3	2
		early peak plantarflexion timing at late swing	3	2
		late peak plantarflexion at late swing	1	1
Frontal	Hip	decreased adduction ROM during early and mid stance phase	2	1
		increased adduction ROM during early and mid stance phase	1	1
		decreased abduction ROM throughout cycle	1	1
		decreased abduction ROM during stance phase	1	1
		increased abduction ROM during late stance	1	1
		increased abduction ROM throughout cycle	2	1
		early peak adduction timing at late stance	1	1
		late peak abduction at late stance (toe off)	1	1

	Knee	increased adduction ROM during mid stance phase increased adduction ROM during late stance phase increased peak adduction at late stance (toe off) increased adduction ROM during early swing phase early peak adduction at early swing late peak abduction at late stance (toe off)	2 6 2 1 2 1	1 3 1 1 1 1
	Ankle	increased peak adduction at late swing phase increased adduction ROM during late stance increased adduction ROM during swing phase increased adduction ROM throughout cycle Decreased adduction ROM during late stance Decreased adduction ROM during swing phase decreased peak adduction at late swing decrease peak abduction at late stance (toe off) decreased abduction ROM during early and mid stance phase early peak adduction timing at late swing late peak abduction at late stance (toe off)	5 4 5 1 2 2 1 1 2 2 1	3 3 4 1 1 1 1 1 1 1 1

Abbreviations: ROM= Range of motion

4.2.5.5.7 Summary of physiotherapy treatments given and altered movement patterns observed by the treating clinicians to all individuals with knee pain

Information about the physiotherapy treatments given and the altered movement patterns observed or treated by the clinicians was extracted from the documentary clinicians' notes. This information was used alongside the findings from the interviews and movement analysis interpretations to address the main aim: **To explore the acceptability of SMAFT from the perspective of its users, when used alongside physiotherapy (TAU), within the physiotherapy clinical practice of a UHB**.

A summary of the physiotherapy treatments given, including the exercises prescribed, advice, education, or other treatment techniques used for each individual and each physiotherapy treatment session, is presented in Appendix X. In general, the findings exhibited that physiotherapy treatments given by the treating clinicians were inconsistent across all individuals with knee pain, in terms of their targeted joints and muscles and their types and applications. Consequently, this can give insight that clinicians' treatment plans were tailored for each individual.

The focus of the physiotherapy treatments was on prescribing exercises and providing advice and education. The purpose of the prescribed exercises covered improvements to strength, flexibility, balance, and functionality variously (Table 36). The most common exercises prescribed were strengthening exercises, which were commonly targeted at the gluteal, quadriceps, and calf muscles. These strengthening exercises were prescribed in varied applications and positions with varying amounts of load and repetitions.

Other common exercises prescribed were functional exercises. Squats, sit to stand, lunges, and running were examples of the functional exercises documented by the clinicians. It was observed that the prescription of functional exercises was integrated to some extent with education about how to enhance their performance. However, there was little information documented involving providing feedback and educating individuals so as to improve their performance of functional activities. Stretching exercises were also prescribed to some of the individuals by their treating clinicians to target different lower limb muscles, such as hip flexors, adductors, and medial rotators, knee extensors, and ankle plantar flexors. Less commonly, balance and stabilisation exercises were prescribed for some of the individuals. Other treatment techniques, including manual therapy and myofascial release, were documented only with one individual. In addition, one individual was advised to be seen by a podiatrist to have a shoe insole fitted (Appendix X).

On the other hand, based on observations provided in the clinicians' notes, there was relatively little documented information about the altered movement patterns the clinicians observed and treated. These also appeared to be limited in terms of detailed information about what the movement alteration type was, when it had occurred along the movement cycle, and what activity it was observed during. Moreover, the approach used to report the altered movement patterns across the individuals with knee pain and movement analysis sessions was inconsistent (Appendix X).

In conclusion, physiotherapy clinicians used varied treatment strategies across individuals and tailored their treatment plans. Strengthening exercises targeting the buttocks, thighs, and leg muscles were the focus of the treating clinicians when managing the individuals with knee pain. Rich information about feedback and education to improve the individuals' performance in functional activities was lacking. In addition, limited and inconsistent information about the types and timing of the altered movement patterns observed and treated was present in their notes.

Table 36: Summary of the various exercises documented and used by the treating clinicians with all individuals with knee pain including the muscles targeted, applications and positions, and doses

Type of exercise	Targeted muscles	Applications and positions	Doses
Strengthening	Gluteal muscles	- Side lying with hip abduction with and without Thera band - Pelvic drop exercise - Side plunk exercise - Hip thrust exercise - Frog pumps exercise	NA 3 x 15 reps NA NA NA
	Quadriceps muscles	- Static - Dynamic knee extension (OKC)	NA 3 x 12 reps (with 15 Kgs)
	Hamstrings muscles	Lying position with hip and knee in 90	NA
	Calf muscles	Eccentric heel drop	3 x 15 reps twice a day
	Iliopsoas and Quadriceps muscles	Straight leg raise exercise	NA
	Gluteal, Quadriceps, and Hamstrings muscles	Leg press exercise	With increased reps
Stretching	Calf muscles	NA	3 x 12 reps (gastrocnemius) 3 x 6 reps (soleus)
	Hip flexors muscles	NA	3 x 20 secs
	Quadriceps muscles	NA	3 x 30 secs

	Hip medial rotators muscles	Hip and knee in 90	NA
	Hip adductor muscles	NA	NA
Functional	NA	Squat with education on: - Increase hip flexion - Keep heels flat - Increase forward trunk lean - Increase knee flexion - Improving symmetry with timing - Improving symmetry between legs	1 x 15 reps NA NA NA NA NA
	NA	Lunge	NA
	NA	Sit to stand on single leg	NA
	NA	Running with education on: - Wider steps	NA
Balance and proprioceptive	Trunk and lumber muscles	Neutral spine exercises	NA
	NA	Balance exercise on single leg	NA

Abbreviations: Kgs= Kilograms, NA= Not reported, OKC= Open kinetic chain, Reps= Reptations, Secs= Seconds

4.2.5.6 Stage I: Qualitative results

Qualitative findings from the participants' interviews (individuals with knee pain and treating clinicians) addressed the following objective in this case study: **To investigate users (individuals with knee pain and their treating clinicians) acceptability for using SMAFT alongside physiotherapy (TAU) within physiotherapy clinical practice.**

Thematic analysis of participants' interviews for five individuals with knee pain and two treating clinicians was conducted. The findings revealed three key themes related to the research objective of SMAFT's acceptability within clinical practice. Theme one is 'Practicality of the movement analysis sessions' with two associated sub-themes. Theme two is 'Usability of movement analysis feedback report' with two associated sub-themes. Theme three is 'Perceived benefits of the sensor-based movement analysis feedback toolkit' with four associated sub-themes. Each theme and its associated sub-themes will be presented in order (Figure 11). The study participants (individuals with knee pain and treating clinicians) are each identified by a pseudonym and an identification number.

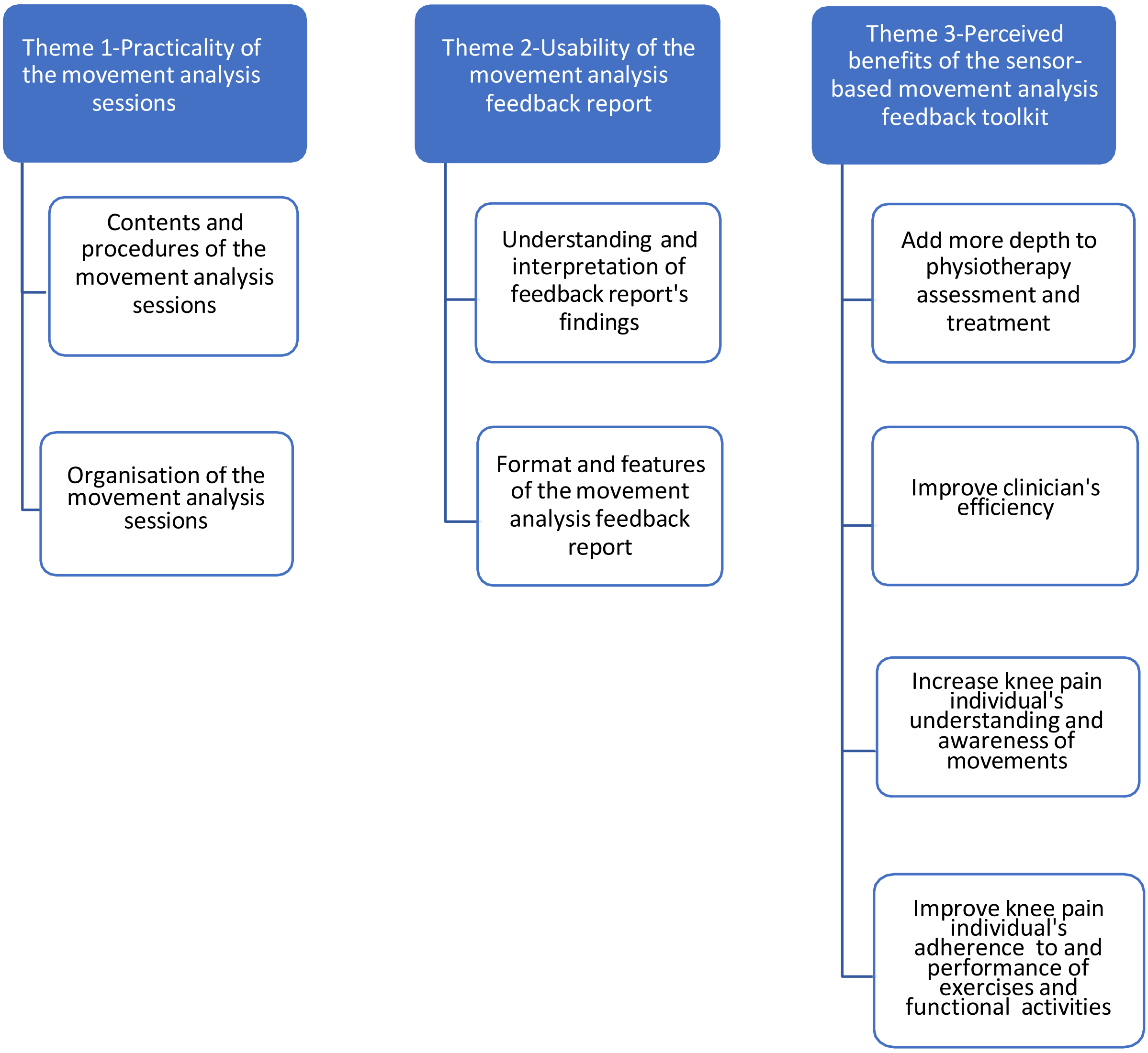


Figure 11: Final themes and sub-themes

4.2.5.6.1 Theme 1- Practicality of the movement analysis sessions

This theme demonstrates the individuals and their clinicians' perspectives on how practical it would be to implement sensor-based movement analysis sessions in the real-world (clinical practice) alongside physiotherapy (TAU) for individuals with knee pain. The working definition of practicality in this theme is the extent to which sensor-based movement analysis sessions could be integrated into physiotherapy (TAU) within the clinical practice as planned. Findings relating to the individuals and clinicians' actual experiences of the movement analysis sessions are presented under the current theme. The two underlying sub-themes: 'Content and procedures of the movement analysis sessions', and 'Organisation of the movement analysis sessions' are detailed below.

4.2.5.6.1.1 Sub-theme 1- Content and procedures of the movement analysis sessions

This sub-theme illustrates the practicality of the content and procedures in the movement analysis session as experienced by the individuals with knee pain and supervised by the treating clinicians.

Both the treating clinicians and two out of the 5 individuals with knee pain identified some challenges with using sensor-based movement analysis during the movement analysis sessions. One individual and one clinician expressed a negative view of the size of the zip-fastened T-shirt to be worn during the session to place some IMU sensors. The following quotation was taken from interviews:

> "I'm um, not the biggest, nor the smallest of people. That jacket was tight. It was like being a rotisserie chicken, it was tight, I couldn't breathe." **(George, P001)**
>
> "I guess the jacket that we used on the patients were … found to be quite tight and stiff." **(Clinician, PH002)**

Another challenge related to the stigma of wearing the IMU sensors and performing the functional tasks in front of people. This was mentioned by two individuals in the following extracts:

> "I mean obviously like in hospital and stuff people were kind of looking and watching, but that doesn't really bother me much." **(Nancy, P005)**
>
> **"**Only the first time, the rest I think I wasn't bothered, I knew I was going to go out there. But yeah, the first time, it was a little bit like oh God, don't look at me." **(George, P001)**

In addition, a clinician mentioned that following strict instructions and keeping still in the standing position required for a successful calibration process could be considered a challenge. This may impact the time taken to achieve an excellent quality calibration, and consequently affect the time available for the clinician to analyse and interpret the report's findings. The clinician (PH002) portrayed this issue in the following extract:

> "You know, calibration I think once or twice, um, was possibly a challenge, just by people keeping static. Um, so yeah, some … that had a little bit of time element, but I guess in the future those things may be ironed out, to do it quicker." **(Clinician, PH002)**

The selection of functional tasks included in the movement analysis session was discussed by all individuals and clinicians. Three individuals and both clinicians portrayed the appropriateness of the functional tasks selected in terms of their coherence:

> "We did jumps and we also did, well we did single leg squats. But yes I think it pretty much covered everything we needed for mine, yes; nothing I can think of off the top of my head." **(Joe, P006)**
>
> "I think they're appropriate for the patients that we saw. I think most of them had um, patellofemoral er, symptoms of generalised knee pain." **(Clinician, PH002)**

However, both clinicians expressed concerns about the level of challenges presented by the tasks included for all individuals with knee pain. The following extract was taken from interviews with the clinicians:

> "It was quite graded, you know, so you know, gait was … was fine, double leg squats, single leg squats, I think for some people were quite challenging." **(Clinician, PH002)**

This was supported by two individuals and indicated a challenge in terms of the existence of pain during the performance of some functional tasks, which may prevent the individuals from performing all or some of the task's trials:

> "In my second session I think it was I couldn't do the single leg squat because my knee was really sore, it was quite painful that day. So that one obviously was a bit painful but that was the only time I couldn't do it." **(Nancy, P005)**

Therefore, some suggestions were proposed by some individuals and clinicians to address this. It was suggested by both clinicians that the tasks be based on the individual's age, condition, and goals. In addition, they offered some examples of tasks with high and low levels of challenge to consider. This was portrayed in the following quotations taken from interviews with clinicians:

> "I guess if you were looking at an older patient you might want to do like sit to stand or something like that. So that might depend on the age range of the people that you are seeing. Because like a 60 year-old, some are playing tennis, and might be jumping, whereas other 60 year-olds might be quite sedentary and just sit and stand or something like that." **(Clinician, PH001)**

> "I also would have liked beyond that, as a next step, to look at those who were performing at a higher level, to look at um, you know, horizontal jump, horizontal hops, single leg hop, double leg hops, I think that would tend to examine sports stuff … some of these people, once they're at a good level, um, can we then test them at that appropriate level." **(Clinician, PH002)**

This was in agreement with the suggestion made by two of the individuals to include functional tasks based on an individual's sport and interests. The following extract was taken from the interviews with individuals:

> "I would say maybe running because for me that was kind of what started the injury, so I think that would have been interesting to see." **(Nancy, P005)**

Furthermore, one individual suggested that the decision concerning the selection of the tasks included needs to be based on the treating clinician:

> "Maybe potentially it might be something maybe if you were to consult with the physio … beforehand, you know they might want something else added but that's the only thing I can think of." **(Joe, P006)**

4.2.5.6.1.2 Sub-theme 2- Organisation of the movement analysis sessions

This sub-theme presents individuals and clinicians' opinions regarding whether the organisation of the movement analysis sessions in terms of their timing, frequency and spread over the treatment course, and flow with treatment sessions proceeded as planned.

<u>Timing of the movement analysis sessions</u>

The majority of the individuals with knee pain and both clinicians were happy about the amount of time spent on the movement analysis sessions. Examples of this were illustrated in the following quotations:

> "Fine really. I just thought ... I don't think it took like too much time and I think it was helpful so it didn't waste any time." **(David, P003)**

> "In terms of timing, but it's only 40 minutes, I think it's adequate time." **(Clinician, PH002)**

Some challenges that may impact the timing of the movement analysis session and the following treatment session were pointed out by a few individuals and clinicians. One clinician (PH002) indicated a challenge in the individual's compliance with the time of the movement analysis session, which may have an impact on the overall timing for the movement analysis and treatment sessions:

> "I guess, um, it is a sort of challenge, getting the patient to come in at certain times. And I think I've got a couple of patients who come in late, some have organised times, they turned up late, and therefore this leaves less time to do the data collection and I guess the same with all patients, some patients come late, some come early, so you've got the same kind of issues." **(PH002)**

Another clinician (PH001) mentioned that the individuals who have to come in for the earliest available appointment in the morning may lose the opportunity to receive a movement analysis session because the department is closed. The following extracts were taken from interviews with clinicians:

> "I mean obviously it takes more time, there's only certain patients who can do that time, not everyone has got the time to be able to come and spend an extra half an hour per appointment to be able to use the analysis." **(Clinician, PH001)**

Another challenge that might impact the time taken for movement analysis sessions was discussed by two individuals, and one clinician considered the individual's familiarisation with the movement analysis session procedures. There was an agreement between the two individuals and the clinician, explaining that the individuals became more familiar with the tasks and data collection procedures over time (first movement analysis session compared to the subsequent sessions). The following extracts were taken from the individuals' and clinicians' interviews:

> "I think we were slightly quicker the second time once we knew, I had more idea what was going on and that sort of thing, like what they expect." **(Joe, P006)**

> "It's just having familiarity with the equipment I guess. And once the patient is familiar with the straps going on, the subsequent sessions then were much quicker, much easier, the patient was familiar with the type of movement and the activities and exercises." **(Clinician, PH002)**

To eliminate these challenges, one clinician suggested sending the individuals information about the procedures for the movement analysis session (over and above the research participant information sheet) beforehand, to familiarise them with the procedures:

> “I remember I sort of discussed the sort of things that they'd be doing within the sessions, so at least they had a bit of help, so that certainly I think, helped the session, it wasn't so much of a surprise. So when they came in, they came in familiar with it, or had some familiarity, um, so it wasn't all new. So I guess um, I guess having some kind of um, a heads up, or some sort of website they could look at this sort of thing, that you're going to be taking part in, would maybe help at the session.” **(Clinician, PH002)**

One challenge identified by a clinician was the amount of time taken to reprocess the files required to develop the feedback reports:

> “There was an issue around the time of getting the sensor feedback done, and then having the ability to provide feedback to patients, whilst still in the department at the same time. So um, largely what we would do is do the data collection, and then see that patient after, um, and sometimes there were issues er, which software was a bit slower, you know, in terms of processing, was a bit slower, in order to get the feedback to then discuss it with the patient, after they'd done the data collection.” **(Clinician, PH002)**

Due to this challenge, it was illustrated by both clinicians that the feedback reports for the majority of the individuals' sessions were only ready close to the end of the treatment session. This potentially reduced the amount of time the treating clinician had to interpret the feedback report and discuss it with the individual. The following quotation was taken from the clinician interview:

> “I'd have the feedback form, just before they were completing, I was seeing them, so it was more of a quick add in at the end, um, I didn't feel that it was a valued um, time.” **(Clinician, PH002)**

As a result of the delay in developing the feedback reports, one clinician reported that the time for the follow up treatment sessions had been extended to allow sufficient time to discuss the feedback report and modify the treatment plan:

> "I think possibly because of the process and speed again, to get the feedback, was then um, slower, than that agent and the treatment time, so I adjusted my follow up session to approximately 45 minutes. Sometimes it was for an hour, and that was just a call made to the patients, on an individual basis." **(Clinician, PH002)**

Elsewhere, one clinician (PH001) and one individual (Joe, P006) highlighted that if there was insufficient time to interpret the report on the day of the treatment session, the opportunity to make targeted adjustments to the treatment plan based on the findings had been missed. The following extracts were taken from interviews with the individuals and clinicians:

> "I guess perhaps the other thing is that if you were doing it with a patient, the first time we did it we had the information right at the end and I had given him all the plan of stuff to do… I feel like I needed to implement it, that I knew that information soon afterwards. Whereas I couldn't see him for a month." **(Clinician, PH001)**

> "I just think maybe it might be best for the physio to potentially have a little bit of time or a little bit more time, rather than just on the day to take a look at it, so then they can use that to shape what I do, what exercises they give me to take home." **(Joe, P006)**

<u>Flow of the movement analysis and treatment session</u>

Three individuals were all happy about the flow of the sessions, and expressed their preference for having the movement analysis session followed directly by the treatment session on the same day. Examples of this were portrayed in the following extract:

> "I think it's definitely better to have them one after the other… Like you've just done it and then you can look back then straightaway and talk about it, instead

of leaving it for a few days or a couple of weeks or something, you've maybe forgotten what you did." **(David, P003)**

On the other hand, the clinicians had a contrasting opinion regarding the flow of the sessions due to the challenges they encountered that impacted their time and limited their opportunities to take advantage of the findings of the feedback reports. Both clinicians expressed their preferences for splitting the movement analysis session and the treatment session over two separate days:

> "I think instead of being able to then deliver a programme immediately off the back of it, on top of the stuff I've already given them I guess you just need to see them a big quicker next time. So you want to see them maybe within a week to implement the findings from the report sooner, rather than leaving it a month, and then you at that point see them again anyway, which means they are not going to have made necessary changes because you haven't addressed all the findings." **(Clinician, PH001)**

However, the clinicians also expressed concern about the availability within the physiotherapy setting and the load of the assigned clinician. Clinician (PH001) explained this challenge:

> "I guess it depends on how often you can or you want to or sometimes in the NHS it's fitting in when you can see them again. So with him I probably would have wanted to see him more frequently but I couldn't because the patient did not have enough space at times convenient to him." **(Clinician, PH001)**

It was also mentioned by one clinician (PH002) that this decision needed to be taken in consultation with the individual, since the selected approach may not be suitable for all individuals.

<u>Frequency and spread of the movement analysis sessions</u>

Most of the individuals with knee pain were happy about the frequency of the movement analysis sessions experienced and their distribution over their treatment course. An example of this was portrayed in the following extract:

> “I think that's quite good to be fair because it was kind of sort of when I needed to see the physio. It wasn't too short that it was like too repetitive, it was kind of every like 3-4 weeks at a time” **(Nancy, P005)**

One individual (George, P001) expressed negativity regarding the frequency and spread of the movement analysis sessions he received, indicating that sessions were required to cover the entire period of the treatment course and were spread over the beginning, middle, and end:

> “Well I was shocked when someone, I think it was you or [clinician] said it was my last one, I thought we were having more… I thought this would go on until [clinician] kicking me out the door and no more than that… Well ideally, I’d want one in the beginning, the middle and the end instead of using up three straightaway.” **(George, P001)**

This was agreed by the personal preference of one clinician (PH001) to have three or four movement analysis sessions spread over the start, middle, and end of the treatment course:

> “One at the beginning, one in the middle to motivate them to see that there are changes, to motivate them to continue to do what they are doing, and then one at the end to analyse the overall changes perhaps.” **(Clinician, PH001)**

Two individuals and both clinicians indicated that the spread of the movement analysis sessions over the treatment course should be dependent on the individual’s kinematic outcomes, as provided by the feedback report, and thus it can be decided whether further movement analysis sessions are needed. The following quotations were taken from the clinician interviews:

> “According to the individual, yeah. And some of them may … may have just needed um, one assessment, to say look, you know, biomechanically it looks like you're moving well, this is really good, your focus now just needs to be on strength, get on with it, we don't need to do this again.” **(Clinician, PH002)**

Therefore, two individuals and one clinician agreed that the number and spread of the movement analysis sessions over the treatment course should be based on a mutual decision between the treating clinician and the individual with knee pain:

> "I think it needs to be a, um, like a mutual or a collaborative decision between you and the patient, so say look, how do you feel you're getting on … fine, not concerned about stuff. Okay, best see how we get along with the next session, and maybe plan the movement analysis later. Um, so it was … I think again, it would be done on an individual basis, not a predefined." **(Clinician, PH002)**

> "It doesn't have to be once a month or whatever, I think it'd be better for the physio to set the sessions and when they happen." **(Joe, P006)**

Also, both the clinicians and the two individuals explained that there needs to be sufficient time between the sessions to allow for change. An example of this was given in the following extract:

> "Well obviously it takes time, I think at the start, I do feel like it takes time for biomechanical changes to occur, you know when you're trying to get muscles firing better, quicker that kind of thing. I don't think it needs to be too frequently, maybe like… So I guess I probably would have maybe like every, I don't know, like 6-8 weeks is maybe better." **(Clinician, PH001)**

4.2.5.6.1.3 Summary of the main findings of Theme 1- Practicality of the movement analysis sessions

Individuals with knee pain and treating clinicians discussed the practicality of the two components of the movement analysis sessions (content and procedures, and organisation). In terms of the content and procedures, some challenges were indicated, which related to the size of the zip-fastened T-shirt worn during the session, the stigma of wearing IMU sensors, and the unsuitability of the functional tasks included.

On the other hand, the majority of the individuals were happy with the organisation of the movement analysis sessions in terms of their timing, flow, and frequency and spread. However, clinicians had a concern regarding the time available for interpreting feedback report results and discussing them with the individuals. They highlighted two main sources that may impact the timing and delay the development of the feedback reports in a timely manner (individual's familiarisation with the session's procedures and software reprocessing). In addition, some individuals and clinicians mentioned that the frequency and spread of sessions need to be individualised and cover the entire period of the treatment course. Suggestions about how to eliminate most of the challenges pointed out under this theme were portrayed by both individuals and clinicians.

In general, based on the individuals and clinicians, the delivery and content of the SMAFT's movement analysis sessions integrated into physiotherapy (TAU) for individuals with knee pain appear practical. However, the challenges mentioned by some of the individuals and clinicians might impact their acceptability of the toolkit. Therefore, it is crucial to consider them when further developing SMAFT.

4.2.5.6.2 Theme 2- Usability of movement analysis feedback report

This theme explores the usability of the movement analysis feedback report received by the treating clinician and the individual with knee pain following each movement analysis session from their perspectives. The working definition of usability as stated under this theme is the extent to which a movement analysis feedback report was user-friendly as a means of understanding and interpreting kinematics findings. The two underlying sub-themes: 'Understanding and interpretations of the report's findings', and 'Format and features of the feedback report' are detailed below.

4.2.5.6.2.1 Sub-theme 1- Understanding and interpretations of the feedback report's findings

This subtheme presents individuals with knee pain and treating clinicians' opinions about their understanding and interpretations of the feedback report's findings and the requirements to enhance the process of understanding and interpretation.

<u>Understanding of the feedback report's findings</u>

Both the clinicians and 3 out of 5 of the individuals with knee pain responded positively in terms of their understanding of the feedback report. However, two individuals observed that they found the graphs complicated and could not understand them:

> "I guess that was the only thing really about the graphs because they were quite complicated, I didn't really understand what a lot of them meant." **(Nancy, P005)**

Thus, the same individual preferred seeing the avatar videos rather than the feedback report:

> **"**I mean the graph was alright but maybe like, for me like I am quite visual, maybe seeing the avatar erm even if it was like stills from it where like you could actually see the visual presentation of the movement where like things could be like improved, so like my hip dropping, seeing that in picture helps more than the graph." **(Nancy, P005)**

This was supported by one clinician, who gives explained their personal preference for the avatar videos over the report's graphs:

> "I'd prefer those, they are the quickest way of getting the information into my brain I guess rather than the graphs, which take a little bit more time to look at ... but are still helpful. Just more time-consuming." **(Clinician, PH001)**

Both the clinicians gave examples of how they understood and applied the content of the feedback report. It was indicated by one clinician that the temporo-spatial data can be used to correlate their findings with an individual's movement patterns during the performance of different functional activities. Clinician (PH002) explained this in the following extract:

> "I was looking at the temporo-spatial data from the first page, just as a quick referral, to cast an eye over it, to look at um, the gait, does it look relatively normal ... you're looking to see … you're looking trying to confirm always against what you've seen observationally. Does it match, does it correlate, does it kind of … does it validate kind of what you've seen I guess?" **(Clinician, PH002)**

Both the clinicians expressed their positive perceptions and their understanding of the waveform graphs and what the graphs displayed:

> "It was progressive, so you use … it would be quite simple to look, you knew it was the sagittal plane on the left, frontal plane on the right. Um, you could see the hip, knee, and ankle." **(Clinician, PH002)**

One clinician (PH002) demonstrated how it helped their understanding of how the individual was moving:

> "Just understanding what that means, um, so if you're kind of breaking it down, you're kind of seeing the person physically doing it, you're seeing the waveform, and you're breaking it down into um, smaller numbers, you're looking at the intricacies of the movement. And then you're trying to build it back up to how that looks in the full moving pattern again." **(Clinician, PH002)**

Another advantage of the waveform graphs is that they help them to compare the range of movements of the individual's affected limb against the non-affected one during their performance of functional tasks. This was portrayed by both clinicians, and an example is given in the following extract:

> "Really good to have a look at whether, the waveforms ... Having a look at the difference between the left and right side in terms of how much the valgus there is, how much varus at the knee, how much pronation on the ankle and how much flexion-extension there is, to how it changes with biomechanics when he's walking. Because of the anterior knee pain that he experiences." **(Clinician, PH001)**

In addition, one clinician (PH002) indicated that the clinician can analyse the movement pattern performed by an individual across the movement cycle of the functional task. More specifically, the use of the waveform graphs allows the clinician to identify the time period across the whole activity movement cycle, to determine when alterations in movement patterns occur. The following quotation taken from the interviews presents this:

"Would be a helpful thing in terms of looking through um, the way forward, going from zero to you know, heel strike to heel strike, you can see through that movement pattern what was occurring. And you could follow that through, because it was time sequenced." **(Clinician, PH002)**

Positive perceptions about the between-session waveform graphs were reported by both clinicians, as useful for monitoring an individual's progress over time and for simplifying the discussion with an individual about their movements. This was illustrated by the following extract taken from the interviews with clinicians:

"Also like it's interesting to look at the difference between the first and the second appointment as well, in terms of have there been any improvements. And there were changes, so that was helpful to see. I guess if you spent time going through that with a patient that's going to be motivating for him as well." **(Clinician, PH001)**

This was supported by one individual (Nancy, P005), who positively expressed the potential benefit of comparing changes in the waveforms over time:

"But also in the last session where we looked back and sort of compared like from the first session to now you can then sort of gave a good erm sense of like how, if you are getting better and how." **(Nancy, P005)**

The last component of the feedback report was the consistency plots for the movement trials of a particular functional task. One clinician expressed a negative perception about the consistency plot as a result of the inconsistencies in the waveform between the affected and non-affected limbs. Clinician (PH001):

"No, I don't think the consistency plots showed us that much if I remember rightly. They were a little bit generally inconsistent bilaterally, so not necessarily sure that they added that much… but I don't know that they were necessarily that helpful with this particular patient for some reason. And they were fairly inconsistent both sides, like it didn't give us much information." **(Clinician, PH001)**

On the other hand, the other clinician regarded them as important, as consistency between trials may be an indication of an individual's muscle strength and endurance. The following quotation taken from the interviews presents this view:

> "… it was the format of the movement repeatedly over time. So um, the repetitive nature of the movement, did they have muscle endurance in terms of strength, you're kind of … you're reasoning for things that even though you've tested them." **(Clinician, PH002)**

<u>Requirements needed to improve users' understanding of the feedback report</u>

For the individuals with knee pain, the importance of discussing the movement report with their treating clinician was indicated as an important factor in helping their understanding:

> "I just think maybe erm if we, if you could factor in a part where you sit with the, or the physio sits with the patient just to give erm more detailed feedback and just go through the report. That's the only thing that I would add." **(Joe, P006)**

In addition, one of the individuals (Joe, P006) suggested providing the individual with a summary of the findings within the feedback report to enhance their understanding. The following quotation was taken from interviews with the individuals with knee pain:

> "Well again it's like the, you know the report is really aimed at professionals, but if erm, you know it might be something for the person doing the, producing the report like yourself or the professional maybe just to give you know a bit of a conclusion or you know a bit of a, just maybe adding something that would help the layman like myself just to understand it a little bit more... So you know a little bit of a summary, that type of thing would be quite good or a little bit of what the findings exactly mean, maybe on the day or what might be better, then just in the erm, in the body of the report itself at the end perhaps, or a summary at the beginning." **(Joe, P006)**

Both the individuals and the clinicians agreed that the physiotherapist was the most appropriate clinician to discuss the movement report with, as it could influence the proposed treatment:

> "Probably the physiotherapist… because then I think if you look ... by discussing it, then they can give them more of an idea of what exercises ... or whatever they need to give to you to help you." **(David, P003)**

> "I think it would be … would be … I certainly think physio has got the skill and the experience to put it into practice." **(Clinician, PH002)**

It was highlighted by both the clinicians that training and experience using the report was essential to help them use the movement analysis reports, and apply them to their treatments:

> "Probably a little bit of either online training or er, some training package, or spending an hour or two hours kind of going through a PowerPoint presentation on waveform patterns, and what they look like, and how I can understand, and apply it? Or whatever medium that's through, whether through the internet, web based or face to face." **(Clinician, PH002)**

4.2.5.6.2.2 Sub-theme 2- Formats and features of the movement analysis feedback report

This subtheme presents the individuals with knee pain and treating clinicians' opinions about the format and features of the feedback report, including their perceptions, personal preferences, and suggestions.

Two of the individuals expressed positive perceptions regarding the presentation of the feedback report. The following quotation affords an example taken from the interviews:

> "I don't think the data was badly presented, it looked to be quite clear. I liked this, as I said the videos with the avatar were quite good and then obviously the report itself from what I had seen, you know, stated which exercise and which action as well, so that was quite clear." **(Joe, P006)**

The knee pain individuals and clinicians explained their preferences for receiving feedback reports in an electronic format. The following extract taken from the interviews portrays typical responses:

> "So I think that would be handy, the PDF, I think it wouldn't be worth giving it in paper because god knows where it would end up." **(Joe, P006)**

Reported advantages of the electronic format included viewing on one's own device and ease of viewing:

> "As a PDF or something like that I could see on my own personal laptop that would be quite handy." **(Joe, P006)**

> "I guess I prefer email probably because it is just sort of easy, you can kind of go back and forth." **(Nancy, P005)**

In terms of the limitations of the paper-based format, both the clinicians pointed out that each feedback report included multiple sheets that are difficult to print out and attach to the individual with knee pain file. The following extract was taken from the interviews with the clinicians:

> "It will be too much paper. Not good for the environment." **(Clinician, PH001)**

It was additionally indicated that by printing out the feedback report, the features of the coloured waveforms presented in the electronic format may be lost. Clinician (PH002) illustrated this:

> "But at the moment, you know, I'd look at the feedback report, and forward that via email, it looks about right, so print it out, then I haven't got the benefit of the colours, um, it's kind of how that data is presented." **(Clinician, PH002)**

One clinician (PH002) suggested establishing a digital platform, via which the clinician could access the feedback report, the avatar, and the individual's notes at the same time all on one platform, and make markers, comments, and highlights as needed. This may also be advantageous for providing easy access to the feedback report and the avatar videos for the individuals with knee pain, so that they can review the report and play the avatar videos at any time and place.

<u>Features of the movement analysis feedback report</u>

All of the individuals with knee pain indicated positive perceptions about the overall benefits of the feedback report. These positive perceptions concerned the feature of visualisation of the findings within the report:

> "The results concern having the sensors, because you can see, I can see the difference from every session we've had." **(George, P001)**

> "I liked being able to look at the feedback." **(David, P003)**

This was supported by one clinician who was happy about the visualisation feature, particularly for the range of movements in different lower limb joints at different planes:

> "I really like being able to see how much abduction and adduction there is during the gait cycle of the hip, and how much valgus and varus at the knee, how much flexion-extension there is because you can then, particularly with valgus and varus abduction adduction you can then kind of, and how much pronation and supination." **(Clinician, PH001)**

It was also suggested that a feature of the feedback report that can be used as a reference point for comparison if physiotherapy is required in the future:

> "You never know; perhaps from my point of view if I get the report and some of the avatar stuff, it is something I can hold onto and say if it's a problem that rears its head again then it would be something I would be able to supply to the next physio as well, in case it was needed or if I wanted to see, pardon me, someone privately it would be a resource they could use as well." **(Joe, P006)**

4.2.5.6.2.3 Summary of main findings of Theme 2 – Usability of movement analysis feedback report

This theme presented individuals with knee pain and clinicians' opinions about the usability of the feedback report in terms of understanding its findings, and the features and format of it. Overall, the clinicians were happy about the ease of use of the feedback report and expressed their understanding of its various components when interpreting findings. However, understanding of the feedback report among some of the individuals with knee pain was indicated as an issue. Therefore, to improve individuals' understanding, the individuals and clinicians portrayed some requirements and suggestions, such as the importance of discussing the report's findings with the treating clinician and providing a summary of the findings within the report.

Regarding the format and features of the feedback report, most of the individuals and clinicians presented their personal preference for an electronic format, highlighting its advantages compared to a paper-based format. Individuals also highlighted some features of the feedback report that are impacted positively by its use among users. These features concerned the visualisation of the findings in a waveform graph format and the use of the report as a reference point if physiotherapy is required in the future.

The individuals and clinicians' perceptions of the format and presentation of the feedback report and their illustration of its features support its usability. However, the challenge of individuals' understanding of the feedback report should be taken into account in any future development of the toolkit.

4.2.5.6.3 Theme 3- Perceived benefits of sensor-based movement analysis feedback toolkit

This theme demonstrates the perceived benefits of using SMAFT in clinical practice from the individuals with knee pain and treating clinicians' perspectives, and how these benefits were achieved. The working definition of benefit in the current theme considers the advantage of using SMAFT alongside physiotherapy (TAU) within the context of clinical practice. The three underlying sub-themes: 'Increased depth to physiotherapy assessment and treatment', 'improve clinician's efficiency', 'increased individual's understanding and awareness of movements', and 'increased individual's motivation and adherence towards exercises and functional performance’ are detailed below.

4.2.5.6.3.1 Sub-theme 1- Increased depth to physiotherapy assessment and treatment

This subtheme presents individuals and clinicians’ perspectives with regard to how SMAFT enhances physiotherapy care. These were: Objectively identifying altered movement patterns, increasing the clinician’s understanding of movements, informing clinical decisions, tailoring treatment, and monitoring progress.

<u>Identifying altered movement patterns objectively</u>

Three of the 5 individuals with knee pain and both clinicians agreed that SMAFT ensures clinicians’ assessments and treatments are more specific, as they were provided by objective kinematic data within the feedback report. The objectivity of SMAFT allows clinicians to identify altered movement patterns that they could not otherwise identify using a subjective method, such as an observational analysis. The following extracts were taken from the interviews:

> “But I do think it has helped show up a few things that potentially maybe you know, not saying [clinician] would have missed these, but it's just you know it is something that can be recorded and then obviously the physio has made a diagnosis then, but obviously you've got the findings in the report that can be considered afterwards. So I think it helps maybe perhaps that they are given a more in-depth analysis by someone of the problems they have.” **(Joe, P006)**

> “Obviously the information that we found in the movement analysis report, erm, enabled me to give the patient more - it helped me to assess the patient more appropriately, finding the biomechanical movement patterns that are occurring with the avatar, and using the graph and you can analyse that better, which means that you can then give better, assess them more appropriately and assess the observations based on that, based on more scientific kind of data, rather than erm just opting for grading and objectives and observation of

movement. Erm it’s a bit more scientific and got numbers and graphs that are attached to it which is nice.” **(Clinician, PH001)**

Increasing clinicians’ understanding of movements and informing clinical decision

It was expressed positively by both clinicians that by analysing the feedback report and identifying the altered movement patterns, the understanding of how individuals move during the performance of different functional activities increased. The following quotations were taken from the interviews:

“But then added to my understanding of his movement patterns further, with some of the other patterns of motion that were going on so it was quite interesting seeing him shifting side to side when he was doing I think a squat. So just kind of gave me extra information perhaps my naked eye didn't see.” **(Clinician, PH001)**

“It gets me to look a little bit more impact, I look at the individuals differently possibly. Um, I look a little bit more at the intricacies, so sometimes the movement patterns and how they're performing it, and the future movements relating to the same activities.” **(Clinician, PH002)**

This might guide the clinician in making the most appropriate decisions about each individual’s assessment and treatment plan:

“It gives you, as a clinician, um, hard evidence to suggest that what you're doing is correct, or that it's ideal. I guess it can confirm or clarify whether you're barking up the right … barking up the right tree, you know, like … you're on the right lines I guess. Um, so confirmation of that feedback is … is um really important.” **(Clinician, PH002)**

Therefore, one clinician illustrated that taking a decision based on the objective findings of the feedback report could improve clinicians’ confidence in their assessment and treatment:

“But also brought them into it to say um, it gave them confidence in what you were saying as a physio was then relevant, and not just being said um, as far as that, it was more individualised, it was more a personalised um, assessment, based on the movement patterns." **(Clinician, PH002)**

Tailoring individuals with knee pain treatment

All the individuals and clinicians agreed that the individuals' physiotherapy treatments might be advantageous when using SMAFT through tailoring the treatment plan for each individual. More specifically, treatment could be individualised based on the altered movement patterns identified during the different functional tasks:

> "They can use that to shape what I do, what exercises they give me to take home, in that way if you know what I mean." **(Joe, P006)**

One individual presented an example of how physiotherapy treatments were tailored based on the altered movement patterns identified in the feedback report:

> "Because for example like when I was doing squats, I was having knee pain ... and looking at the feedback, it showed that my heel was rising off the ground. So, because we looked at that, in my appoint ... in my physio appointment then, I was given exercises to work on my ankles, like obviously calf-stretching but then things like exercises as well, like calf-raises." **(David, P003)**

Monitoring progress

The majority of the individuals and both clinicians indicated that SMAFT helped them monitor progress by allowing them to compare their movement patterns objectively between sessions. One individual and one clinician explained this in the following extracts:

> "But also in the last session, where we looked back and sort of compared like from the first session to now you can then sort of gave a good erm sense of like how, if you are getting better and how." **(Nancy, P005)**

> "Also It is interesting to look at the differences between the first and the second appointment as well, in terms of have there been any improvements. And there were changes, so that was helpful to see." **(Clinician, PH001)**

4.2.5.6.3.2 Sub-theme 2- improve clinician's efficiency

This subtheme illustrates how clinicians may improve their efficiency of thought using SMAFT. Both clinicians discussed how clinical decisions are taken based on such an objective toolkit for analysing an individual's movement patterns may save the clinician's time. The following extract taken from the interviews with clinicians portrayed typical responses:

> "I think it probably made me a little bit more efficient, it kind of cut through um, it kind of … not cutting corners, but it gives you, you've got a limited time with the patient, you've got 20 minutes in a follow up session. That can buy you time, so having some of that data and that feedback can give you a bit of a heads up quicker." **(Clinician, PH002)**

Thus, one clinician mentioned that as long as the clinician's productivity can be enhanced by seeing a larger number of individuals because of the reduced contact time with the individual:

> "I think it makes you, you know, more efficient, in terms of the type and the style of exercise that you're getting that patient to perform and create. Um, productivity, actually you're seeing more patients, but it may be just more of a quality experience than anything else." **(Clinician, PH002)**

4.2.5.6.3.3 Sub-theme 3- Increase knee pain individual's understanding and awareness of movements

This subtheme shows individuals and clinicians' opinions with regard to the influence of using SMAFT for enhancing individuals' understanding and awareness of their movement patterns during their performance of a variety of functional activities. Two of the individuals expressed that their understanding of their knee problems and their awareness of altered movement patterns increased after discussing the findings of the feedback reports with their treating clinicians. An example of this was given by two individuals:

> "Where I was doing things like going up and down the stairs, the feedback showed that when I was doing things like that, my hips were dropping, so that

showed us that really I needed to focus more on stretching my glutes." **(David, P003)**

"I wasn't aware of if some of the movements that I was actually were being done correctly and by getting feedback I could see that erm maybe I wasn't in the right position for some of the exercises. Erm so that was important for me to see that." **(Clare, P007)**

This was confirmed by both clinicians:

"I think he obviously found a benefit and he found it really helpful and really interesting to understand his movement a bit more. So I think he also saw a benefit for him as well." **(Clinician, PH002)**

4.2.5.6.3.4 Sub-theme 4- Improve individuals with knee pain adherence and performance of exercises and functional activities

This subtheme illustrates how the use of SMAFT could be used to influence an individual's adherence and performance to their physiotherapy exercises and functional activities from the individuals and clinicians' perspectives. The majority of the individuals discussed that their motivation and adherence to the exercises and recommendations given by the treating clinicians were increased by the use of SMAFT. Monitoring progress makes individuals more eager to follow their clinicians' recommendations and advice about performing exercises. The following extract is taken from interviews with one individual:

"Like I said it's the after being with you and then going in to see [clinician] and [clinician] having the results there and then. It sort of sets the way then for when you go home and right, I need to do this, I need to do that because you could see the results were there in front of you." **(George, P001)**

Both clinicians agreed with this, and explained that the increase in individuals' understanding and awareness of their movement patterns when visualising them during their physiotherapy treatment sessions might improve their motivation and adherence to their exercises:

> "And that shows a change, so um, in terms of behaviour, that guides them into doing more exercises… engaging or um, self-management strategies, so they can get on without the need to always come into the physio department there. I guess there's lots of um, you know, ways that they can actually influence, going forwards." **(Clinician, PH002)**

It was also mentioned by the individuals that understanding the findings of the feedback report in terms of movement patterns influenced positively on their performance of exercises, including correcting how they move when performing different exercises. The following quotation was taken from the interviews:

> "I think it would just help me to erm, you know perform the exercises erm much better than what I was doing just on my own." **(Clare, P007)**

In addition, one of the individuals indicated that SMAFT could be used as a motivation to improve an individual's engagement in physiotherapy treatments:

> "I was always excited to see the results, as I said, I always wanted to see the results, to see if I'd beaten, done better than I did, the last time I see them, the first one I was a bit like, I dunno what this is, but then after that one, I come back again and we could see the difference." **(George, P001)**

4.2.5.6.3.5 Summary of main findings of Theme 3- Perceived benefits of sensor- based movement analysis feedback toolkit

When summarising this theme, the individuals with knee pain and clinicians indicated several potential benefits arising from using SMAFT within clinical practice. These benefits were related to the use of SMAFT to enhance physiotherapy assessment and treatment through objectivising assessment, improving clinical decision making, tailoring treatment, and monitoring progress. It was also discussed that its beneficial uses resulted in further benefits for individuals with knee pain by increasing their awareness of movements and adherence towards exercises, as well as for clinicians by improving their efficiency. Highlighting these potential benefits to the users of SMAFT suggested the acceptability of using it alongside physiotherapy (TAU) within physiotherapy clinical settings.

4.2.5.6.4 Overall summary of the qualitative results

Thematic analysis of the qualitative interviews for individuals with knee pain and their treating clinicians resulted in three key themes related to the acceptability of SMAFT within the clinical practice of physiotherapy. These three themes were 'Practicality of the movement analysis sessions', 'Usability of the movement analysis feedback report', and 'Perceived benefits of the sensor-based movement analysis feedback toolkit'. Overall, the qualitative findings of semi-structured interviews proposed that SMAFT seemed acceptable, and the individuals with knee pain and the clinicians saw the toolkit as a positive addition to physiotherapy (TAU) within clinical practice. Individuals and clinicians portrayed several potential benefits of SMAFT to enhance physiotherapy assessment and treatment, increase clinician's efficiency, and improve individual's understanding of movements and motivation towards exercises. Moreover, the majority of the individuals and clinicians were content with the practicality of the procedures and the organisation of the movement analysis sessions, as well as the usability of the feedback report. However, some challenges were experienced and reported. The three main challenges concerned the time available for clinicians to interpret the report and discuss it with individuals, individuals' stigma about wearing IMU sensors in front of other people, and difficulty understanding the findings presented in the report. Therefore, these challenges suggest further refinements of SMAFT that should be considered when undertaking future development.

4.2.5.7 Stage II: Integration of the quantitative and qualitative findings

At this stage, key findings from the qualitative and quantitative arms of this case study are integrated. The findings are presented in a narrative format, as recommended by Creswell and Plano Clark (2017). The integrated findings address the research aim of the current study: **To explore the acceptability of SMAFT from the perspective of its users, when used alongside physiotherapy (TAU), within the physiotherapy clinical practice of a UHB.**

A summary of the main findings from different sources for each data component is shown in Table 37. In general, the qualitative interviews of individuals with knee pain and treating clinicians suggested that SMAFT was considered to be an acceptable toolkit for use alongside physiotherapy (TAU) within the clinical practice from the perspective of being beneficial, practical, and usable. These qualitative findings of acceptability were supported by the quantitative findings relating to pain and function levels reported by individuals with knee pain in the KOOS and NRS questionnaires, which presented a trend of reducing pain and improving function for individuals with knee pain over time. The integration of these findings may give a greater understanding of the effect of using SMAFT alongside physiotherapy (TAU) and how SMAFT produces its effects. Therefore, discussing users' perceived benefits of SMAFT, alongside the Behaviour Change Wheel (BCW) framework, might inform this (see Section 4.2.6.2.3).

Moreover, the overall summary of the interpretation of the feedback reports from all individuals with knee pain showed a varied range of altered movement patterns across all individuals and tasks. The wide variations in the way in which individuals performed functional tasks suggest a highly individualised change in movement patterns in response to chronic knee pain. This indicates individualised tailored treatment plans are needed. In addition, treatment strategies, such as feedback movement retraining and education, should be introduced to correct the unnecessary movement alterations identified, in order to improve pain and functional levels.

This was evident by analysing clinicians' notes, which showed that the clinicians used different treatment strategies and applications across individuals with knee pain and tailored their treatment plans using SMAFT, which had the potential to improve their pain and function. Therefore, a complete picture of the acceptability of SMAFT within the clinical practice was demonstrated. However, it was surprising that treating clinicians' notes contained relatively little information regarding the altered movement patterns identified and treated. In addition, a lack of rich information about the direct feedback and education given by the clinicians to individuals with knee pain on their performance of functional activities was reported in their notes. The lack of detailed information regarding individuals' altered movement patterns and how they could be targeted during treatment suggests a need for assessing whether SMAFT is used in clinical practice as planned (intervention fidelity) in future research.

In summary, the integration of the findings of the quantitative and qualitative components supported the clinical acceptability of SMAFT by demonstrating a comprehensive view of its acceptability within clinical practice. However, the aspect of how users used the kinematic data provided by SMAFT to inform their treatment was not fully reached and needs further investigation.

Table 37: Summary of the main findings from the users' interviews, KOOS and NRS questionnaires, interpretations of movement analysis feedback reports, and the clinicians' progress notes

Data sources	**Qualitative findings**	**Quantitative findings**		
	Participants' interviews	**KOOS and NRS questionnaires**	**Interpretation of feedback reports**	**Clinicians' documentary notes**
Summary of main findings	Using SMAFT within the physiotherapy clinical practice appeared acceptable from the perspective of being beneficial, practical, and usable.	There is a trend towards improving an individual's pain and function over time (across movement analysis sessions).	Varied altered movement patterns were identified across all the individuals with knee pain during varied functional tasks. Few altered movement patterns were found to be inconsistent across individuals.	Physiotherapy treatments given by the treating clinicians were inconsistent across individuals with knee pain, and the treatment plans were tailored for each individual. Lack and inconsistent information about the altered movement patterns observed and treated by the treating clinicians and the feedback and education given was found in the clinicians' notes.

Abbreviations: KOOS = Knee Injury and Osteoarthritis Outcome Score, NRS = Numeric Rating Scale, SMAFT = Sensor-based Movement Analysis Feedback Toolkit

4.2.6 Discussion

4.2.6.1 Summary of the main findings of the case study

The aim of this case study was to explore the acceptability of SMAFT for users (individuals with knee pain and treating clinicians) when used alongside physiotherapy (TAU) within the physiotherapy clinical practice of a UHB. This was done by conducting a mixed-methods case study to explore the users' acceptability of SMAFT from different research components. This is essential to provide a unique insight into users' perspectives on SMAFT and enhance the understanding of how its design, application, and delivery are perceived.

Individuals with knee pain and their treating clinicians were considered the units of analysis for the case study (physiotherapy services in a UHB). Seven individuals with knee pain were involved in the current study through their participation in movement analysis sessions provided by SMAFT alongside their physiotherapy (TAU). Five of the seven individuals and two of the three clinicians completed semi-structured interviews. Overall, the findings from this case study demonstrated a complete picture of acceptability within clinical practice by integrating the findings from multiple sources of evidence. Moreover, although the integration of a preliminary version of SMAFT into physiotherapy (TAU) for individuals with knee pain appeared to be acceptable from the perspective of being beneficial, practical, and usable, some challenges regarding SMAFT's usability and practicality were identified. A better understanding of the design and delivery of SMAFT within clinical practice was thus achieved, and further investigations and refinements for future development were noted. The key findings will now be discussed in accordance with each research objective.

4.2.6.2 Research objective 1 - To investigate users' acceptability for using SMAFT alongside physiotherapy (TAU) within the physiotherapy clinical practice

This case study provided an in-depth understanding of users' acceptability of SMAFT within clinical practice. An inductive process was chosen to provide a rich and deep understanding of the perspectives of users towards SMAFT, allowing for novel and unanticipated instances. The thematic analysis of the semi-structured interviews suggested users were supportive of the use of SMAFT alongside physiotherapy (TAU) for individuals with knee pain within the context of clinical practice. Positive user responses identified the potential benefits of SMAFT, adding more depth to their physiotherapy assessment and treatment, increasing their awareness of movements, enhancing individuals' adherence towards exercises, and improving clinicians' efficiency. However, as this is an early stage developmental study, further evaluation of SMAFT using robust studies to determine its impact on physiotherapy treatment, clinicians, and individuals with knee pain is required. Such studies should be conducted applying the varied iterative stages of development set out in the MRC framework (Skivington et al. 2021).

Furthermore, it seemed practical to integrate movement analysis sessions into physiotherapy (TAU), and the feedback report appeared to be user-friendly for use in clinical practice. However, some challenges were indicated that may reduce users' clinical acceptability (a detailed discussion about clinical challenges is presented later in sections 4.2.6.2.2.4 and 4.2.6.2.2.5). These challenges need to be considered and addressed prior to conducting further testing of SMAFT. These qualitative findings will now be compared with previous literature and discussed in line with the theoretical framework of acceptability (TFA).

4.2.6.2.1 Comparison of qualitative findings with previous literature

Achieving a better understanding of the acceptability of the use and integration of wearable technology in clinical settings, involving users' preferences, challenges, and benefits, has been investigated in the musculoskeletal field (Papi et al. 2015; Belsi et al. 2016; Papi et al. 2016; Lin et al. 2019). A limited number of studies have explored the perspectives of users (individuals with pain and treating clinicians) on wearable technology in terms of identifying users' requirements in order to inform further technological developments prior to clinical implementation (Papi et al. 2015; Belsi et al. 2016; Papi et al. 2016; Lin et al. 2019).

Papi et al. (2015) and Papi et al. (2016) explored the opinions of users (individuals with knee OA and treating clinicians) regarding the use of a sensor-based monitoring tool in the rehabilitation of knee OA. The findings showed that users saw the tool as a positive addition to clinics, highlighting uses and benefits such as informing clinical decisions, tailoring treatment, improving adherence towards treatment, and saving time (Papi et al. 2015; Papi et al. 2016), which is in line with the current study's findings. However, these studies were limited by the responses of knee OA individuals and clinicians towards the sensor-based tool investigated, as these were based on a demonstration and explanation of the tool without actually using it. The unique aspect of exploring users' acceptability in the current study is that individuals and clinicians had full experience of using SMAFT alongside physiotherapy (TAU) within clinical practice prior to the interviews. Using SMAFT in a real-world environment allows more accurate opinions about acceptability to be obtained.

4.2.6.2.2 Discussion of qualitative findings in line with the Theoretical Framework of Acceptability (TFA)

Users' perceptions of constructs within the Theoretical Framework of Acceptability (TFA), as outlined by Sekhon et al. (2017), provided in-depth information regarding whether SMAFT was deemed an acceptable toolkit, and in what way. Therefore, it is pertinent to discuss the findings under the framework constructs to provide an overview of how acceptable users found SMAFT.

4.2.6.2.2.1 Affective Attitude: Participants' positive and negative feelings toward SMAFT and its use alongside physiotherapy (TAU) within the clinical practice

Users reported overall positive perceptions towards their attendance at sensor-based movement analysis sessions and using the feedback reports. In general, there appeared to be a positive skew towards SMAFT. The novelty of employing such technology in clinical practice was one of the main reasons why individuals with knee pain had a positive attitude towards SMAFT. These positive attitudes towards SMAFT were also evident due to users' identification of the perceived benefits and features of using SMAFT, which will be discussed in the following section. Participants' positive statements about SMAFT in interviews were always linked to its perceived benefits. A relationship between the positive feelings towards intervention and its functionalities and benefits is evident (Papi et al. 2015; Dunphy et al. 2017). For instance, Papi et al. (2015) noted that the individuals with knee OA had positive attitudes towards a sensor-based tool. There was a positive effect on their adherence and motivation to participate in exercise regimes as they recognised the tool's benefit of monitoring movement function objectively.

4.2.6.2.2.2 Intervention coherence: Understanding SMAFT and how it works

The theme of 'Perceived benefits of the sensor-based movement analysis feedback toolkit' identified in this case study supported this particular construct of the TFA. The theme highlights that the main purposes of applying SMAFT in clinical practice were well-understood by its users. The users were able to demonstrate how SMAFT added to their physiotherapy assessment and treatment in terms of objectively identifying altered movement patterns, informing clinicians' decisions, tailoring treatment, and monitoring progress. This can be explained by the fact that clinicians' understanding of SMAFT may be gained from the study guidelines and training that they were provided with, which present the purpose of SMAFT and how to use it. In addition, the discussion between the individuals with knee pain and their treating clinicians during the recruitment process, as well as the brief introduction performed by the lead researcher (M.F.) about the study's aim and procedures, may have helped individuals gain a clear overview of SMAFT's purpose and how it works. Thus, the information gained by the participants prior to participation that integrated with their real-life experience of using SMAFT might have given them a more comprehensive understanding of how it works. This is crucial in any new intervention, as a lack of education about its purpose and how it works may be considered a barrier to its use (Lin et al. 2019).

Moreover, both the clinicians reported that the feedback report was well-formulated and easy to use. The clinicians highlighted that the ease of use of the feedback reports results from the presentation of the waveform kinematics for the affected limb joints alongside the waveforms for the non-affected limb joints. This was in accordance with a previous study that reported that the use of biomechanical data obtained by wearable technology was enhanced by clinicians, as data was shown against normal reference ranges for the purpose of comparison and goal setting (Lin et al. 2019).

It is worth noting that both of the clinicians who participated in the current case study have a range of previous experience in describing and interpreting the waveform graphs included in the feedback report. The usability of feedback reports by clinicians with no prior experience of them has not yet been explored and therefore needs to be investigated in future. It has been suggested that if healthcare professionals have a poor understanding of what the outputs presented by any system mean, this will undoubtedly detract from the perceived value of the system (Short et al. 2004). Training on the use of any technology used to support clinical decisions has been found to provide an extra advantage for healthcare professionals and will have an impact on their acceptance and use of it (Venkatesh et al. 2002; Shibl et al. 2013). Therefore, a period of familiarisation and training prior to using the feedback report in clinical practice is recommended, especially for inexpert clinicians (Archer et al. 2020). This would allow clinicians to navigate the report confidently, distinguish between the normal and abnormal waveforms presented in the graphs, understand what the graphs mean, and interpret them for application in physiotherapy treatment.

On the other hand, some individuals with knee pain found it difficult to understand the findings of the feedback report, which may influence its acceptability. Some individuals reported that the waveform graphs included in the feedback report were complicated and difficult to understand. Therefore, they suggested for having a summary of the findings of the feedback report presented in a simpler and more concise manner, which make it easier for them to understand and use the feedback report. This was evident in previous literature found that the detailed data should be presented to specialists only while short and simpler materials need to be offered to patients (Grudniewicz et al. 2016; Lin et al. 2019). In addition, a brief training tutorial about what the findings mean and how to interpret them could be conducted by the treating clinician prior to receiving the first movement analysis session. As with clinicians, individuals could also be provided with guidelines on how to interpret the report; these would present the contents of the feedback report and explanation of how to use them. This would make it easier for individuals to use the feedback report.

4.2.6.2.2.3 Perceived effectiveness and Self-efficacy: SMAFT perceived benefits of physiotherapy (TAU) for managing individuals with knee pain, and users' confidence to perform required behaviours

In the current study, all the users endorsed SMAFT as a useful and beneficial tool to be employed alongside physiotherapy (TAU). Perceived effectiveness was a central tenet of acceptability for most individuals and clinicians, with views on benefits being linked to increased confidence and positive attitudes towards SMAFT. The qualitative findings showed that SMAFT was able to support physiotherapy clinicians in building confidence when taking clinical decisions as the objective information obtained by SMAFT. The interviewed clinicians reported that integrating SMAFT into physiotherapy (TAU) improved their efficiency by reducing the number of treatment sessions required and the time needed for these sessions. A systematic review conducted by (Bright et al. 2012) demonstrated a trend of improved clinician workload and efficiency when tools were used to support clinical decision making. Scheitel et al. (2017) found that clinicians had a significant time-saving of 3 minutes and 38 seconds when using a tool called MayoExpertAdvisor (MEA) to inform clinical decisions by calculating cardiovascular risk scores and determining the appropriate cholesterol treatment. Compared to the current study, SMAFT can provide clinicians with objective data about how their individuals are moving, which can help them with their clinical decisions. However, interpreting this data and designing a treatment plan based on it is the responsibility of the clinician. Thus, it is essential to ensure that clinicians use SMAFT in the way they are expected to use it (intervention fidelity) and to evaluate the effect of its use on their work's load.

Another perceived benefit of SMAFT amongst the majority of the interviewed individuals with knee pain is the improvement of their understanding and awareness of movements during functional tasks. This was crucial in building individuals' confidence to perform functional activities and exercises in an appropriate manner. Also, increased awareness was evident as a way to improve their self-management, as monitoring their physical activity and providing feedback on their exercise performance enhanced their engagement in their self-care (Chiauzzi et al. 2015; Thornton et al. 2016; Dunphy et al. 2017). Individuals indicated that this improvement in understanding movements resulted from visualising their movement patterns in the forms of waveform graphs within the feedback report, and avatar videos. It was suggested that visualising information about specific movement characteristics, such as joint kinematics (knowledge of performance), can improve an individual's movement performance through the detection and correction of performance errors (van Vliet and Wulf 2006; Hunt and Takacs 2014). This is very important in terms of rehabilitation because increased individual awareness of performance errors may enhance motor learning of a more optimal movement pattern (Schmidt and Lee 2019; Charlton et al. 2021).

Movement visualisation plays an important role in a number of therapies that depend on performance feedback, such as virtual reality, mirror therapy, and functional retraining with feedback. It is evident that movement retraining using individualised feedback can improve movement patterns (knowledge of performance) performed by individuals with knee pain by enabling them to visualise their movement performance (Noehren et al. 2011; Willy et al. 2012; Shull et al. 2013b; Roper et al. 2016). The improvements in these movement patterns were not only observed during the retraining practice; instead, individuals switched to forming new movement patterns that were acquired over a longer period of time. Therefore, a future robust study is required to consider the role of movement visualisation and assess the effect of SMAFT on altered movement patterns in individuals with knee pain.

Moreover, most of the individuals with knee pain stated that their motivation and adherence towards the exercises prescribed by their treating clinicians improved after using SMAFT. This finding was in line with the findings of a study conducted by Dunphy et al. (2017). Dunphy et al. (2017) developed a web-based tool called TRAK, which is designed to provide individuals undergoing ACLR with a tailored exercise plan that includes videos, progress logs, information, and remote contact support. This tool is considered to motivate patient users to adhere to their exercises and treatment, as it provides them with feedback on their exercises and movements' performance (Dunphy et al. 2017). Compared to the current study, the objective kinematic feedback provided by SMAFT allowed individuals with knee pain to visually assess their movement patterns and monitor their progress over sessions. It has been suggested that providing feedback can help improve the low therapy compliance seen in rehabilitation, as it supports patients with regard to exercise instructions and feedback on performance (Friedrich et al. 1998; Ayoade and Baillie 2014). This can provide a motivational nudge to comply with the optimal exercise regime (Friedrich et al. 1998; Ayoade and Baillie 2014). Hence, as the current case study provided an insight into this perceived benefit of SMAFT, it is important to carry out an accurate study to evaluate the effect of SMAFT on individuals' adherence to treatment and exercises.

The aforementioned potential benefits of SMAFT, particularly with regard to increasing individuals' knowledge and awareness of movement, and improving their motivation and adherence to exercise regimens, can provide insight into its advantages with regard to changing individuals' rehabilitation behaviours. This suggests a need to understand this relationship and evaluate its impact on overall treatment outcomes. Therefore, a discussion of the findings provided in the current case study, in terms of SMAFT's functionalities and benefits, and in accordance with the Behaviour Change Wheel (BCW) model is presented later in section 4.2.6.2.3.

As discussed above, using SMAFT alongside physiotherapy (TAU) may benefit users (individuals with knee pain and clinicians). However, SMAFT still requires further refinements, and additional evaluation of its impact on physiotherapy treatment using more robust studies is needed. In adherence to the MRC framework, these refinements and assessments should be conducted through the varied iterative stages of development (Skivington et al. 2021).

4.2.6.2.2.4 Burden and Opportunity cost: The amount of effort required to use SMAFT, and the extent to which the benefits, profits, or values must be given up engaging in SMAFT

Although, some individuals with knee pain and clinicians were satisfied with the practicality of the movement analysis sessions and the ease of use of the feedback report provided by SMAFT, a few burdens were reported.

First, the perceived pain that accompanied the performance of some functional tasks, particularly the SLS task, was considered a challenge. It was evident that the presence of pain associated with movements while wearing sensors can affect patients' acceptability (Cancela et al. 2014). In the current study protocol, the individual was instructed to perform the tasks within the tolerated pain level. It was not necessary for the individual to complete the task if he or she was unable to perform it or would have found it difficult to do so. If a task was not performed because of the pain experienced, the comprehensive choices of tasks involved in the current study's protocol may compensate for the exclusion of any task. For example, the SA and SD tasks were biomechanically similar to the SLS task, as both required the recruitment of similar muscle groups and concentric and eccentric quadriceps control (Zeller et al. 2003; Benedetti et al. 2007; Richards et al. 2008; Lubahn et al. 2011). This is achieved with a large range of knee flexion with the eccentric and concentric control of hip and ankle extensor muscles (Benedetti et al. 2007; Richards et al. 2008; Boudreau et al. 2009; Lubahn et al. 2011). Moreover, DLS served as a large part of the VJ task (McGinnis 2013). The VJ included three phases (preparatory, propulsive, and flight), where squatting was involved in the first two phases (McGinnis 2013).

The challenge of exercise causing increased pain highlights the importance of clinician involvement in decisions regarding the inclusion of functional tasks. Thus, for the future development of SMAFT, it is recommended that the inclusion of functional tasks should be guided by the clinical assessment and impressions of the physiotherapy treating clinician. Consequently, it is not necessary for each individual with knee pain to complete all tasks, as this should depend on their conditions and goals.

Second, physiotherapy clinicians were concerned about the late timing of receiving the feedback report following each movement analysis session, which may lack their time to interpret its findings and share them with individuals during the session. This issue might explain the lack of detailed information documented by clinicians in their notes about individual's movement alterations and how they could be addressed during functional activities. In addition, this could lead to an extra load on clinicians and individuals by extending the time required for the follow-up treatment sessions, which may be considered a cost that must be given up for clinicians to engage in SMAFT. Consequently, clinicians mentioned their preference for holding the movement analysis session and the physiotherapy treatment session on two different days to allow adequate time for the analysis and interpretation of the feedback report. However, this solution may not be acceptable for the individual with knee pain, as extra visits to the clinic for kinematic data collection may prove to be a burden. To the researcher's knowledge, this challenge has not been reported in previous literature. Therefore, this challenge needs to be highly considered in the future development of SAMFT and addressed before testing its feasibility in clinical settings.

The source of the delay in developing the feedback report in relation to the unexpectedly long time required to reprocess the data collected using a high-definition (HD) mode was recognised by the lead researcher (M.F.) during the data collection stage for the first four individuals and discussed with the research supervisors. Two modes could be used to achieve reprocessing: real-time (automatic) or high-definition (HD) mode. HD reprocessing enables a more consistent estimation of the position and direction of each body segment to be obtained by reducing any magnetic distortions that may occur during the data collection process (Schepers et al. 2018). Magnetic distortions were measured within the different sites of the data collection (physiotherapy services at the UHB) and were found to be within acceptable limits. It was therefore agreed to reprocess the data using the real-time (automatic) mode while collecting data for other individuals and sessions. This reduced the amount of time needed for data reprocessing (the mean time taken using the HD mode was 29 minutes compared to 18 minutes for the automatic mode). Clinicians thus received the feedback report earlier and had plenty of time to interpret the report's findings and share them with the individual. Therefore, the future development of SMAFT must ensure that the feedback report is provided to clinicians in an appropriate and timely manner using an automatic mode for data reprocessing.

In summary, all the issues described above may have a negative impact on individuals with knee pain as well as on treating clinicians' clinical practicality and the usability of SMAFT. This was crucial for the outcome of this case study, as it is necessary to identify users' perspectives regarding such elements to inform the best design of SMAFT for use in clinical practice. Thus, these issues should be taken into account in future development and testing, according to the iterative stages of development of the MRC framework.

4.2.6.2.2.5 Ethicality: How SMAFT fits into the users' value systems

Some individuals with knee pain identified a particular issue regarding their value systems. They reported experiencing social embarrassment when wearing the zip-fastened T-shirt, headband, and gloves and when placing sensors on the body within clinical settings and whilst performing functional activities in front of others. It has been suggested that users' acceptability of a sensor technology may be influenced by the context in which the sensors are worn, with individuals feeling self-conscious when being observed by other people (Cancela et al. 2014).

These findings are in agreement with two previous studies that explored the acceptability of wearing sensors in patients with Parkinson's disease and stroke (Simone et al. 2007; Cancela et al. 2014). Simone et al. (2007) found that some stroke participants with hand dysfunction felt embarrassed and felt they looked funny when wearing a sensor-based finger flexion monitor continuously to measure their hand functions in public. Similarly, Cancela et al. (2014) reported that individuals with Parkinson's disease felt more comfortable if the four wearable sensors placed on their lower forearms and legs, in addition to the belt sensor, to continuously monitor symptoms, were not visible to other people. Compared to the current study, individuals with knee pain were required to wear a zip-fastened T-shirt, a headband, and gloves and place 17 wearable IMU sensors on different places on their body, which may make them more noticeable. However, this was only needed for a short time during the movement analysis session and inside the physiotherapy department. Therefore, this needs to be explored further with a larger sample and addressed before testing SMAFT's feasibility in clinical practice.

There are two suggested ways of reducing people's apprehension. The first suggested method is to make the wearable sensors less visible by hiding them within clothing.

However, this requires sensors' transmission and accuracy to be tested if they are worn under clothes. Another method is to use and place the sensors on the lower limbs and sacrum only in cases when the kinematics of the upper body and trunk do not need to be analysed. Using only lower limb sensors can reduce an individual's embarrassment, as the zip-fastened T-shirt, headband, and gloves are not required to be worn. Therefore, future development of SMAFT should consider these suggestions.

In summary, the stigma associated with wearing sensors in front of other people in clinical settings may reduce SAMFT's clinical usability among users (individuals with knee pain), and two possible solutions to resolve this issue were discussed. However, further investigation to assess the impact of this on users' acceptability is required, and an evaluation of the effectiveness of the proposed solutions as a way to improve their acceptability needs to be performed.

4.2.6.2.2.6 Summary of qualitative findings discussion of TFA constructs

In summary, the TFA informed our understanding of the phenomena of interest, with themes incorporating concepts relevant to the seven constructs of the TFA. Satisfying all acceptability constructs can provide a comprehensive overview of users' perspectives when using SMAFT within clinical practice. Based on the constructs discussed, SMAFT is considered an acceptable toolkit for use alongside physiotherapy (TAU) within clinical practice from the perspective of benefits. However, some challenges regarding SMAFT's practicality and usability were reported. These included the stigma of wearing sensors in front of other people, the lack of time taken for clinicians to interpret the kinematic report's findings, and challenges understanding the report's findings for the individuals with knee pain. Therefore, the constructs of 'Ethicality', 'Burden' and 'Opportunity cost' to which these challenges relate require further investigation.

4.2.6.2.3 SMAFT and the Behaviour Change Wheel

As previously discussed, the benefits of using SMAFT alongside physiotherapy (TAU) in terms of improving individuals' understanding and awareness of movements and improving their motivation and adherence to exercise provided an insight into its advantage in changing an individual's rehabilitation behaviours. Therefore, discussing the aforementioned functionalities and benefits of SMAFT in accordance with the Behaviour Change Wheel (BCW) model is needed.

Human behaviour change has been highlighted as a key ingredient for a successful intervention, as changing behaviours can result in positive outcomes (Michie et al. 2011). The Behaviour Change Wheel (BCW) was developed by Michie et al. (2011) to guide behaviour change interventions. Based on BCW, three stages need to be considered when designing a behaviour change intervention (Michie et al. 2011). The first stage is to understand behaviour which the COM-B model identifies as a product of interactions between conditions of capability, motivation, and opportunity.

The second stage of BCW requires the identification of intervention options for each component of the COM-B model (capability, opportunity, and motivation) by selecting from a predefined list of functions and policy categories of the BCW (Michie et al. 2011). The selection of function options in the current study was based on their relevancy and tendency to change the exercise behaviour within each component. Furthermore, the examples of selected functions were informed by the findings of the interviews with individuals with knee pain regarding the identified benefits of using SMAFT and how these affect their exercise behaviour (examples of these were discussed in the previous section). The following table presents the intervention functions in relation to the BCW, examples of functions created by SMAFT, and their effect on exercise behaviour (Table 38).

The last stage of the BCW involves identifying content and implementation options (Michie et al. 2011). In this stage, behaviour change techniques (BCT) should be considered by allocating the most effective and practised techniques that have a tendency to change exercise behaviour in individuals with knee pain. Michie et al. (2013) developed a standardised structured taxonomy of 93 BCTs categorised into 16 groups. These BCTs can be utilised to support the functions of SMAFT identified in the current study in order to target exercise behaviour and describe the content.

Overall, although BCW was not used from the outset to guide the development of SMAFT in this study, discussing the functions of SMAFT alongside the BCW model suggested the potential use of SMAFT as a behaviour change intervention. Hence, this should be considered in future studies, and the development of SMAFT should be guided by the BCW as recommended by the MRC framework to identify and use theory to develop the intervention (Skivington et al. 2021).

Table 38: Exercise behaviour, intervention function options by the BCW and function developed by SMAFT within the COM-B model's components

COM-B model	Intervention functions identified by BCW	Functions mapped from BCW adapted from SMAFT context	Effect of functions on exercise behaviour
Physical Capability	- Training - Education - Persuasion	- Individualised exercise plan - Avatar videos and feedback reports showing movement during exercises	- Use appropriate exercises - Improve the physical skill to perform the exercises correctly
Psychological Capability	- Education - Persuasion	- Avatar videos and feedback reports showing movement during exercises - Education and discussion with the clinician about movements	- Understand movement alterations associated with exercises based on objective tool - Understand what exercise is more important based on kinematic alteration identified - Understand the link between exercise and recovery
Physical Opportunity	- Environmental restructuring - Enablement	- Receiving movement analysis session at the same location of physiotherapy treatment session - Receiving a Feedback report following each movement analysis session	- Access to equipment (movement analysis session) - Access to kinematic information
Social Opportunity	- Persuasion	- Shared monitoring with clinicians	- Attending physiotherapy

Reflective Motivation	- Incentivisation - Persuasion - Education	- Monitoring progress by visual materials (avatar videos and feedback report that can show graphs comparing kinematic waveform over sessions)	- Performing exercises to achieve goals - Individual's belief that the exercises given are appropriate as they based on an objective movement analysis tool
Automatic Motivation	- Education - Incentivisation	- Education and discussion with clinician about movements	- Performing exercises habitually

Abbreviations: BCW = Behaviour Change Wheel, COM-B = capability, opportunity, and motivation components of Behaviour Change Wheel model

4.2.6.3 Research objective 2 - To describe the content of altered movement patterns identified in individuals with knee pain who used SMAFT

The interpretation findings of the feedback reports identified varied altered movement patterns at lower limb joints in the sagittal and frontal planes across all individuals with knee pain. Most of the movement alterations identified were not consistent across individuals. This finding may be supported by the pain adaptation theory discussed previously in the current thesis, which suggests that inconsistent non-stereotypical motor adaptation behaviours can be a result of pain or tissue injury (Hodges and Tucker 2011). These motor adaptations can include the redistribution of activity within and between muscles and alterations in movements (Hodges and Tucker 2011). These adaptations are performed to protect the affected tissue and reduce the pain by unloading the affected part, which can be beneficial over a short-term period (Hodges and Tucker 2011). However, these short-term protective benefits might lead to negative long-term consequences when the movement alterations persist over a long period of time (unnecessary movement alterations) (Hodges and Tucker 2011). These negative consequences can reduce physical activity levels and increase the risk of further pain (Hodges and Tucker 2011). Examples of some consistent altered movement patterns identified in the current study are discussed below in turn according to pain adaptation theory.

A few altered movement patterns were found to be consistent across individuals during functional task performance. Individuals with knee pain appeared to perform functional tasks with reduced knee flexion and ankle dorsiflexion movements during stance (when individuals load the affected limb). This finding of reduced sagittal movement at the knee and ankle joints is in line with the findings of previous studies on gait (McCarthy et al. 2013; Rahman et al. 2015; Ismailidis et al. 2020; van der Straaten et al. 2020), jump (Nunes et al. 2019; Baellow et al. 2020), and stair negotiation (Iijima et al. 2018; van der Straaten et al. 2020). Reduced knee flexion has been found to be accompanied by an increase in the thigh and leg muscle coactivation during the stance phase of the walking task (Childs et al. 2004). Therefore, these combined alterations in kinematics and muscle activation might lead to stiff movements in the lower limb joints and reduce pain (Childs et al. 2004; Hodges and

Tucker 2011), which was evident in the current study findings. This was supported by a study, conducted by van der Straaten et al. (2020), that reported a significant relationship between the reduced knee flexion movement observed in individuals with knee OA and pain. However, despite this short-term benefit of pain reduction, the sustain of these alterations over time may lead to an increase in the joint compressive load, which might reduce the femoral contact area where the load is applied, causing further pain, and reducing physical function (Childs et al. 2004). Therefore, a future robust clinical trial needs to investigate whether SMAFT can permanently modify the altered movement patterns identified in individuals with knee pain.

Another consistent altered movement pattern identified across individuals and functional tasks was increased ankle adduction when bearing load on the affected limb. Individuals seemed to bear weight on the affected limb with a toe-in position (increased ankle adduction and foot internal rotation). It has been suggested that increased toe-in angle might be performed by individuals with knee OA as a compensatory movement when walking, as it decreases the load (KAM) on the medial compartment during the early stance phase of the gait cycle and thus reduces pain (van den Noort et al. 2013). This could be supported by using feedback movement retraining in the treatment of individuals with knee OA to increase toe-in angle (Shull et al. 2013a; Booij et al. 2020). Toe-in gait laterally shifts the centre of pressure (COP) and reduces KAM (Shull et al. 2013a; Booij et al. 2020). However, despite the potentially reduced load caused by increasing ankle adduction, it may increase the risk of other lower limb injuries, such as PFPS, medial tibial stress syndrome, and ankle sprain (Douglas Gross et al. 2011; Neal et al. 2014). It has been proposed that increased ankle adduction can lead to increased internal rotation movements at the tibia with respect to the talus (Boling et al. 2009). This in turn could be associated with increased femoral rotation movement causing patellar malalignment and increased compression on the lateral facets of the patella (Boling et al. 2009). Therefore, this movement alteration could be associated with further knee pain during the performance of functional activities, which was observed in the current study.

Pain adaptation theory recommends that clinical treatment should establish a plan to restore optimal motor control and modify motor adaptations (redistribution of muscle activity and alteration of movement) (Hodges 2011; Hodges and Tucker 2011). In the current study, physiotherapy clinicians commonly prescribed exercises that aim to improve the function of specific muscles in order to modify muscle activity redistribution and improve movement patterns based on kinematic feedback provided by SMAFT. This was obvious by prescribing strengthening, stretching, and proprioception exercises to target muscles around the knee joint, such as the gluteal, quadriceps, hamstrings, and calf muscles. Furthermore, the findings suggest that SMAFT helped individuals to improve their understanding and awareness of movements, which may enhance their motor learning of a more optimal movement pattern (as discussed previously in Section 4.2.6.2.2) (Schmidt and Lee 2019; Charlton et al. 2021). In addition, SMAFT was advantageous in terms of objectively identifying altered movement patterns, informing clinical decisions and tailoring treatment. However, this could not be confirmed due to the lack of detailed information documented in clinicians' notes. Hence, this needs to be tested in future studies. Overall, SMAFT gave insights into its use to modify the motor adaptations that occur at different stages and levels of the nervous system, as suggested by pain adaptation theory (Hodges 2011; Hodges and Tucker 2011). However, this could not yet be confirmed, as SMAFT still requires more varied iterative stages of development.

Moreover, altered movement patterns might result from other factors, such as muscle weakness (Lewek et al. 2002; Bennell et al. 2004). There is a high incidence of weakness in the quadriceps muscles in individuals with knee OA (Slemenda et al. 1997; Hassan et al. 2001; Lewek et al. 2004). The role of the quadriceps during the performance of functional activities is obvious, especially during the weight acceptance phase (Bennell et al. 2004). For example, during gait, the quadriceps are responsible for eccentrically controlling knee flexion movement and absorbing shock at the knee during the stance phase (Lewek et al. 2004). Weakness in the quadriceps muscles can lead to an insufficient reduction of the large compressive forces at the knee, and thus an increase in impulsive loading may be produced (Mikesky et al. 2000). Reduced knee flexion during the weight acceptance phase of gait has been found to be associated with quadriceps muscle weakness in individuals with knee pathologies (Lewek et al. 2002). A comparison of affected and non-affected limbs in individuals with knee OA found significant quadriceps weakness in the affected limb, which is associated with the asymmetrical alteration of reduced sagittal knee flexion in both limbs during the stance phase of gait (Mizner and Snyder-Mackler 2005). This was in agreement with the findings of the current study as the movement patterns of the affected limb were compared to the non-affected limb. Therefore, a potential weakness of the quadriceps could be the underlying cause of the reduced knee sagittal movement. This is very important in terms of rehabilitation as exercises are required to improve the strength of the weakened quadriceps. More importantly, unilateral strengthening exercises need to be carried out to address the weakness in the affected limb, which was observed in the current study.

4.2.6.4 Strengths and limitations of the study

4.2.6.4.1 Strengths of the study

The current study has several strengths that may add credibility to the findings. Firstly, the use of a mixed-methods study design gave greater credibility and insight than using a stand-alone quantitative or qualitative approach. For instance, through integrating the findings from the interpretation of feedback reports and clinicians' notes, a complete picture of the acceptability of SMAFT within physiotherapy services in a UHB was demonstrated. This may add to the acceptability dilemma of exploring the use of SMAFT in depth with a qualitative component.

Secondly, a case study design allowed users' acceptance of SMAFT to be explored in depth within a real-world context (physiotherapy service in a UHB) from multiple sources of evidence. In addition, as the current study employed a single rather than multiple case study design to explore acceptability, this allowed research to be focused on the case selected to explore acceptability more deeply and comprehensively. Consequently, future research could build on the findings of this single case study by exploring the acceptability of SMAFT in further cases and comparing the findings.

A further strength of the study was the originality of exploring the acceptability of this type of toolkit that is used alongside physiotherapy (TAU). The unique aspect of this involves investigating users' acceptability (from actual experience) towards providing and sharing kinematic feedback information given by wearable IMU sensors within the clinical practice. Moreover, the acceptability of SMAFT within clinical practice was explored from two different perspectives (individuals with knee pain and treating clinicians). It is important to investigate both users' perspectives on the design, usability, and practicality of SMAFT prior to its potential implementation in clinical settings (Papi et al. 2015; Papi et al. 2016).

Finally, the acceptability of SMAFT in the current case study was explored in line with the TFA. Employing this framework's constructs allowed for a comprehensive understanding of users' acceptability of SMAFT by exploring their perspectives from multiple constructs. It is therefore recommended that future studies related to the acceptability of SMAFT consider this framework and its seven constructs.

4.2.6.4.2 Limitations of the study

Several limitations that might impact the findings of this study should also be discussed. Firstly, the physiotherapy clinicians who participated in the current study were not provided with the standardised reporting template used for interpreting waveform graphs within the feedback reports because of the time required to use it. It would be advantageous for clinicians to use this template to improve the consistency of the reporting of the altered movement patterns identified amongst clinicians and provide adequate detail about the type, amount, and timing of the movement alterations. This issue was obvious when clinicians' notes were observed and analysed, as there was inconsistent reporting of the altered movement patterns identified and the rich description of these alterations was lacking. Therefore, it is very important to improve reporting consistency by providing clinicians with a standardised template to ensure they use SMAFT in an effective way. To achieve this, further investigations regarding how to implement it and evaluations of the time required to use it are needed.

Moreover, in this early stage developmental study, the lead researcher (M.F.) was responsible for setting up the equipment, collecting the kinematic data, and creating movement analysis feedback reports. The lead researcher has experience with clinical movement analysis and has received adequate training to utilise the sensor-based movement analysis system and develop a feedback report. It is as yet unclear who would be the most appropriate person to conduct these functions, since investigating this is beyond the scope of the current study. Therefore, this should be considered in future studies concerning SMAFT's development.

Furthermore, the clinicians who participated in the current case study have a range of previous experience describing and interpreting the waveform graphs included in the feedback report. It is thus unclear whether clinicians with less or no experience can adequately interpret the kinematic findings provided. As a result, this suggests clinicians should be trained before using this toolkit. Detailed information regarding training is presented in the current chapter, section 4.2.6.5.

Finally, a potential limitation was the lead researcher conducted all interviews with different types of participants (individuals with knee pain and clinicians) and coded and reviewed the transcripts. It is understood that using the lead researcher as an interviewer might affect the responses of participants by inducing more positive answers when the interviewees are aware of the study's purpose and the role of the lead researcher. However, in this PhD study, it was not feasible to employ an interviewer who was unknown to participants due to the limits of time and funds. In order to reduce the impact of the lead researcher on participants, participants were encouraged at the beginning of each interview to give answers that reflected the reality of their perceived experience. In addition, involving research supervisors in the process of coding and reviewing some interviews and conducting regular meetings with them might promote criticality and challenge assumptions.

4.2.6.5 SMAFT development

A better understanding of how SMAFT should be designed for clinical practice was gained from the challenges highlighted by its users regarding its clinical usability and practicality. The chief challenges affecting its usability were the lack of time available for clinicians to interpret the report's findings, and to discuss them with individuals, and limited understanding the findings among individuals with knee pain. Moreover, the stigma of individuals wearing sensors in the presence of other people; and the frequency and spread of the movement analysis sessions, were indicated to be challenges for the clinical practicality of SMAFT. All of these challenges were discussed in detail, including their suggested solutions, in the current chapter, section 4.2.6.2.2.

In addition, further barriers impacting the practicality and usability of SMAFT beyond the scope of the current case study should be indicated. These barriers include determining the most appropriate person to deliver SMAFT, the time needed for clinicians to use a standardised template, and establishing whether clinicians with less or no experience can adequately interpret the kinematic findings provided. All of these challenges were highlighted in the "limitations of the study" section above (section 4.2.6.4.2).

These challenges and barriers suggested a need for further evaluations and refinements to SMAFT. Therefore, a refined version was developed using the Template for Intervention Description and Replication (TIDier) checklist, which guides design to assure completeness and quality when reporting an intervention description (Hoffmann et al. 2014). The TIDier framework can provide the appropriate information to assist in translating evidence into clinical practice. The TIDier checklist consists of 12 items about who, what, when, where, how, and why the intervention is used. These items enabled the collection of complete and sufficient information regarding the delivery of SMAFT, without which clinicians may not be able to transfer the knowledge obtained into clinical practice in a reliable manner (Hoffmann et al. 2014). The complete TIDier template for SMAFT is presented in Table 39. It should guide future developmental studies in the reliable use of SMAFT.

Table 39: Description of SMAFT using criteria from the TIDieR checklist

TIDier checklist criteria	Description
Intervention name	Sensor-based Movement Analysis Feedback Toolkit (SMAFT)
Theory	SMAFT intervention functions were linked to individual with knee pain exercise behaviours by discussing the components of Behaviour Change Wheel (BCW) (Michie et al. 2014).
What intervention (procedures) and purposes	SMAFT is a portable movement analysis system, involving wearable IMU sensors, a feedback report and avatar videos based on movement analyses, and a standardised reporting template. The feedback report included temporo-spatial and waveform angular kinematics of lower limb joints in the sagittal and frontal planes during the movement cycle of functional exercises. The purpose of using SMAFT alongside physiotherapy (TAU) is to enhance patient-centred care, guide clinical decision-making, and monitor progress.
Who deliver	- Investigating the most appropriate person responsible for setting-up equipment, collecting data, and developing feedback reports was beyond the scope of the current study. Currently, a trained clinical assistant can carry out this component, although further studies are needed to investigate and evaluate the effectiveness of this. - The use of kinematic data provided by SMAFT should be achieved by: • Trained physiotherapy clinicians working in a musculoskeletal physiotherapy setting (see training component below). • Trained individuals with knee pain involved at all stages of their care (see training component below).

How (mode of delivery)	- Individuals with knee pain received movement analysis sessions alongside their physiotherapy (TAU). Individuals are instructed to perform different functional exercises while their movements are recorded by the IMU sensors. - Following each session, a feedback report is sent in a PDF format to the treating physiotherapy clinician, and avatar videos are displayed on a laptop screen. The clinicians are required to print out feedback reports and attach them to individuals' files. - The clinicians perform their own analysis and interpretation of the feedback report and avatar and share findings with their individuals. In response to these findings, the clinicians tailor individuals' treatment plans and monitor progress. - The individuals with knee pain use these kinematic findings to improve their understanding and awareness of movements and consequently enhance their centre-care management.
Where (location of delivery)	Physiotherapy service
When (timing of delivery)	At the first consultation session, SMAFT is introduced by the physiotherapy clinician, and movement analysis sessions are then scheduled for the following treatment sessions as agreed with the individuals with knee pain.
How much (frequency, spread, how long, schedule)	- The number of movement analysis sessions and their distribution over the treatment course should be individualised and determined based on a mutual decision between the physiotherapy clinician and the individual with knee pain, according to the individual's progress and the treatment's goals. - Movement analysis session is scheduled on the same day of the treatment session. Individuals are asked to attend an hour earlier than the treatment session for the first movement analysis session and half an hour earlier for the following sessions.
Tailoring (individualisation)	Individualised treatment plan is produced by the physiotherapy clinician.

Modifications	- Functional tasks performed by individuals with knee pain should be individualised and selected by the treating physiotherapy clinician based on the individual's condition and progress. - In the event that an individual is not happy to wear sensors in front of people, IMU sensors should preferably be covered by loose clothes to make them less noticeable and reduce embarrassment. Alternatively, lower limb sensors can only be used when the kinematics of the upper limbs do not need to be analysed. - Kinematic data collected by the Xsens software should be reprocessed in real-time (automatic) mode in order to offer physiotherapy clinicians adequate time to use the reporting template, interpret the feedback report's findings, and discuss them with the individuals. - Adequate/additional time is required for clinicians to use the standardised template for interpreting waveform graphs within the feedback reports. Further studies are needed to investigate and evaluate this issue.
Training	This case study suggests a need for training physiotherapy clinicians and individuals with knee pain on how to appropriately use SMAFT and integrate it into physiotherapy (TAU). Hence, a detailed description of the content of the training in addition to its methods and amount is shown in Table 40.
Intervention fidelity	- It is anticipated that individualised treatment plans will be modified by the physiotherapy clinician at least once along the individual's treatment course. Therefore, fidelity can be assessed by monitoring the modified treatment plans (timing and content). - Assessing individuals' adherence to movement analysis sessions and investigating the reasons for non-attendance.

Abbreviations: BCW = Behaviour Change Wheel, IMU = Inertial Measurement Unit, SMAFT = Sensor-based Movement Analysis Feedback Toolkit, TIDier checklist= the Template for Intervention Description and Replication checklist, TAU = treatment as usual

Table 40: Training for Physiotherapy clinicians and knee pain individuals in future trials

	Physiotherapy clinicians	Individuals with knee pain
Purposes of training	- Enhance ability to analyse, interpret and discuss feedback report findings. - Improve skills to adequately use the standardised reporting template. - Application of SMAFT into individual's treatment. - Improve skills to adequately train individuals how to use SMAFT.	- Improve use and understanding of the feedback report components and findings. - Improve familiarity with the procedures of movement analysis session.
Assessment of training success	- Recording of screen and audio of task completion using SMAFT for mock individual with knee pain treatment scenario. - Monitoring physiotherapy clinicians completion of standardised reporting template.	
Content of training	- Introduction of SMAFT. - Interpreting feedback report and avatar findings using the standardised template. - Developing individualised treatment plans. - Discussing findings with individuals. - Training individuals.	- Introduction of SMAFT. - Interpreting feedback report and avatar findings.
Methods of delivery	- Practical task. - Feedback report's interpretation guidelines. - Q&A session with the lead researcher.	- Video presentation (movement analysis session procedures and feedback report interpretation). - Feedback report's interpretation guidelines.
Amount of training	Half day	30 minutes

Abbreviations: Q&A = Question and Answer, SMAFT = Sensor-based Movement Analysis Feedback Toolkit

4.2.6.6 Implications

4.2.6.6.1 Research implications

The findings of the current study suggested a need for further investigations of SMAFT, particularly to determine the most appropriate person to deliver SMAFT, and the time needed for clinicians to use the standardised template for adequately interpreting the kinematic data presented in the feedback report. Investigating these particular issues is vital if we are to satisfy all the components of TIDier checklist used to define the refined version of SMAFT comprehensively.

Furthermore, in keeping with the MRC's guideline recommendations (Skivington et al. 2021), an evaluation of SMAFT's cost-effectiveness is warranted to comprehensively complete the development stage and move on to the next stage (feasibility). As a part of the feasibility evaluation, which is beyond the scope of the current PhD thesis, the potential impact of SMAFT on modifying individuals' exercise behaviours needs to be examined comprehensively using the BCW framework. In addition, users' acceptability of the refined SMAFT should be assessed through an in-depth investigation of all the TFA constructs, so as to give a comprehensive perspective on its clinical acceptability. Moreover, a feasibility study should be performed to investigate whether SMAFT is used as planned within clinical practice (fidelity). As this study highlighted additional insights gained from conducting a mixed-methods design, it is recommended that the mixed-methods approach be used for any further evaluation of SMAFT.

4.2.6.6.2 Clinical implications

Integrating SMAFT into physiotherapy (TAU) for individuals with knee pain within clinical practice could be advantageous for users (clinicians and individuals with knee pain), as previously discussed in section 4.2.6.2.2.3. However, this should be taken with caution, as SMAFT still requires further evaluation of its effect on physiotherapy treatment using more robust studies. Also, the practicality and usability of SMAFT within clinical practice raises a number of limitations, suggesting the need for further refinements and evaluations. Therefore, in adherence with the MRC framework, the use of SMAFT within clinical practice should be warranted until further development is achieved and its iterative stages completed.

4.2.7 Conclusion

The current mixed-methods case study aimed to explore the acceptability of SMAFT by users within the physiotherapy services of a UHB. The findings demonstrated a complete picture of SMAFT's acceptability within clinical practice by integrating quantitative and qualitative data gained from multiple sources of evidence. However, although the use of SMAFT alongside physiotherapy (TAU) within physiotherapy clinical practice seemed acceptable in terms of its benefits, usability, and practicality, this exploration yielded important information regarding the design and delivery of SMAFT. Thus, it is apparent from the collected data that additional refinement and testing should be done in accordance with the MRC framework prior to engaging in further development. Thus, the TIDier checklist template was used to explicitly define and describe a refined version of SMAFT, which can then be implemented to assist with future developmental studies.

Chapter 5: Conclusion

5.1 Introduction

This final chapter summarises the main results of the research studies conducted across the two phases of this PhD thesis. This is followed by highlighting the strengths and limitations of the entire PhD thesis. Finally, the key implications and recommendations from this PhD thesis for education, clinical practice, and future research are presented. Although each study across the two phases of this PhD thesis has its own strengths, limitations, and implications, the general strengths, limitations, and implications of the project as a whole are discussed in this chapter.

5.2 Thesis summary

The overall aim of this PhD thesis was to further develop and evaluate the acceptability of a sensor-based movement analysis feedback toolkit (SMAFT) for clinical practice using an iterative process. The MRC guidelines for developing and evaluating complex interventions (Skivington et al. 2021) provided the theoretical structure for the current PhD thesis.

This PhD thesis comprised two phases. Phase I concerned a staged development of SMAFT and consisted of one developmental study. The findings in the study supported the development of SMAFT by creating a standardised reporting template to ensure accuracy and consistency during the process of feedback report interpretation by SMAFT's users. This study, in addition to previous research in this field (highlighted in Chapter 3, section 3.2), was essential to inform the components of SMAFT, and involved developing a preliminary version of it. SMAFT is a portable movement analysis system that consists of body-worn inertial sensors, a feedback report based on movement analysis, and a standardised reporting template.

Phase II investigated the design and delivery of SMAFT (defined in Phase I) within a real-world environment by engaging stakeholders, as recommended by the MRC guidelines

(Skivington et al. 2021). Therefore, the users' acceptability of SMAFT was explored within a case study of physiotherapy services in a UHB (Phase II). The findings of the study in Phase II indicated that using SMAFT alongside physiotherapy (TAU) in clinical practice appeared acceptable, as it was regarded as beneficial, usable, and practical. Integrating quantitative and qualitative components gave a more comprehensive view about SMAFT's acceptability within clinical practice. However, some challenges regarding SMAFT's clinical practicality and usability were indicated by users. Therefore, the findings recommended some refinements for the design and delivery of SMAFT prior to further testing. Therefore, the refined SMAFT (design and delivery) was clearly described using the TIDier checklist. Also, recommendations for the next stage of SMAFT development in line with the MRC framework are presented later in this chapter.

5.3 Strengths and limitations

5.3.1 Strengths

The use of the MRC framework for the development of complex interventions (Skivington et al. 2021) in guiding the development of SMAFT was a major strength of the current PhD thesis. Following the MRC recommendations ensured that SMAFT was systematically developed in four iterative stages. As the current PhD thesis comprises the development phase of the MRC framework, the recommended elements within this phase (identifying key uncertainties, considering context, engaging stakeholders, developing programme theory, and refining intervention) were considered (Skivington et al. 2021). Adhering to these recommendations ensured that the development of SMAFT was achieved based on the best available evidence.

Another strength considered in the current PhD thesis was the inclusion of the TIDier checklist template for describing SMAFT. By following this checklist's items, SMAFT was clearly and adequately described (Hoffmann et al. 2014). This step was crucial to be conducted at this stage of SMAFT's development to ensure its consistent use (design and delivery) during the next development and feasibility trials. In case of potential success of SMAFT through these trials, using TIDier will ensure that the evidence is translated into clinical practice in an adequate manner and that physiotherapy clinicians can use SMAFT consistently.

Furthermore, the use of both quantitative and qualitative approaches to inform the development of SMAFT was another strength of this PhD thesis. The use of a mixed-methods approach in designing the study in Phase II added more depth to the exploration of SMAFT's acceptability from users' perspectives. Integrating both quantitative and qualitative components demonstrated a complete picture of acceptability for using SMAFT within physiotherapy clinical practice. Therefore, the inclusion of different research approaches to address varied objectives increased the robustness of the development of SMAFT.

5.3.2 Limitations

Comparing the angular waveforms for the affected limb versus the non-affected one, for identifying altered movement patterns within the feedback reports in the current PhD thesis, helped interpret the feedback report's findings and thus individualise treatment plans. It would also be useful to look at this against a reference for an averaged kinematic waveform adapted from a biomechanical database that represents normal and abnormal movement patterns for healthy and individuals with knee pain during different functional tasks. However, this was not feasible during the current PhD project due to the timeline and funding. This should be considered in the future and may be added to the kinematic waveform graphs presented in the feedback report.

5.4 Implications and recommendations

The main recommendations from the current PhD thesis and their implications for education, clinical practice, and research are discussed below.

5.4.1 Education

Reviewing the literature for this PhD thesis highlighted the importance of using kinematic feedback provided by IMU sensor technology alongside physiotherapy (TAU) within the clinical practice in order to address the need for individualised physiotherapy treatments for individuals with knee pain. There is increasing evidence about the accuracy, consistency, and usefulness of this technology outside a controlled laboratory environment (Tadano et al. 2016; Al-Amri et al. 2018; Teufl et al. 2018; van der Straaten et al. 2019). For example, this PhD thesis added to the body of evidence about the acceptability of using this technology to provide kinematic information for use alongside physiotherapy (TAU). However, it has been indicated that the implementation of technologies in clinical practice may be limited by insufficient knowledge and confidence about their use (Demain et al. 2013; Hughes et al. 2014). This suggests a need to increase awareness of such technologies in education. Including information about varied technologies in the undergraduate and postgraduate curriculum may increase knowledge and awareness about them and consequently facilitate their potential future use in clinical settings.

5.4.2 Clinical practice

This PhD thesis highlighted some points that need to be considered in clinical practice. First, SMAFT should be considered as an alternative to the traditional 3D optoelectronic motion capture in clinical practice due to its accuracy, consistency, and comprehensiveness in quantifying kinematics in all planes of movement during dynamic tasks. In addition, SMAFT has the advantage of providing a feedback report presenting kinematic data in a waveform format and an avatar demonstrating an individual's movement during functional tasks, which could be used as a visual means to analyse, discuss, and treat altered movement patterns within clinics.

Moreover, the standardised reporting template developed in the current PhD thesis should be considered by physiotherapy clinicians when interpreting kinematic waveform graphs. This could improve clinicians' accuracy and consistency when interpreting kinematic waveforms and thus avoid variations in relevant clinical decision making. However, investigating its clinical usability, particularly for the time required to be used by physiotherapy clinicians, is needed.

In addition, the results showing the need for individualised physiotherapy treatment for people with knee pain, combined with the results of users' acceptability of SMAFT, suggest that clinicians should consider the use of SMAFT alongside physiotherapy (TAU) within clinical practice. However, caution should be exercised as further developments of SMAFT and evaluation of its effect on physiotherapy treatment are still needed (feasibility testing and implementation).

5.4.3 Future research

There are several recommendations for future research considering the development of SMAFT. First, the current PhD thesis suggested a need for further modifications to SMAFT, and a refined version of SMAFT was thus explicitly defined. This refined SMAFT should be used in future developmental studies.

Moreover, this PhD thesis made some recommendations for the next version of the feedback reports given by SMAFT. It is recommended that an electronic version of the movement analysis feedback report is established. This can allow users to annotate and draw to highlight the amount, nature, and timing of the altered movement pattern. In addition, avatar videos can be attached to the waveform graphs and presented on one platform to easily illustrate the movement cycle for each activity. This electronic version of a feedback report is suggested to make it easier to use the kinematic waveform data and enhance the interpretation process. If this new version of the feedback report is developed, further research to test its usability and practicality will be required.

Also, in keeping with the MRC's guideline recommendations (Skivington et al. 2021), the findings of the two studies in this PhD thesis and the findings of previous work related to the development of SMAFT informed the first developmental stage of the MRC framework. Most of the core elements of the developmental stage suggested by this framework were satisfied. However, one element concerning the economic considerations of SMAFT still needs to be evaluated. This can be conducted by assessing the costs and benefits of using SMAFT in clinical practice. Multiple frameworks can be used to guide economic evaluation, such as a cost-benefit analysis and a cost-sequence analysis.

Once all the core elements are satisfied and the development stage is complete, an evaluation of the feasibility of SMAFT in clinical settings is recommended. Although this is beyond the scope of the current PhD thesis, the aim should be to determine whether it is feasible to use SMAFT alongside physiotherapy (TAU) for individuals with knee pain within clinical settings. It is recommended that different aspects of feasibility, including recruitment and retention rates, users' engagement, adherence to the study protocol, the incidence of adverse effects, and intervention fidelity, be examined. In addition, as a part of this feasibility study, the acceptability of the refined version of SMAFT should be evaluated by employing the TFA to ensure comprehensiveness by involving various acceptability constructs (Sekhon et al. 2017). Furthermore, considering the Behaviour Change Wheel (BCW) is highly recommended to comprehensively understand the advantage of SMAFT in changing individuals' exercise behaviours.

In conclusion, this PhD thesis has contributed to the development of SMAFT for use alongside physiotherapy (TAU) for individuals with knee pain within the context of clinical practice. The findings suggested a need for further refinement and evaluation of SMAFT, specifically in terms of its practicality and usability. A refined version of SMAFT was therefore comprehensively defined using the TIDier checklist. Future research should also be undertaken alongside the development of SMAFT, in line with MRC framework guidelines.

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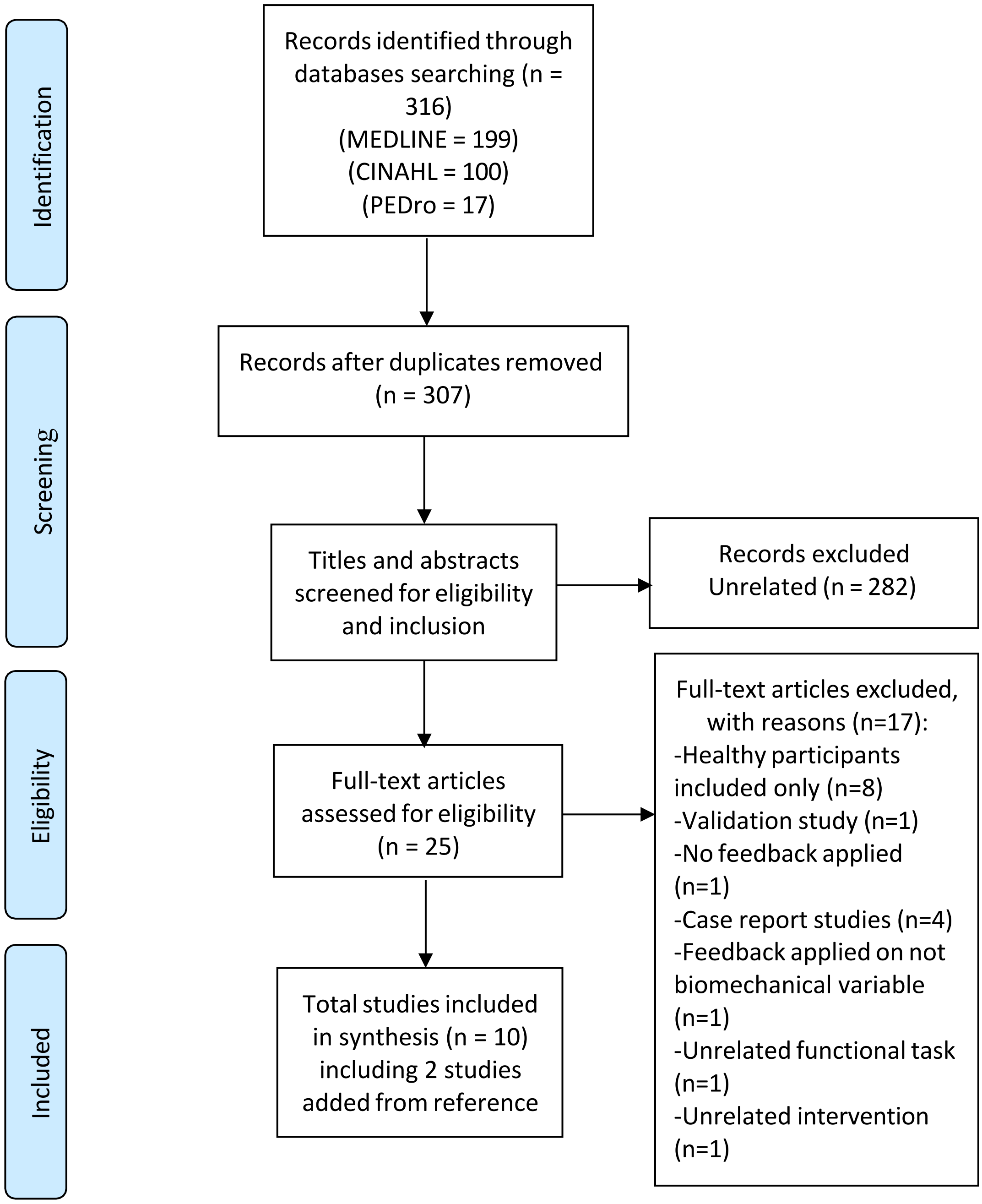
Appendices

Appendix A: An example of a PRISMA flow diagram presenting the search and refinement processes applied to the studies related to the search strategy of feedback and altered movement patterns



Appendix B: Comparisons between Using a 2D Motion Analysis Method and a Sensor-based 3D Movement Analysis System for Assessing the Lower Limb's Kinematics during Several Functional Activity Tasks

1. Introduction

It is unclear whether movement analysis, which is provided by the technology involving inertial sensors, has a role to play in clinical practice. Thus, it is essential to compare traditional movement analysis methods in clinics (2D video analysis) with sensor-based 3D movement analysis. To the best of the researcher's knowledge, this has not been done (using IMU sensors as a 3D movement analysis method to compare angular kinematics with a 2D video analysis). Hence, evaluating the correlation and agreement between a 2D video analysis and a 3D movement analysis system obtained by IMUs to quantify lower limb angular kinematics in different planes is needed. This needs to be conducted during a battery of functional activities with different levels of challenge, ranging from a double leg support task (DLS) to a single leg task (SLS), to a high-speed complex task (SLDH).

1.2 Aim

The aim of this study was to examine the correlation and agreement between sensor-based 3D movement analysis and camera-based 2D video analysis when quantifying lower limb joint angular kinematics during several dynamic functional tasks.

1.3 Hypotheses

Based on the previous literature (Gwynne and Curran 2014; Herrington et al. 2017; Schurr et al. 2017; Mousavi et al. 2020; Neal et al. 2021), the following hypotheses were developed:

H1: There will be at least moderate correlation (ICC > 0.5) between angular kinematics measured at the hip, knee, and ankle joints in the sagittal plane, as quantified using a camera-based 2D movement analysis and a sensor-based 3D tool during DLS, SLS, and SLDH tasks.

HO1: There will be no correlation between the sagittal plane angular kinematics at the hip, knee, and ankle joints extracted from the 2D video analysis and the kinematics extracted from the sensor-based 3D tool during DLS, SLS, and SLDH tasks.

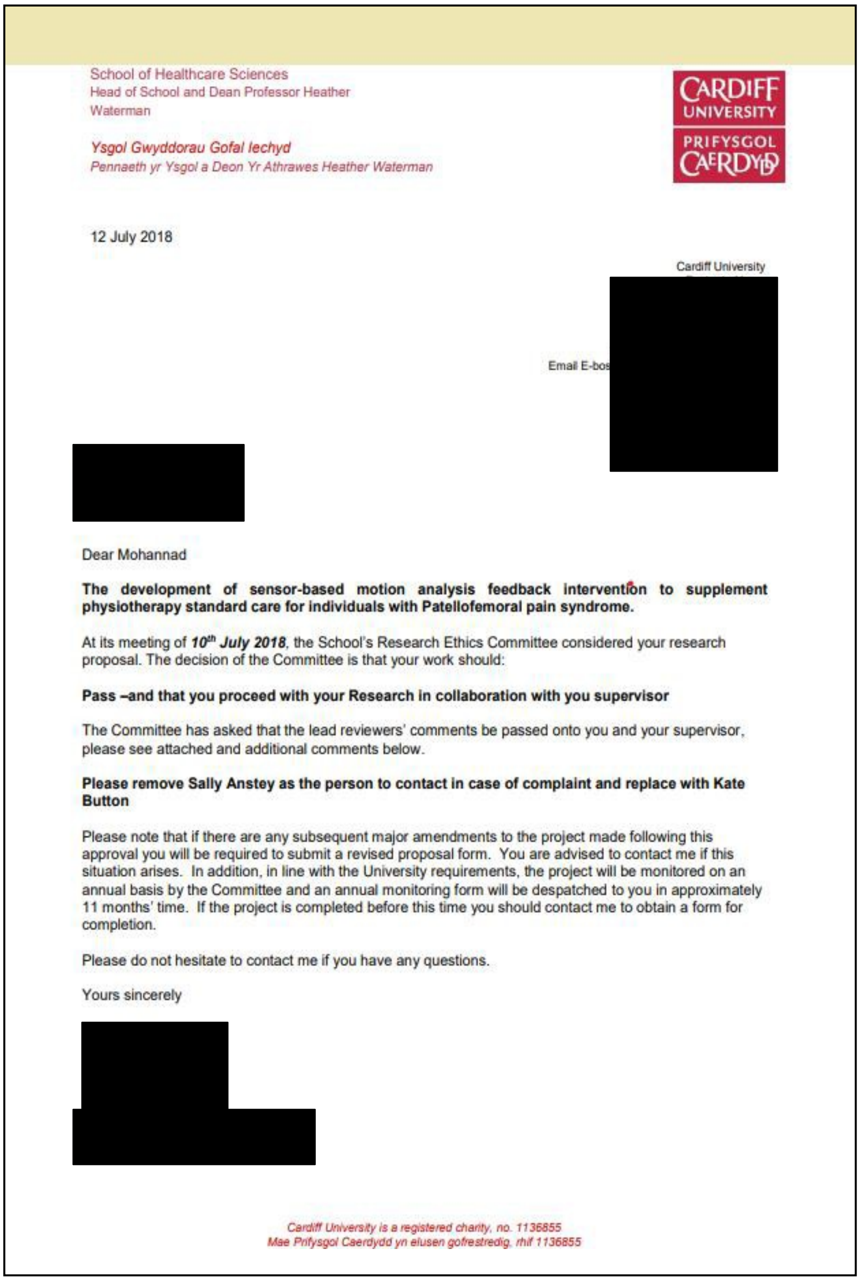
H2: There will be at least moderate correlation (ICC > 0.5) between angular kinematics measured at the hip and knee joints in the frontal plane, as quantified using a camera-based 2D movement analysis and a sensor-based 3D tool during DLS, SLS, and SLDH tasks.

HO2: There will be no correlation between the frontal plane angular kinematics at the hip and knee joints extracted from the 2D video analysis and the kinematics extracted from the sensor-based 3D tool during DLS, SLS, and SLDH tasks.

1.4 Materials and Methods

1.4.1 Study design

A correlational study design was used. This study has ethical approval from Cardiff University, School of Healthcare Sciences (12/07/2018) (Figure 1). In addition, it was a part of the global ethics for the Versus Arthritis Biomechanics and Bioengineering Centre at Cardiff University as approved by the Wales Research Ethics Committee 3, reference number (10/MRE09/28).



School of Healthcare Sciences
Head of School and Dean Professor Heather Waterman

Ysgol Gwyddorau Gofal Iechyd
Pennaeth yr Ysgol a Deon Yr Athrawes Heather Waterman

12 July 2018

Cardiff University
[redacted]

Email E-bos[redacted]

[redacted]

Dear Mohannad

The development of sensor-based motion analysis feedback intervention to supplement physiotherapy standard care for individuals with Patellofemoral pain syndrome.

At its meeting of ***10th July 2018***, the School's Research Ethics Committee considered your research proposal. The decision of the Committee is that your work should:

Pass –and that you proceed with your Research in collaboration with you supervisor

The Committee has asked that the lead reviewers' comments be passed onto you and your supervisor, please see attached and additional comments below.

Please remove Sally Anstey as the person to contact in case of complaint and replace with Kate Button

Please note that if there are any subsequent major amendments to the project made following this approval you will be required to submit a revised proposal form. You are advised to contact me if this situation arises. In addition, in line with the University requirements, the project will be monitored on an annual basis by the Committee and an annual monitoring form will be despatched to you in approximately 11 months' time. If the project is completed before this time you should contact me to obtain a form for completion.

Please do not hesitate to contact me if you have any questions.

Yours sincerely

[redacted]

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Figure 1: Ethical approval from the School of Healthcare Sciences, Cardiff University used in the current study

1.4.2 Recruitment

1.4.2.1 Setting

This study was conducted in the physiotherapy laboratory for the School of Healthcare Sciences (HCARE) at Cardiff University.

1.4.2.2 Participants

The participants were healthy volunteers recruited via convenience sampling. At the time of the data collection, it was not practically possible to recruit a pathological sample of interest (populations with knee pain). This was because this study was a preparatory study (conducted in a very early stage of development prior to developing SMAFT) that primarily aimed to compare the sensor-based movement analysis method with the 2D video analysis when quantifying angular kinematics, in order to determine whether the sensor-based movement analysis had a role to play in clinical practice. Also, this study was conducted for training purposes, specifically for the lead researcher (M.F.) to practice data collection and analysis, as mentioned previously in Chapter 3, section 3.2. Therefore, the study was not a core component of this PhD thesis, and thus this type of sample was deemed appropriate.

The participants were recruited via word-of-mouth, using a study flyer that was placed on the Cardiff University advertisement board. The flyer included an invitation, a brief description of the study and its procedures, and contact information. Anybody who was interested in taking part was invited to contact the lead researcher (M.F.) via email, and a PIS (Figure 2) was then sent to them. The PIS stated that the participants were free to withdraw from the study at any time, without prejudice.

The potential participants had at least 72 hours to consider their participation before being contacted again to confirm if they wanted to participate and, if so, book an appointment for data collection. The participants had the opportunity to ask questions and discuss their participation at each stage. After confirming the eligibility criteria on the day of the data collection, an informed consent sheet was signed prior to the commencement of the trials (Figure 2).

[redacted]

VOLUNTEER INFORMATION SHEET

Assessment of joint function in healthy volunteers using three dimensional motion analysis techniques

Part one

You are being invited to take part in a research study with Cardiff University's Arthritis Research Campaign Biomechanics and Bioengineering Centre (ARUKBBC). Before you decide, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. One of our team will go through the information sheet with you. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to participate. Part 1 tells you about the purpose of this research and what will happen to you if you take part. Part 2 gives you more detailed information about the conduct of this research study.

What is the purpose of this research?

This research is part of a series of studies being conducted by ARUKBBC which use an interlinking approach to investigate the effects of disease, injury and/or any related treatment on the biomechanics of the joint compared to healthy joints.

The aim of this part of the research is to investigate the function of healthy joints including knees, hips, ankles, shoulders, elbow, wrists, hands or spine. The data can be helpful when comparing the same measurements in people who have joint problems. Your data can act as the measure of what a healthy joint can achieve. This can be useful when, for example in designing new treatments, improving the design of joint replacements, improving rehabilitation programmes and improving the way that motion is analysed clinically.

Figure 2: Participant Information Sheet (PIS) and Consent Form (CF) used in the current study

Do I have to take part?

It is up to you to whether or not to take part. If you do decide to take part you will be given this information sheet to keep and after you have had enough time to read through it, be asked to sign a consent form. If you decide to take part, you are still free to withdraw at any time or without giving a reason. Should you decide not to take part, you do not have to provide a reason for this decision. However, any data that we may have collected up to the point of withdrawal will be kept for analysis.

What will happen to me if I take part?

You have been asked to take part in this as you are volunteering as a healthy subject. It will allow us further insight into the nature of joint function and how healthy people move.

If you wish to take part you will assessed either in the Cardiff University School of Engineering, Human Motion Analysis Laboratory or in the Cardiff University School of Healthcare Studies (HCARE) Research Centre for Clinical Kinaesiology (RCCK) or in the relevant clinical settings. The number of times we would ask you to attend will be discussed with you when going through this information sheet. The sessions will last a maximum of three hours.

Data will be kept securely for a minimum of 15 from the end of the study years in accordance with good research practice and data protection regulations imposed by Cardiff University in accordance with the Data Protection Act 1998. All data obtained during the study will remain confidential. Access to data will only be available to the investigators attached to the ARUKBBC at Cardiff University. If new information becomes available, we may invite you to take part in a follow-up study in the future, please indicate on the consent sheet if you do not mind us contacting you. With your permission and consent, we may also invite you to take part in other interlinking studies associated with our research. However, you are under no obligation to take in any other or future studies.

What will I have to do?

Before your first assessment you will be asked to sign a consent form which includes the following clause: I understand that I may withdraw from the study at any time without it affecting any ongoing treatment in any way. All participants will be sent a map and directions to the place of assessment. At the beginning of your visit, we will explain the study in full and ask for your consent, bearing in mind that you are free to withdraw at any time. We will ask you to complete questionnaires that will ask you questions about how the problem affects your activities of daily living.

Figure 2: Participant Information Sheet (PIS) and Consent Form (CF) used in the current study (Continuous)

Prior to the start of the assessment, you may be asked to change into appropriate clothing depending on the joint we want to examine (for example shorts and, well-fitting vest for knee, and well-fitting vest, sports bra or swimming costume for shoulder and spine, etc.). This process will be conducted with the upmost professionalism and a screened off area is provided for changing. During laboratory sessions, access to the laboratory is limited and a sign is placed on the door advising other staff not to enter whilst the study is in progress.

Firstly you will have a number of very light plastic round markers attached to the skin and the locations of the markers will be dependent on the joint type under examination. Small, lightweight sensors may also be attached to the skin to record body movements and sensor location will be dependent on the joint under investigation.

You will be asked to perform a range of activities of daily living as appropriate (such as walking with and without walking aids, running, standing, climbing stairs, wheelchair use, lower limb prosthesis use, combing hair, taking hand to mouth). You will be free to stop for a break at any time. The position of the markers on the skin will provide a series of recordings by using cameras that record the position of the markers.

You may be asked to perform some of these tasks on a special treadmill which may or may not be situated in a virtual reality environment. The treadmills are set at floor level and can rotate in an upward/downward direction, move sideways. These movements are controlled and you will be informed if the treadmill will move or rotate. When performing in the virtual reality environment, there will be a screen in front of you that can display a variety of images to give the impression of walking on a forest path or kicking a ball, for example. You will be asked to wear a special harness whilst on all treadmills to prevent you from falling in case you stumble.

When appropriate to the joint under study, muscle activity, muscle function and joint strength may also be determined during these sessions. This will involve placement of electromyography (EMG) electrodes onto the surface of the skin to record muscle activity during joint movement. The locations of the electrodes will be dependent on the muscle groups under examination. Particularly hairy skin may sometimes need a small patch shaving for the sensors to attach (approximately 4×4cm). In order to determine muscle function electrical muscle stimulation will be used. This involves placing similar electrodes to the EMG on your skin. During certain movements a small stimulus will be applied via the electrode on your skin, this will make your muscle contract more and change your movement slightly. This may cause a strange sensation but will not cause any pain.

Throughout the sessions your joint movement will be recorded using standard audio-visual equipment. The recordings will be used for data verification post processing. We may ask if we can cover any identifying tattoos or birthmarks with a bandage. . All data files, including audio-visual files will be stored in encrypted folders on Cardiff University

Figure 2: Participant Information Sheet (PIS) and Consent Form (CF) used in the current study (Continuous)

password protected computers. Cardiff University and NHS members of staff who are directly involved with the study will have access to the files. The audio-visual files will be electronically destroyed up to 15 years from the end of the study. Full participant anonymity will be ensured in all video content used in presentations/publications if you consent for us to use your data in this way, with identifiable features digitally masked when needed.

For studies investigating back pain we will ask you to perform a selection of tasks consisting of everyday functional tasks such as bending, stretching, lifting a cup from a table and finding the best position to sit and stand in. Your spinal movements and how muscles work when walking may be assessed whilst walking on a treadmill at different speeds and different inclinations. We will be looking at which targeted exercise treatments using different instructions are the most beneficial for patients with back pain. These will be compared to treatments currently being used such as general advice and general group exercises.

As a healthy volunteer for a study investigating patient with joint osteoarthritis, we are also determining the best muscle strengthening programmes including how often and how much exercise a patient needs to get an improvement in their joint pain.

For studies investigating wrist movement, we will ask you to have a series of measurements and clinical tests performed on both of your wrists, these will include assessing your grip, range of motion and muscle strength. We will be looking at ways of defining wrist function for comparison of healthy and osteoarthritic joints.
For studies investigating shoulder pain and elbow movement, we will ask you to perform a series of actions to measure how your shoulder and elbow is moving during activities of daily living, total range of mobility, reaching for and lifting lightweight objects, and in some cases, using assistive devices (wheelchair, walking frame, or crutches). You may also be asked to perform simple exercises that a physiotherapist would commonly prescribe. We will be looking at ways of defining shoulder and elbow function for comparison of healthy joints with those that have osteoarthritis or have had treatment for osteoarthritis.

For studies investigating hip, knee, and ankle movement, we will ask you to perform a selection of tasks consisting of every daily activities such as: walking on level ground, ascending and descending stairs and sitting to standing. You may also be asked to perform simple exercises that a physiotherapist would commonly prescribe, including: standing on one leg and bending the knee, standing on tip-toes, walking on a treadmill that may be set to incline. You may also be asked to perform these tasks whilst wearing knee or ankle braces, or orthopaedic shoes or inserts.

Figure 2: Participant Information Sheet (PIS) and Consent Form (CF) used in the current study (Continuous)

We will be looking at how your body responds to these activities in terms of movement and loading of the various joints, including your back and shoulders. As a healthy volunteer for a study investigating patients with joint osteoarthritis, we will be comparing healthy function to that of patients with osteoarthritis and to those who have had treatments for osteoarthritis.

For all studies regular rest and toilet breaks will be provided as often as you need them to assure maximal comfort.

After attendance at the session you will be reimbursed for reasonable travel expenses

Are there any risks in participating in this research?

The measurements taken during the trial involve the placement of very light polystyrene or cork round markers onto the skin or EMG electrodes in various places of the body depending on what joint we will be examining. The markers/sensors/electrodes are placed with sticky tape or peelable silicon rubber which may cause some mild discomfort when it is being removed, similar to removing a small sticking plaster.

Are there any benefits in participating in this research?

We hope to be able to better understand how joints move. There is no intended clinical benefit to the participant from taking part in the study. The information we get from this study may help us to provide future people who have joint disease or injury with improved treatment options.

If the information in Part 1 has interested you and you are considering participation, please read the additional information in Part 2 before making a decision.

Figure 2: Participant Information Sheet (PIS) and Consent Form (CF) used in the current study (Continuous)

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VOLUNTEER INFORMATION SHEET

Assessment of joint function in healthy volunteers using three dimensional motion analysis techniques

Part Two

What if new information becomes available?

Occasionally during the course of a PhD thesis, new information may become available about the investigation being carried out. If this happens, a member of the research team will contact you to inform you about it and discuss with you whether you would like to continue in the study. If, after considering the new information, you decide to withdraw from the study, it will not affect your legal rights. If you are happy to continue, you will be asked to sign an updated information sheet and consent form which contains the updated information.

What will happen if I do not want to carry on with the study?

If you decide you would like to withdraw from the study, we will erase all identifiable material. However, any information collected up to that point will be kept and used unless you tell us that you would like your information removed from the project.

What if something goes wrong?

In the rare circumstance that you are harmed by taking part in this PhD thesis, there are no special compensation arrangements. If you are harmed due to someone's negligence, then you may have grounds for a legal action but you may have to pay for it. Regardless of this, if you wish to complain, or have any concerns about any aspect of the way you have been approached or treated during the course of this study, please contact a member of our team the details of which are in the "What if I wish to lodge a complaint?" section below.

Figure 2: Participant Information Sheet (PIS) and Consent Form (CF) used in the current study (Continuous)

Will my taking part in this study be kept confidential?

Once you have consented to take part in the study, you will be assigned a unique identifier which will linked to your details and will also allow us to track you through the appropriate and relevant arms of the study. All information which is collected about you during the course of the research will be kept strictly confidential. We may share the data we collect with researchers at other institutions including Universities and commercial research organisations, in the UK and aboard. However, any information that leaves the Centre will be anonymised. It will have your name and address removed so that you cannot be recognised from it. In any sort of report we might publish, we will not include information that will make it possible for other people to know your name or identify you in any way. You will simply be referred to by your gender, age, the affected joint and possibly some characteristic such as left or right handedness. If you join the study, some parts of your records and the data collected for the study may be looked at by authorised persons from the University for the purposes of monitoring and auditing. We may share information with external collaborators but all this information will contain no identifiable information about you. Your identity on any video recording will be protected using digital masking for any video used in research presentations.

Will my GP be informed of my involvement in the study?

We do not routinely send a letter to the GP to inform them of your participation in this research. However, with your permission we may contact your GP before getting in touch with you in the future to ensure it is suitable for us to do so. For this reason we ask you to bring details (name, address and telephone number) of the GP with whom you are registered.

What will happen to the results of the research study?

We hope to publish the results of this study in a scientific journal. We may also present the results at a scientific conference or a seminar in a university. We may also publish results on our website. We would be happy to discuss the results of the study with you and send you a copy of the published results. It will not be possible to identify you or images of your joint in any report or publication.

Who is organising and funding the research?

Research staff at the Arthritis Research UK Biomechanics and Bioengineering Centre at Cardiff University and Consultant Orthopaedic Surgeons at the University Hospital of Wales are carrying out the study. The study is part of the Arthritis Research UK Biomechanics and Bioengineering Centre at Cardiff University; it is not funded by commercial sources and runs alongside research in the Cardiff University School of Engineering motion analysis laboratories and Research Centre for Clinical Kinaesiology

Figure 2: Participant Information Sheet (PIS) and Consent Form (CF) used in the current study (Continuous)

at Cardiff University School of Healthcare Studies. Occasionally work associated with these studies may also be supported by commercial companies, we will inform you by sending you a letter when this is the case.

Who has reviewed the study?

This study has been reviewed by Wales Research Ethics Committee 3 (REC 3).

What if I wish to lodge a complaint?

If you wish to make a complaint regarding the way you were approached or treated during the trial, please contact the Arthritis Research UK Biomechanics and Bioengineering Centre Research Administrator on
Telephone: [redacted] Email [redacted]
If you feel your complaint is not adequately addressed then you may escalate your complaint by writing to the School Manager of the host school for the Centre: [redacted] Please ensure you include details of any complaint made so far and correspondence you have so far received.

Contact for further information

[redacted]

This completes Part 2. Thank you for reading this information sheet.

If you agree to take part in this study you will be given a copy of the information sheet and a signed consent form to keep.

Figure 2: Participant Information Sheet (PIS) and Consent Form (CF) used in the current study (Continuous)

[redacted]

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

VOLUNTEER CONSENT FORM

Assessment of joint function in healthy volunteers using three dimensional motion analysis techniques

Study Number:
Volunteer Identification Number for this trial:

You DO NOT have to sign this document. Please DO NOT sign this document unless you fully understand it. If there is ANYTHING which you do not understand please do not hesitate to ask for a full explanation.

To confirm agreement with each of the statements below, please initial the box and amend as necessary:

1. I confirm that I have read and understand the information sheet dated 14 April 2017 (Version 10.2) for the above study and have had the opportunity to ask questions. ☐

2. I understand that my participation in the study is voluntary and that I am free to withdraw at any time, without giving any reason, and without my legal rights being affected but any data collected up to the point of my withdrawal will be kept. ☐

3. I understand that my details will be linked to a unique identifier to allow you to follow me through course of the study ☐

4. You may / may not (please delete as appropriate) contact me in the future to ask if I would be interested in participating in a future PhD thesis/survey ☐

5. I do / do not (please delete as appropriate) agree for you to share anonymised data with external collaborators in the UK and aboard, including commercial companies. ☐

Figure 2: Participant Information Sheet (PIS) and Consent Form (CF) used in the current study (Continuous)

6. I agree for you to video my movements on a video-camera. I understand that if the video is used for research presentations that my anonymity will be ensured using digital masking. ☐

7. I agree to my GP being contacted ☐

8. I agree to take part in the above study. ☐

Name of Volunteer: ____

Signature: ________________________________ Date: ____________

I confirm that I have fully explained the experimental protocol and purpose of the study

Name of Researcher: ____

Signature: ________________________________ Date: _____________

Name of person taking consent: __________________________________ (If different from researcher)

Signature: ________________________________ Date: _____________

GP Details

GP Name:

GP Address:

GP Telephone Number:

Original Centre file, 1 copy for the volunteer, 1 copy for the researcher

Figure 2: Participant Information Sheet (PIS) and Consent Form (CF) used in the current study (Continuous)

1.4.2.3 Eligibility Criteria

All of the participants were included subject to satisfying the following inclusion/exclusion criteria:

Inclusion criteria

- Adults aged 18+ years old
- Able to give written informed consent

Exclusion criteria

- History of any lower extremity, pelvis, or back disorder in the last 3 months that may impair the individual's performance of functional activity tasks
- History of lower extremity surgery in the previous 12 months
- Any neurological or cardiovascular pathology that would affect motion

1.4.3 Sample size

The sample size estimation was determined based upon a guide (in the form of a table) produced by Bujang and Baharum (2017). Steps were taken to determine the minimum sample size needed to attain the pre-specified effect size of the ICC. Thus, based on the two observations (2D and 3D movement analysis methods) made by each participant with an α level of 0.05, power of 90%, R0 of 0, a minimum sample size of 20 was required to achieve statistically significant results (Figure 3) (Bujang and Baharum 2017).

Table 1a Sample size requirement for intraclass correlation with power = 80% and 90%; alpha = 0.05, observation per subject from 2 to 10 and R_0 is set at 0

Observation per Subject	ICC	Number of subjects (power=80%)	Number of subjects (power=90%)
2	0.2	152	210
	0.3	66	91
	0.4	36	50
	0.5	22	30
	0.6	15	20
	0.7	10	13
	0.8	7	9
	0.9	5	6
3	0.2	60	83
	0.3	28	39
	0.4	17	23
	0.5	11	15
	0.6	8	10
	0.7	6	8
	0.8	4	6
	0.9	3	4
4	0.2	35	49
	0.3	18	24
	0.4	11	15
	0.5	8	10
	0.6	6	8
	0.7	5	6
	0.8	4	5
	0.9	3	4
5	0.2	24	34
	0.3	13	18
	0.4	8	12
	0.5	6	8
	0.6	5	6
	0.7	4	5
	0.8	3	4
	0.9	3	3
6	0.2	18	26
	0.3	10	14
	0.4	7	10
	0.5	5	7
6	0.6	4	6
	0.7	4	5
	0.8	3	4
	0.9	3	3
7	0.2	15	21
	0.3	9	12
	0.4	6	8
	0.5	5	6
	0.6	4	5
	0.7	3	4
	0.8	3	4
	0.9	3	3
8	0.2	13	18
	0.3	8	11
	0.4	6	8
	0.5	4	6
	0.6	4	5
	0.7	3	4
	0.8	3	3
	0.9	2	3
9	0.2	11	15
	0.3	7	9
	0.4	5	7
	0.5	4	5
	0.6	4	5
	0.7	3	4
	0.8	3	3
	0.9	2	3
10	0.2	10	14
	0.3	6	9
	0.4	5	6
	0.5	4	5
	0.6	3	4
	0.7	3	4
	0.8	3	3
	0.9	2	3

Figure 3: The sample size required in the current study which is based on Table 1a adapted from Bujang and Baharum (2017)

1.4.4 Ethical considerations

1.4.4.1 Ethical issues related to data collection

The participants were asked to wear fitted shorts and zip-fastened T-shirts throughout the study session. This required better placement of inertial sensors along the participant's body. Privacy for the participants and the researchers was considered by providing a private area for the participants to change their clothes using folded screens and keeping the laboratory door secured throughout the session to avoid disruption. Placing reflective markers on the participant's body was done using a palpation method on anatomical landmarks. Full informed verbal consent was taken before palpating the bony landmarks to ensure the participant's agreement.

As detailed in the consent form, the participants were able to choose to permit the use of their videos for research purposes. The participants were given an opportunity to view their video recordings. The videos were used for research purposes only. They were transferred to a laptop provided by the School of Healthcare Sciences at Cardiff University (HCARE) and then deleted from the cameras on which they were recorded. The research data was then transferred from the laptop to an encryption drive on the university's servers (NAS drive), and then it was deleted from the laptop. This was done on the day of the recording. All of the data could be retained for 15 years following completion of the study and then deleted.

Participant confidentiality was ensured by replacing the individual's name with a unique identification number (ID), which was used to identify the individual throughout the study. All of the personal data (consent forms) was retained securely on the Versus Arthritis Biomechanics and Bioengineering Centre servers. A paper copy of these forms was stored in a locked filing cabinet at a university building, which has a secure gate and doors. Cardiff University's Guidelines for Research Governance and the procedures for good clinical practice in research were also followed.

To the best of the researcher's knowledge, there are no known health risks concerning the proposed protocol. However, skin irritation could occur in individuals with sensitive skin, since the sensors were attached to the skin using double-sided adhesive tape. There were no direct benefits associated with participating in this study.

1.4.5 Instrumentations and equipment

In the current study, two movement analysis tools were compared to quantify lower limb joint kinematics in the sagittal and frontal planes. The first movement analysis tool involved sensor-based 3D movement analysis using the Xsens MVN Awanda system (version 2019.0, Xsens Technologies, Enschede, The Netherlands). The kinematic data was collected at a frame rate of 60 Hz, using the Xsens MVN Analyze software package.

The second movement analysis tool was the camera-based 2D movement analysis using Kinovea video player software (version 0.8.27; Kinovea Open-Source Project, www.kinovea.org). Two GoPro cameras (version GoPro Hero 5.1; GoPro Inc., California, USA) at a frame rate of 30 Hz were used to record the performance of functional tasks on video episodes. To identify lower limb angular kinematics using Kinovea software, retroreflective markers (14 mm in diameter) were placed on the participants.

Body mass and height were measured using digital floor weighing scales (model 862, SECA Ltd., Medical Scales, Birmingham, UK) and a mechanical telescopic measuring rod (Marsden HM-250P Leicester Portable Height Measure, UK). In addition, body measurements were quantified using the Xsens measuring tape (Xsens Technologies, Enschede, The Netherlands).

1.4.6 Validity and reliability

1.4.6.1 Sensor-based 3D motion analysis system

A discussion regarding the validity and reliability of the sensor-based motion analysis system was previously presented in Chapter 2, sections 2.9.1 and 2.9.2.

1.4.6.2 Camera-based 2D movement analysis

A discussion covering the validity and reliability of the sensor-based motion analysis system was presented previously in Chapter 2, section 2.8.1.1.1.

1.4.7 Study procedures

It should be worth noted that an MSc student (T.A.) assisted with the recruitment and data collection processes as part of their MSc dissertation. The student (T.A.) conducted their own research project, that was different than the research in the current study (the aim of their project was to assess the validity and reliability of avatar recordings provided by the Xsens MVN system compared to 2D video recordings when scoring the Landing Error Scoring System (LESS) during jump landing tasks) (Alsaedi et al. 2020). The role of the student in the current research was therefore limited to organising the data collection appointments for the participants, who expressed interest in taking part, and collecting and analysing different kinematic data during various functional tasks. However, the entire process of data collection and analysis for the current research was only done by the lead researcher (M.F.).

The procedures followed in the current study included three phases (preparation, calibration, and data collection). Each phase is presented separately in the following subsections.

1.4.7.1 Preparation procedures

The preparation stage began once the participant arrived in the laboratory. At this stage, the participant's personal information and medical history were taken to check they met the inclusion and exclusion criteria to take part in the study. Then, the participants were asked to change their clothes into shorts and a T-shirt and to take off their shoes. After that, the participant's required measurements (body mass, height, and body dimensions) were quantified.

At the beginning of each session, the anthropometric data, including shoulder height and width, arm span, hip height and width, knee height, ankle height, and foot length, were measured in the standing position according to the Xsens manual guidelines (Xsens Technologies B.V. 2021) (this was previously explained in detail in Chapter 4, section 4.2.4.5.1.1).

Seventeen wireless Xsens MTw2 IMU sensors were placed on the participant's body adhering to the Xsens guidelines (Xsens Technologies B.V. 2021) (this was previously explained in detail in Chapter 4, section 4.2.4.5.1.1) (Figure 4). In addition, retroreflective markers (14 mm in diameter) were placed on the participants according to previous literature (Gwynne and Curran 2014; Krause et al. 2015; Schurr et al. 2017; Kingston et al. 2020; Mousavi et al. 2020). Marker placement was proven to be valid and reliable (Gwynne and Curran 2014; Krause et al. 2015; Schurr et al. 2017; Kingston et al. 2020; Mousavi et al. 2020). These markers were used as reference points to support data analysis and ensure consistency when identifying bony landmarks using Kinovea software. Retroreflective markers were placed by the lead researcher (M.F.) among all the participants and fixed in position using medical grade double-sided adhesive tape. The standardised palpation methods were applied to anatomical landmarks on both sides as follows (Figure 4):

- Anterior superior iliac spine,
- Greater trochanter,
- Mid tibiofemoral joint,
- Lateral femoral epicondyle,
- Lateral malleolus, and
- Mid talocrural joint.

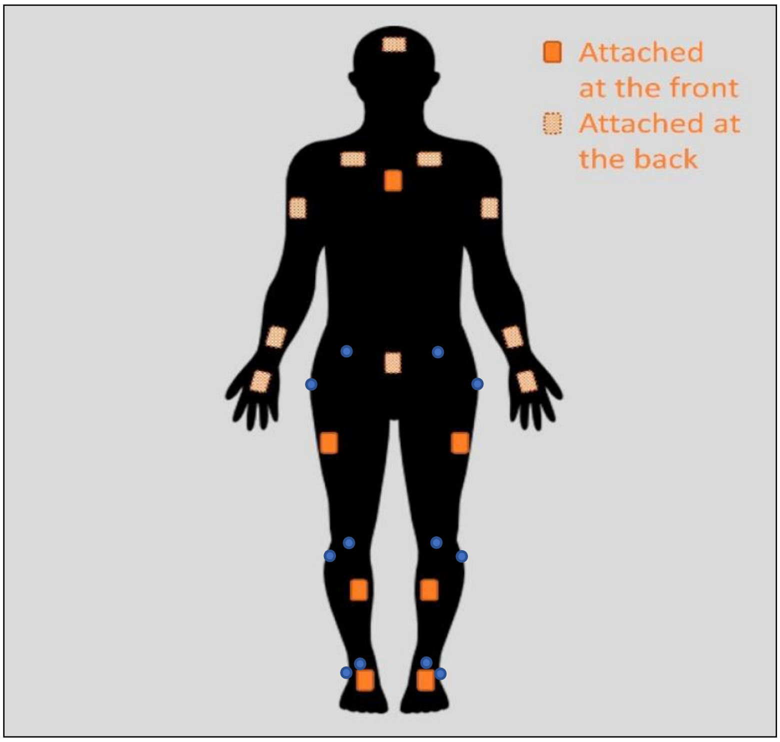


Figure 4: Full body sensors and marker placement (Adopted from Huang et al. 2020)

Key: Orange squares = sensor trackers attached at the front, Beige squares = sensor trackers attached to the back, Blue circles = retroreflective markers

1.4.7.2 Calibration procedures

1.4.7.2.1 Sensor-based 3D motion analysis calibration

This was previously described in detail in Chapter 4, section 4.2.4.5.1.2.

1.4.7.2.2 Camera-based 2D movement analysis system calibration

The video episodes for the functional tasks were recorded using two GoPro cameras. Each camera was fixed to a mountain tripod and adjusted to a height of one metre above floor level at a distance of three metres from the subject (Gwynne and Curran 2014; Scholtes and Salsich 2017) (Figure 5). Identifying the distance between the cameras and the participant's performance area varies in the previous literature (2.4 m, 3 m, 10 m, and 2 m) (Gwynne and Curran 2014; Herrington et al. 2017; Scholtes and Salsich 2017; Schurr et al. 2017; Alahmari et al. 2020). Payton and Burden (2017) suggested the distance between the cameras and the participant's performance area should be as long as possible to minimise out of plane motion performance (perspective error). Thus, with consideration of the space available in the laboratory, a distance of three metres was selected (Gwynne and Curran 2014; Scholtes and Salsich 2017).

One camera was placed perpendicular to the frontal plane, and the other perpendicular to the sagittal plane. In order to control the cameras in terms of starting and stopping recording, the GoPro Studio application (GoPro, Inc., USA) was used with two Apple iPads.

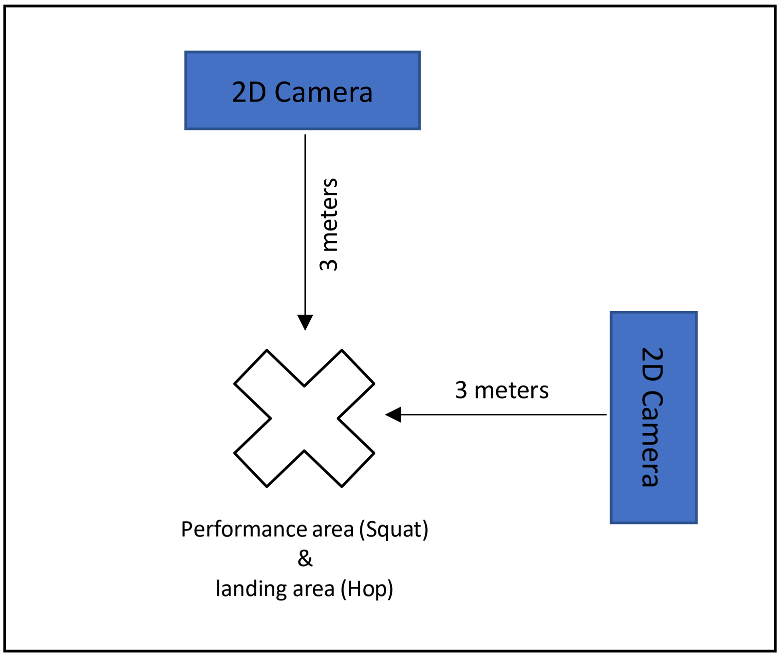


Figure 5: Laboratory set up presenting the location of the 2D camera

1.4.8 Data collection

1.4.8.1 Functional activity tasks to be evaluated

The following three functional activity tasks were selected for inclusion in this study: DLS, SLS, and SLDH. As this preparatory study primarily aimed to assess the correlation and agreement between 2D and 3D sensor-based movement analysis methods when quantifying lower limb joint angular kinematics, there was a need to assess them during a battery of dynamic functional activities with different levels of challenge (complexity and speed) (Al-Amri et al. 2018; Alahmari et al. 2020). This resulted from the fact that it was unclear whether camera-based 2D systems can quantify kinematics during multiplanar dynamic tasks (Alahmari et al. 2020). Furthermore, it was previously proven that the correlation and agreement of the angular kinematics quantified by various movement analysis systems may be reduced (Al-Amri et al. 2018). According to Button et al. (2014), DLS, SLS, and SLDH tasks had different levels of challenge, ranging from a double leg support task to a single leg task and a high-speed complex task, respectively. Therefore, the inclusion of the aforementioned tasks in the current study was deemed appropriate.

Although this study included DLS and SLS tasks that were similar to the tasks included with the development of SMAFT (previously discussed in the literature review, Chapter 2, section 2.6.1), it should be noted that this study was conducted in the very early stages of SMAFT development, before developing the feedback report. Consequently, it was not necessary to match the tasks included in the feedback report (gait, DLS, SLS, VJ, SA, and SD).

1.4.8.2 Pilot study

Two subjects were recruited to complete a pilot study, assisting the researcher to standardise the protocol and ensure the feasibility of the research. In addition, this helped to determine the time needed to complete the data collection for the project, and to identify and overcome challenges and difficulties during the main data collection. As a result of the pilot, no challenges were encountered during the course of the study, and the approximate time needed for each subject was 45 minutes.

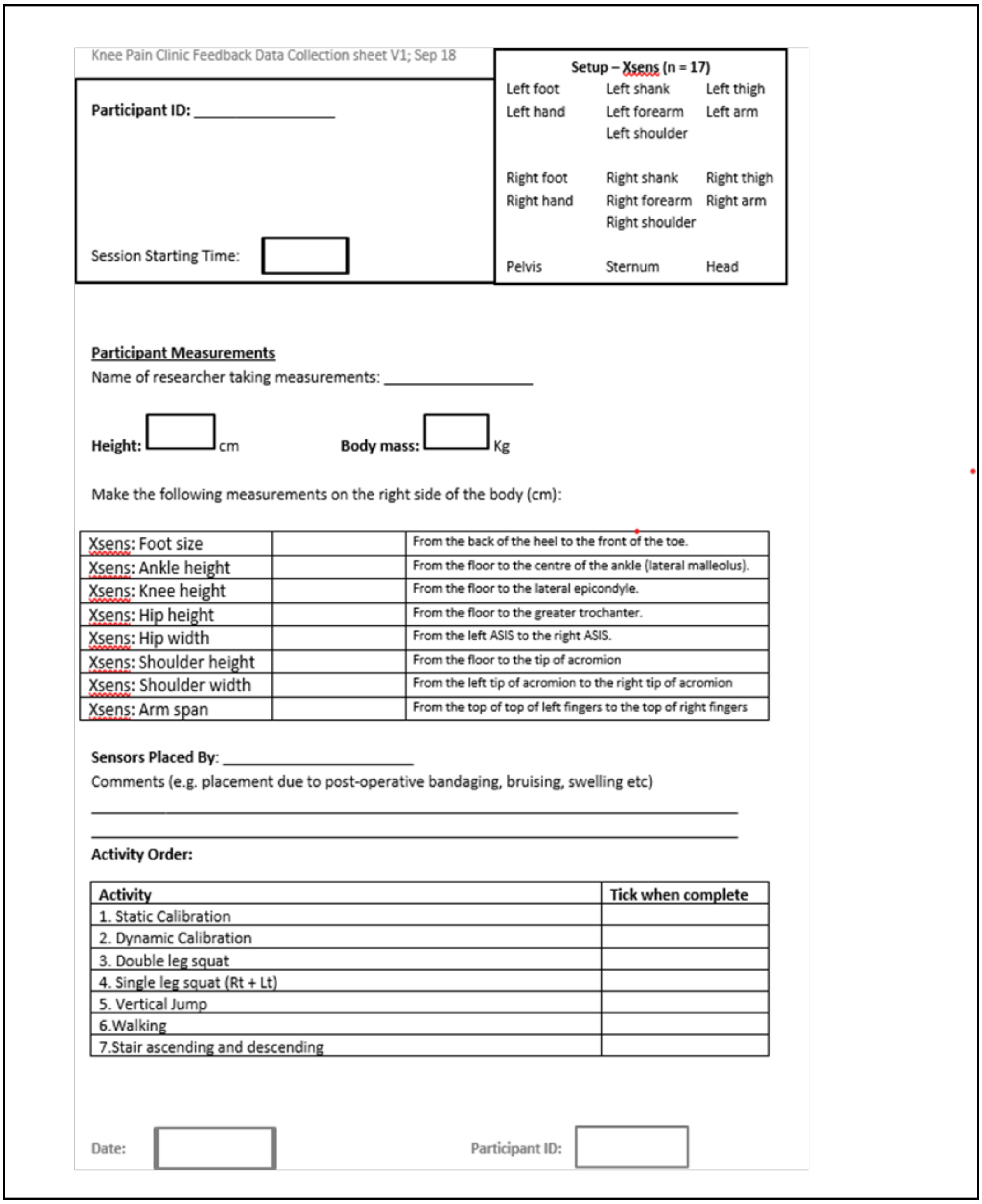
1.4.8.3 Experimental protocol

All the participants were invited to attend a single movement analysis session lasting 45 minutes. Each participant attended individually. Lower limb joint kinematics were collected using 2D and 3D movement analysis systems, while the participants performed five repetitions of the three functional tasks (DLS, SLS, and SLDH).

Prior to commencing the data collection phase, functional tasks were described verbally and then demonstrated to the participants by the lead researcher (M.F.). Two practice repetitions were performed by the participant prior to the five trials for each task in order to generate familiarity with the task (Phillips and van Deursen 2008). The order of the tasks was determined according to their level of challenge, from the easiest to the hardest (Button et al. 2014). Thus, the order of the tasks was as follows: DLS, SLS, SLDH. The following instructions were given to the participants regarding how to perform each task:

- Double leg squat: participants were asked to squat by flexing both knees to a self-determined maximum depth without losing balance, and then return to their starting position.
- Single leg squat: participants were asked to balance on one leg by flexing one knee to a self-determined maximum depth and then return to their starting position.
- Single leg distance hop: participants were instructed to balance on one leg and then hop to a self-determined maximum distance and to maintain their position after landing without losing balance.

For all of the tasks, a trial was considered failed in the following cases; the participant lost their balance, the trial was interrupted, the cameras or the Xsens software were not recording, or the markers and the sensors fell off or moved. If the trial was considered to have failed, it was repeated, dismissed, and not included in the analysis. In order to organise the reporting on the data collection trials and facilitate the analysis of the collected data, a prepared data collection sheet was used (Figure 6). For each participant, each trial was reported and marked with an (S) if successful or (F) if failed. When all the tasks had been successfully completed, the sensors and retroreflective markers were removed.



Knee Pain Clinic Feedback Data Collection sheet V1; Sep 18

Participant ID: ________________

Session Starting Time: [ ]

Setup – Xsens (n = 17)

Left foot	Left shank	Left thigh
Left hand	Left forearm	Left arm
	Left shoulder	
Right foot	Right shank	Right thigh
Right hand	Right forearm	Right arm
	Right shoulder	
Pelvis	Sternum	Head

Participant Measurements

Name of researcher taking measurements: ________________

Height: [ ] cm **Body mass:** [ ] Kg

Make the following measurements on the right side of the body (cm):

Xsens: Foot size		From the back of the heel to the front of the toe.
Xsens: Ankle height		From the floor to the centre of the ankle (lateral malleolus).
Xsens: Knee height		From the floor to the lateral epicondyle.
Xsens: Hip height		From the floor to the greater trochanter.
Xsens: Hip width		From the left ASIS to the right ASIS.
Xsens: Shoulder height		From the floor to the tip of acromion
Xsens: Shoulder width		From the left tip of acromion to the right tip of acromion
Xsens: Arm span		From the top of top of left fingers to the top of right fingers

Sensors Placed By: ______________________

Comments (e.g. placement due to post-operative bandaging, bruising, swelling etc)

____

____

Activity Order:

Activity	**Tick when complete**
1. Static Calibration	
2. Dynamic Calibration	
3. Double leg squat	
4. Single leg squat (Rt + Lt)	
5. Vertical Jump	
6.Walking	
7.Stair ascending and descending	

Date: [ ] Participant ID: [ ]

Figure 6: Data Collection sheet used in the current study

Knee Pain Clinic Feedback Data Collection sheet V1; Sep 18

Start Time: ______ End Time: ______

Trial No.	Activity		Comment (skin marks, NRS)
Trial 1		S F	
Trial 2		S F	
Trial 3		S F	
Trial 4		S F	
Trial 5		S F	
Trial 6		S F	
Trial 7		S F	
Trial 8		S F	
Trial 9		S F	
Trial 10		S F	
Trial 11		S F	
Trial 12		S F	
Trial 13		S F	
Trial 14		S F	
Trial 15		S F	
Trial 16		S F	
Trial 17		S F	
Trial 18		S F	
Trial 19		S F	
Trial 20		S F	
Trial 21		S F	
Trial 22		S F	
Trial 23		S F	
Trial 24		S F	
Trial 25		S F	
Trial 26		S F	
Trial 27		S F	
Trial 28		S F	

Date: ______ Participant ID: ______

Figure 6: Data Collection sheet used in the current study (continuous)

Knee Pain Clinic Feedback Data Collection sheet V1; Sep 18

Notes:

Date: [ ] Participant ID: [ ]

Figure 6: Data Collection sheet used in the current study (continuous)

1.4.9 Data processing

Lower limb angular kinematics for both limbs were recorded in the sagittal and frontal planes using both 3D movement analysis software (MVN Analyze) and 2D movement analysis software (Kinovea) during DLS, SLS, and SLDH tasks. Data was extracted from the right leg only of all participants. This approach was decided upon to ensure the data processing and extraction would be manageable within the timeframe.

For each trial, the sagittal and frontal joint angles of the hip and knee and the sagittal angle of the ankle joint, which corresponded with peak knee flexion (PKF), were extracted using both movement analysis systems. The PKF was defined as "the peak angle between the thigh and shank segments" (Ortiz et al. 2016, p. 67). The decision to select the point of PKF was based on literature proposing that the deepest part of a squat or landing is the most challenging portion of the task, in which poor knee control and kinematic alterations are more likely to arise (Stensrud et al. 2011). The PKF was identified visually by one researcher (M.F.) using the 2D movement analysis software and tracked objectively using the 3D software during the DLS and SLS tasks, and the initial stage of landing in the SLDH task. Data processing using the two systems' software will be discussed in turn.

1.4.9.1 3D data processing

The data collected using the MVN Analyze software was reprocessed with a high-definition (HD) mode. Reprocessing of the data was essential to collect and integrate data collected from all sensors with advanced biomechanical models to establish the position and direction of the human body segments (Schepers et al. 2018). The feature of HD reprocessing of the data was designed to obtain a more consistent estimation of the position and direction of each body segment, thereby reducing any magnetic distortions that occurred during the data collection phase (Schepers et al. 2018).

For each trial, PKF was identified objectively by the lead researcher (M.F.). The "graphs" icon facilitated by the 3D MVN Analyze software, which presents angular waveforms for lower limb joints at the hip, knee, and ankle in the sagittal and frontal planes, was used to identify PKF (Figure 7). This was achieved by tracking the value of knee flexion angle, as presented in the MVN waveforms, alongside the performance of the avatar until it reached its peak (Figure 7). Then, the joint angles for the lower limb joints (e.g., hip, knee, and ankle) in the sagittal and frontal planes presented in the MVN waveforms were recorded (Cooper et al. 2009) (Figure 7). The values for positive joint angles at hip, knee joints in the sagittal and frontal planes indicate flexion and abduction, respectively, and the values for negative angles indicate extension and adduction, respectively (Xsens Technologies B.V. 2021). For the ankle joint, sagittal positive values indicate dorsiflexion, and negative values indicate plantarflexion (Xsens Technologies B.V. 2021).

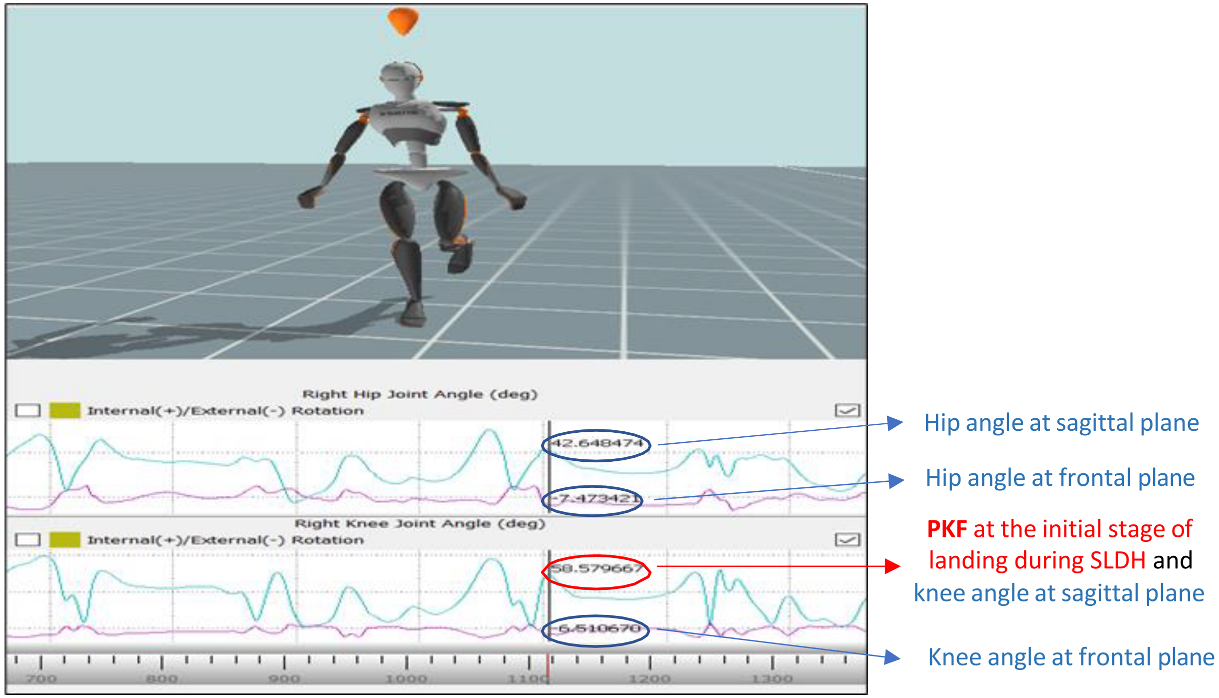


Figure 7: An example of joint angular extractions (hip, knee, and ankle joints) in the sagittal and frontal planes at PKF using the 3D (MVN Analyze/Animate) movement analysis system for one trial of SLDH

Key: Green waveform = Sagittal plane angle (flexion (+) and extension (-)), Purple waveform = frontal plane angle (abduction (+) and adduction (-))

1.4.9.2 2D data processing

Video recordings were processed using movement analysis software (Kinovea). All the successful trial videos were imported into Kinovea software for review and processing. After review, the joint angles of the lower limbs were quantified at a specific video frame, which represents the PKF, on each video file. Identifying PKF was performed by slowly forwarding the video episode frame by frame. PKF was identified in both planes as the one-time frame prior to the point of starting the performance of the knee extension in order to transit the body from the lowest position to a natural upright position (Mizner et al. 2012). For each selected time frame, a still image was zoomed in using the zoom function to ensure optimal visualisation, and then captured and saved. Each saved image was opened individually to measure the joint angles (angle between any two segments). The joint angles were quantified using the "angle" function in the Kinovea software.

The method used for quantifying the angles of the lower limb joints was based on previous studies comparing the lower limb joint angular kinematics provided by 2D and 3D movement analysis methods in the sagittal plane (Dingenen et al. 2015; Schurr et al. 2017; Mousavi et al. 2020) and frontal plane (Willson and Davis 2008; Schurr et al. 2017). With regard to the angles of the sagittal plane, the hip flexion angle was measured as the angle between a line bisecting the lateral border of the thigh, connecting the marker on the greater trochanter with the marker on the lateral femoral condyle, and another line bisecting the lateral border of the trunk, drawn from the marker of the greater trochanter to the acromioclavicular joint (Dingenen et al. 2015; Schurr et al. 2017; Mousavi et al. 2020). The knee flexion angle was measured as the angle performed by two lines bisecting the thigh and the shank, linking three markers on the bony landmarks: the greater trochanter, the lateral femoral condyle, and the lateral malleolus (Dingenen et al. 2015; Schurr et al. 2017; Mousavi et al. 2020). The ankle dorsiflexion angle was measured as the angle between the line bisecting the lateral border of the shank and formed by the lateral femoral condyle and the lateral malleolus markers and a line bisecting the lateral border of the foot, which was drawn from the lateral malleolus marker to the head of the 5^{th} metatarsal bone (Dingenen et al. 2015; Schurr et al. 2017; Mousavi et al. 2020) (Figure 8).

For the frontal plane angles, the hip abduction angle was measured as the angle between a vertical line extending from the ASIS marker to the floor (perpendicular to the ground) and a line bisecting the frontal border of the thigh, linking the ASIS to the midpoint of tibiofemoral joint markers (Schurr et al. 2017). The knee abduction angle was measured as the angle extending from the ASIS and the midpoint of the talocrural joint markers, with the midpoint of the tibiofemoral joint marker considered the fulcrum (Willson and Davis 2008; Schurr et al. 2017) (Figure 9).

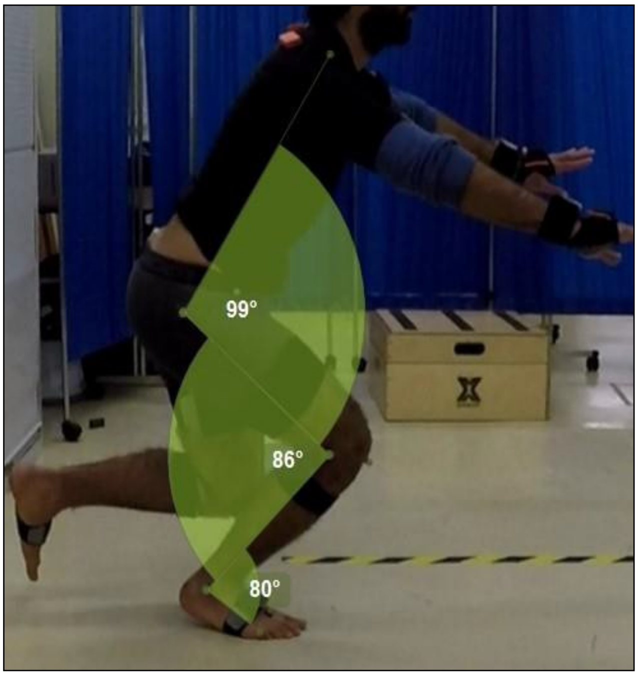


Figure 8: An example of joint angular extractions (hip, knee, and ankle joints) at PKF in the sagittal plane using the 2D (Kinovea) movement analysis system

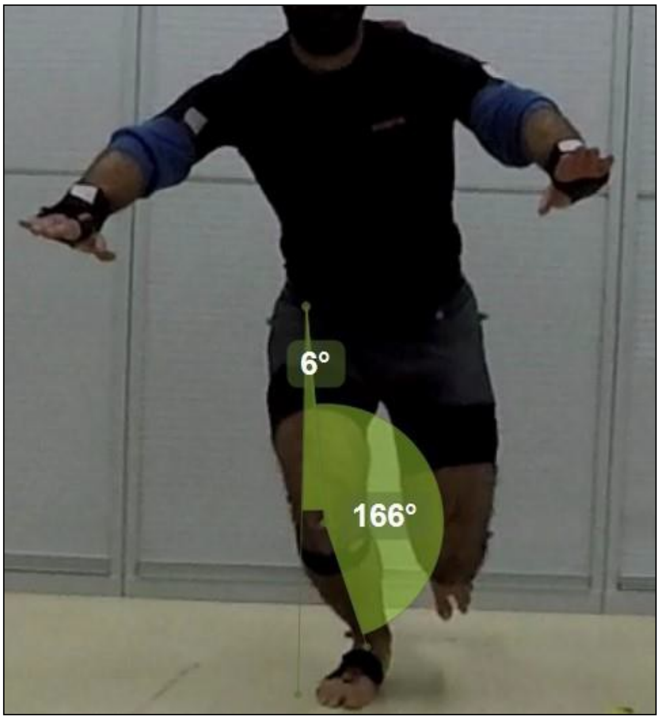


Figure 9: An example of joint angular extractions (hip and knee joints) at PKF in the frontal plane using the 2D (Kinovea) movement analysis system

After quantifying the angles between the segments, the angles were subtracted from a perfect vertical line (180 for hip and knee joints and 90 for ankle joint) using Microsoft Excel. This method of calculating joint angles was reliable and is commonplace in the previous literature (Munro et al. 2012; Scholtes and Salsich 2017; Schurr et al. 2017; Ramirez et al. 2018; Mousavi et al. 2020; Neal et al. 2020). In the sagittal plane, the angles for the hip, knee, and ankle joints were calculated relative to 180° for the angle between the trunk and thigh segments, 180° for the angle between the thigh and shank segments, and 90° for the angle between the shank and foot segments, respectively (Schurr et al. 2017; Mousavi et al. 2020; Neal et al. 2020). The values for the positive joint angles in the sagittal plane indicate flexion for the hip and knee joints and dorsiflexion for the ankle joint, and the values of negative angles indicate extension for the hip and knee joints and plantarflexion for the ankle joint (Schurr et al. 2017; Mousavi et al. 2020; Neal et al. 2020).

In the frontal plane, the angle for the hip joint was taken as is, because the angle was measured by linking a line extending over the thigh segment at a vertical line extending from the ASIS to the floor of 180° (perpendicular to the ground) (Schurr et al. 2017). The angle for the knee joint was calculated as 180°, denoting the angle between the thigh and shank segments) (Munro et al. 2012; Scholtes and Salsich 2017; Schurr et al. 2017; Ramirez et al. 2018). In the case of the value of the hip angle; when the knee marker was located medial to the vertical line, it was found to be negative (adduction). The hip angle was found to be positive (abduction) if the knee marker was located lateral to the vertical line (Schurr et al. 2017). In terms of the value of the knee joint; when the knee marker was medial to a line connecting the mid-point of the ankle with the mid-point of the thigh, the angle was negative (knee adduction). The knee angle was positive (knee abduction) if the knee marker was lateral to the line connecting the ankle with the thigh (Willson and Davis 2008; Schurr et al. 2017). In cases where the marker of the ASIS was not visible, and difficult to identify due to the excessive movement of trunk flexion during the performance of the functional task, a line was drawn from the marker of the knee bisecting the frontal border of the thigh (Figure 10).

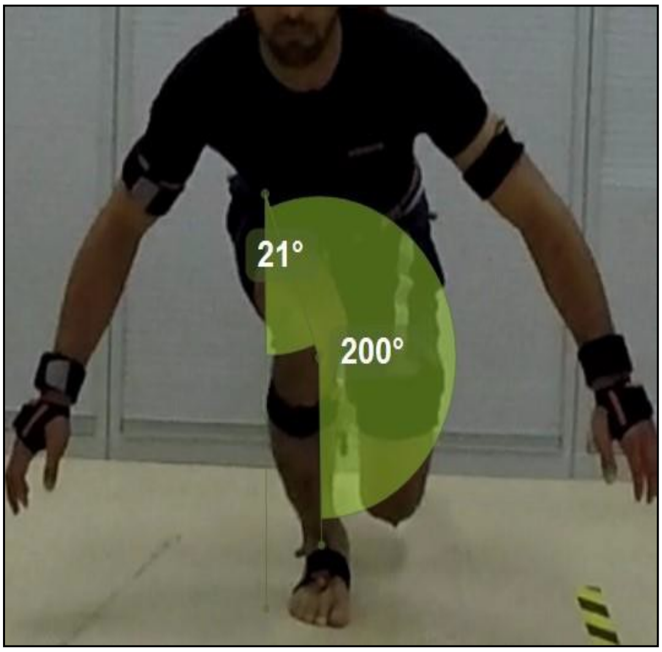


Figure 10: An example of joint angular extractions (hip and knee joints) at PKF in the frontal plane using the 2D (Kinovea) movement analysis system when excessive trunk flexion is performed and when the anterior superior iliac spine (ASIS) marker is not visible for quantification

1.4.10 Statistical analysis

1.4.10.1 Descriptive statistics

A summary of the statistics describing the participants' age, gender, height, body mass, and body mass index (BMI) were collated. Additionally, a descriptive analysis of the data for each functional task (DLS, SLS, and SLDH), each right-side lower limb's joint (hip, knee, and ankle), and each plane of movement (sagittal and frontal) was calculated using Microsoft Excel software (Microsoft Office, Excel software, version 2013). Firstly, the average scores for the joint angular kinematics for each participant (across all repetitions) for each task were calculated. Then, a descriptive analysis was performed to establish the mean, standard deviation, and 95% confidence interval, prior to averaging across all the participants using the same methods. Moreover, a paired sample t-test was used to identify the statistically significant differences between the mean joint angle values provided by the two movement analysis methods (Ross and Willson 2017).

1.4.10.2 Normality testing

The Shapiro-Wilk test was used to assess the normality of the data for each joint angular kinematics in both the sagittal and frontal planes during the three tasks (Shaphiro and Wilk 1965). The criterion for significance was set at ($p < 0.05$).

1.4.10.3 Inferential statistical analysis

A comparison was performed for each task (DLS, SLS, and SLDH), each right-side lower limb's joint (hip, knee, and ankle), and each plane of movement (sagittal and frontal), correlating the data extracted from the 3D Xsens MVN Analyze software with data provided by the 2D Kinovea software.

Although bivariate tests, such as the Pearson and Spearman correlation tests, are commonly used for evaluating associations between measurements (Karras 1997), they are not viewed as appropriate tests in this situation due to their limitations. Bivariate tests may be subject to systematic measurement bias because of their assumption that the association between two measurements is linear (Karras 1997). More precisely, a perfect correlation could arise even when one measure is consistently greater than the other measure (Liehr et al. 1995). Moreover, statistical significance might be attained, even though the association between the two measures may be considered poor (Karras 1997). It is therefore recommended to use a univariate test, such as the ICC test, to assess the correlation of the measurements (Karras 1997; George et al. 2000). The advantage of the ICC test among the other correlation tests is that ICC considers the differences in terms of the means of the measurements obtained with each test (Karras 1997; Liu et al. 2016). On the other hand, the ICC test does not present the range of associations between measures (George et al. 2003). Also, it can only be used to identify the strength of the correlation between measurements, without providing their agreement (George et al. 2003). Thus, it is recommended to combine this test with other methods, such as the Bland-Altman plot (Peat et al. 2020). ICC was calculated using the Statistical Package for the Social Sciences (SPSS) software Version 23.0 (IBM Corporation, Chicago, IL, USA). The values for ICC were interpreted as poor (less than 0.5), moderate (0.5 to 0.75), good (0.75 to 0.9), and excellent (greater than 0.9) (Koo and Li 2016). The significance level was set at $p < 0.05$ for all the analyses.

Therefore, comparisons of the kinematic data for the two types of software were performed using the ICC and Bland and Altman's limits of agreement (LoA).

The Bland-Altman method, with an average mean difference and 95% limits of agreement (LoA), was employed to evaluate the correlation between the two movement analysis methods for each outcome measure (joint angular kinematic). The Bland-Altman plots were produced using SPSS software Version 23.0.

Bland and Altman (1986) developed a graphical approach to describing the agreement between two methods of measurement by setting limitations (LoA). The Bland-Altman approach provides a visual representation to make the outcome measures readily interpretable by the clinician, establishing whether the two measures agree (Schurr et al. 2017; George et al. 2000). The Bland-Altman graph is a scatter plot, where the y axis represents the differences between the two measurements and the x axis represents the mean values of these measures (Bland and Altman 1986; Giavarina 2015). Each Bland-Altman plot should have three reference lines, which are drawn to represent the average mean difference and the 95% upper and lower limits of agreement (Bland and Altman 1986; Giavarina 2015). The higher the agreement, the closer the average mean differences are to zero, and the smaller the standard deviation (Bland and Altman 1986; Giavarina 2015). Specifically, a significant magnitude of bias (systematic error) can be indicated when the zero line is not located within the 95% confidence intervals for the average mean difference of the joint angle measure (Giavarina 2015). Moreover, the Bland-Altman approach includes calculating the 95% LoAs, which reflect 95% of the differences between the two measurements (Myles and Cui 2007). The calculation of the LoAs is based on the following equation:

$$95\%\ LoA = d \pm 2SD$$

(LoA = Limits of Agreement; d = Average Mean Difference; SD = Standard Deviation of the Differences)

A closer agreement is presented by a narrower range between the two LoAs. However, there are no well-defined criteria for what constitutes a narrow or wide LoA, and this is determined by the researcher's subjective view, which is heavily influenced by the clinical context (Giavarina 2015). This could be seen as one of the Bland-Altman approach's limitations (Bunce 2009).

The advantage of the Bland-Altman method is that it is not affected by biases that influence correlational methods (Pearson, Spearman, and ICC correlation tests) (George et al. 2000). More evidently, each dot shown on the scatter plot graph indicates one observation from each data set. This attribute means this analysis differs from other correlation tests, in which cohort variables are considered. Furthermore, this method allows for detecting systematic error by investigating the distribution of the data, and the estimation of the size of the random error by calculating the range between the limits (Damsted et al. 2015; Giavarina 2015).

1.5 Results

1.5.1 Demographic Data

Twenty-five subjects (23 males and 2 females) met the eligibility criteria set and agreed to participate and sign the consent form. The descriptive statistics for the sample population are summarised below (Table 1).

Table 1. Participants' demographics data

Participants	Mean	±SD	Range
Age (years)	29.16	4.2	23 - 40
Height (cm)	172.64	7.2	154 - 186
Body Mass (Kg)	75.96	15.24	41 - 100.2
BMI (Kg/m^2)	25.49	4.18	17.29 - 31.93

Abbreviations: Cm= Centimetre, Kg= Kilogram, Kg/m^2= Kilogram per meters squared, m=meter, SD= Standard deviation

1.5.2 Normality testing and homogeneity of variance

Before commencing a statistical analysis, the Shapiro-Wilk test was employed to assess the normality of the data for each joint angle measure in both sagittal and frontal planes during the three functional tasks (Table 2). All the outcome measures in all planes of movement for all tasks were found to be normally distributed.

1.5.3 Descriptive statistics and statistical significance

The mean and standard deviations for the results for the lower limb joint angles recorded at the PKF during the tasks of DLS, SLS, and SLDH with the sensor-based 3D and camera-based 2D motion analysis methods are summarised below (see Table 3). In addition, paired sample t-test results were used to identify the statistically significant differences between the mean joint angle values, as provided by the two movement analysis methods presented in Table 3.

For the sagittal plane, mean hip, knee, and ankle joint angles at PKF, extracted via 3D and 2D movement analysis methods during all tasks, revealed a statistically significant difference ($p < 0.05$), except for the hip flexion during the SLDH task ($p = 0.736$) (Table 3). It was apparent that the mean hip flexion is always greater when measured in 2D (Kinovea) for all functional tasks (by 10.6° during DLS, 9.9° during SLS, and 0.7° during SLDH). Meanwhile, the mean knee flexion and ankle dorsiflexion at PKF were always greater when measured in 3D (MVN Analyze software) for all tasks (by 11.2° and 24.2° during DLS, 6.6° and 23.8° during SLS, and 3.5° and 15.6° during SLDH, respectively).

In terms of the frontal mean angles of the hip and knee joints at PKF during all tasks, a paired t-test exhibited a statistically significant difference between the mean joint angles extracted from the two movement analysis methods ($p < 0.05$). Mean hip and knee adduction was always greater when measured using 2D (Kinovea) for the SLDH task (by 8° and 5.3°, respectively). Conversely, during the SLS task, the mean hip and knee adduction were always greater when quantified with a 3D movement analysis (by 5.1° and 5°, respectively).

Also, it was noticed that the 2D frontal angles at hip and knee joints were found to be overestimated during the DLS task (mean frontal hip = 50.42° and knee = -60.37°) as compared to the same angles during the SLS and SLDH (mean frontal hip = -10.03° and -10.68°, and knee = -1.49° and -7.85°, respectively). Similarly, there was a huge variability between the 2D hip and knee frontal angles compared to the same 3D angles during the DLS task (mean frontal hip = 50.42° vs. 10.37° and knee = 60.37° vs. -2.61°, respectively).

Table 2: Normality testing results for all joint angle measures in sagittal and frontal planes during all functional tasks in the current study

Task	Plane of movement	Kinematics (Joint angles)	Shapiro-Wilk	
			Statistics	Significance
DLS	Sagittal	Hip Flexion (°)	.960	0.417
		Knee Flexion (°)	.969	0.619
		Ankle Dorsiflexion (°)	.969	0.625
	Frontal	Hip Abduction (°)	.937	0.129
		Knee Abduction/Adduction (°)	.933	0.103
SLS	Sagittal	Hip Flexion (°)	.933	0.103
		Knee Flexion (°)	.876	0.06
		Ankle Dorsiflexion (°)	.928	0.077
	Frontal	Hip Adduction (°)	.966	0.546
		Knee Adduction (°)	.979	0.863
SLDH	Sagittal	Hip Flexion (°)	.974	0.758
		Knee Flexion (°)	.967	0.593
		Ankle Dorsi/Plantarflexion (°)	.954	0.331
	Frontal	Hip Adduction (°)	.926	0.078
		Knee Adduction (°)	.968	0.606

Abbreviations: DLS= Double leg squat, SD= Standard deviation, SLDH= Single leg distance hop, SLS= Single leg squat, 2D= Two-dimensional, 3D= Three-dimensional, (°)= Degree

Key: Positive values (+) indicate flexion and dorsiflexion in the sagittal plane, and abduction in the frontal plane, Negative values (-) indicate extension and plantarflexion in the sagittal plane and adduction in the frontal plane

Table 3. Descriptive statistics for all lower limb joint angle measures at PKF in sagittal and frontal planes during all functional tasks

Task	Plane of movement	Kinematics (Joint angles)	3D MVN Mean (±SD)	2D Kinovea Mean (±SD)	P t-test
DLS	Sagittal	Hip Flexion (°)	106.85 (15.10)	117.46 (21.12)	<0.05*
		Knee Flexion (°)	124.16 (17.52)	112.94 (15.63)	<0.05*
		Ankle Dorsiflexion (°)	26.88 (6.48)	2.63 (6.85)	<0.05*
	Frontal	Hip Abduction (°)	10.37 (4.97)	50.42 (32.78)	<0.05*
		Knee Abduction/Adduction (°)	-2.61 (4.38)	60.37 (35.52)	<0.05*
SLS	Sagittal	Hip Flexion (°)	79.49 (17.83)	89.41 (19.03)	0.003*
		Knee Flexion (°)	89.95 (10.81)	83.4 (10.68)	<0.05*
		Ankle Dorsiflexion (°)	31.66 (5.33)	7.88 (6.83)	<0.05*
	Frontal	Hip Adduction (°)	-15.18 (5.66)	-10.03 (5.46)	0.001*
		Knee Adduction (°)	-6.52 (4.62)	-1.49 (10.21)	0.018*
SLDH	Sagittal	Hip Flexion (°)	51.45 (15.49)	52.14 (16.86)	0.736
		Knee Flexion (°)	61.48 (11.50)	58.02 (8.95)	0.003*
		Ankle Dorsi/Plantarflexion (°)	14.36 (6.82)	-1.2 (6.74)	<0.05*
	Frontal	Hip Adduction (°)	-2.24 (5.88)	-10.68 (5.54)	<0.05*
		Knee Adduction (°)	-2.50 (3.93)	-7.85 (10.13)	0.011*

Abbreviations: (°)= Degree, *= significant difference ($p < 0.05$), 2D= Two-dimensional, 3D= Three-dimensional, DLS= Double leg squat, P t-test= P value of the sample paired t-test, SD= Standard deviation, SLDH= Single leg distance hop, SLS= Single leg squat

Key: Positive values (+) indicate flexion and dorsiflexion in the sagittal plane, and abduction in the frontal plane, Negative values (-) indicate extension and plantarflexion in the sagittal plane and adduction in the frontal plane

1.5.4 Correlation and agreement

1.5.4.1 Interclass correlation coefficients

The ICC values for all the kinematic variables at PKF in the sagittal and frontal planes during all tasks were provided by sensor-based 3D and 2D movement analysis methods presented in Table 4. In the sagittal plane, the ICC values for the joint angles for the hip, knee, and ankle during all the tasks exhibited a moderate to excellent correlation (ICC = 0.735 - 0.968) between the two movement analysis methods. Specifically, the ankle dorsi/plantarflexion angles showed the lowest ICC values when compared to sagittal hip and knee angles in SLS and SLDH tasks (ICC ranges 0.735 – 0.790); meanwhile, the ICC values for the knee flexion angles were the highest across all tasks (ICC ranges 0.868 – 0.968) (Table 4).

In the frontal plane, the hip and knee joint angles demonstrated a poor correlation between the 2D and 3D movement analysis methods for all tasks (ICC = 0.137 – 0.369). The knee abduction/adduction angle was obtained with the lowest ICC values for each functional task in comparison to the hip abduction/adduction angle.

Table 4. The correlation between the 2D and 3D movement analysis methods using Interclass Correlation Coefficients (ICC) for all lower limb joint angle measures at PKF in the sagittal and frontal planes during all functional tasks

Task	Plane of movement	Kinematics (Joint angles)	ICC	95% CI
DLS	Sagittal	Hip Flexion (°)	0.762	0.46 to 0.90
		Knee Flexion (°)	0.968	0.93 to 0.99
		Ankle Dorsiflexion (°)	0.790	0.53 to 0.91
	Frontal	Hip Abduction (°)	0.150	-0.93 to 0.63
		Knee Abduction/Adduction (°)	0.138	-0.97 to 0.62
SLS	Sagittal	Hip Flexion (°)	0.797	0.54 to 0.91
		Knee Flexion (°)	0.868	0.70 to 0.94
		Ankle Dorsiflexion (°)	0.737	0.40 to 0.88
	Frontal	Hip Adduction (°)	0.137	-0.96 to 0.62
		Knee Adduction (°)	0.165	-0.90 to 0.63
SLDH	Sagittal	Hip Flexion (°)	0.879	0.73 to 0.95
		Knee Flexion (°)	0.895	0.76 to 0.95
		Ankle Dorsi/Plantarflexion (°)	0.735	0.40 to 0.88
	Frontal	Hip Adduction (°)	0.369	-0.46 to 0.73
		Knee Adduction (°)	0.32	-0.42to 1.99

Abbreviations: (°) = joint angle degree, CI= Confidence interval, DLS= Double leg squat, ICC= Interclass correlation coefficient, SLDH= Single leg distance hop, SLS= Single leg squat

Key: Green colour= Excellent correlation (ICC > 0.9), Yellow colour= Good correlation (ICC ranges 0.75 – 0.89), Orange colour= Moderate correlation (ICC ranges 0.50 – 0.74), Red colour= Poor correlation (ICC < 0.50)

1.5.4.2 Bland-Altman plots for agreement between the sagittal and frontal plane angular kinematics at PKF provided by the 2D and 3D movement analysis methods during the DLS, SLS, and SLDH tasks

Using the Bland-Altman method, a scatter plot was produced for each lower limb joint angle in both the sagittal and frontal planes (Figures 11, 12, and 13). The average mean differences and limits of agreements (LoAs) for all the joint angles are summarised in Table 5. Overall, the Bland-Altman plots in Figures 11, 12, and 13 depict the values for the joint angles at PKF in the sagittal and frontal during all tasks spread around the average mean difference and within the LoAs, aside from some outliers (shown as data points outside the lower and upper LoAs slightly outside the LoAs. However, a significant magnitude of bias was indicated, as the zero line (line of equality) is not located within the 95% confidence intervals for the average mean difference values for all sagittal and frontal joint angles, except for the hip flexion angle during the SLDH task (95% CI = -4.85 to 3.48) (Table 5).

In the sagittal plane angles at PKF during the SLDH task, the average mean difference values for hip, knee, and ankle joint angles were smaller (average mean difference = 0.69°, 3.45°, and 15.56°, respectively) than the same angles when measured during the DLS and SLS tasks. For the frontal plane angles at PKF during the DLS task; there were significantly greater average mean difference values for the angles at hip and knee joints (average mean difference = 40.05° to 62.98°, respectively) in comparison to those obtained during the SLS and SLDH tasks.

Interestingly, there were significantly greater average mean difference values for the frontal joint angles at hip and knee during the DLS (average mean difference = 40.05° to 62.98°, respectively) in comparison to those obtained during the SLS and SLDH tasks (average mean difference hip = -5.15° and 8.44°, and knee = -5.03° and 5.35°, respectively).

Table 5. Average mean difference and 95% LoA values for all the lower limb joint angle measures provided by the 3D and 2D movement analysis methods in the sagittal and frontal planes during all functional tasks

Task	Plane of movement	Kinematics (Joint angles)	Average mean difference° (±SD)	Confidence interval (95% CI)	95% LoAs
DLS	Sagittal	Hip Flexion (°)	-10.60° (15.92)	-4.03 to -17.17	-41.81 to 20.60
		Knee Flexion (°)	11.213° (6.344)	10.1 to 12.34	-1.22 to 23.65
		Ankle Dorsiflexion (°)	24.24° (5.33)	22.04 to 26.44	13.79 to 34.69
	Frontal	Hip Abduction (°)	-40.05° (31.71)	-53.14 to -26.96	-102.21 to 22.11
		Knee Abduction/Adduction (°)	-62.98° (34.26)	-48.84 to -77.18	-130.12 to 4.16
SLS	Sagittal	Hip Flexion (°)	-9.92° (14.87)	-5.48 to -17.29	-39.06 to 19.21
		Knee Flexion (°)	6.551° (7.22)	3.65 to 9.45	-7.60 to 20.71
		Ankle Dorsiflexion (°)	23.75° (5.32)	21.56 to 25.94	13.33 to 34.17
	Frontal	Hip Adduction (°)	-5.15° (7.22)	-2.20 to -8.09	-19.12 to 8.86
		Knee Adduction (°)	-5.03° (9.88)	-0.96 to -9.11	-24.4 to 14.33
SLDH	Sagittal	Hip Flexion (°)	-0.69° (10.09)	-4.85 to 3.48	-20.46 to 19.08
		Knee Flexion (°)	3.452° (6.11)	1.26 to 5.64	-8.52 to 15.42
		Ankle Dorsi/Plantarflexion (°)	15.56° (4.99)	13.5 to 17.62	5.77 to 25.35
	Frontal	Hip Adduction (°)	8.438° (6.94)	5.87 to 11.00	-5.16 to 22.04
		Knee Adduction (°)	5.349° (9.72)	1.34 to 9.36	-13.7 to 24.4

Abbreviations: (°)= joint angle degree, CI= Confidence Interval, DLS= Double leg squat, LoAs= Limits of agreement, Lt= Left lower limb, Rt= Right lower limb, SD= Standard deviation, SLDH= Single leg distance hop, SLS= Single leg squat

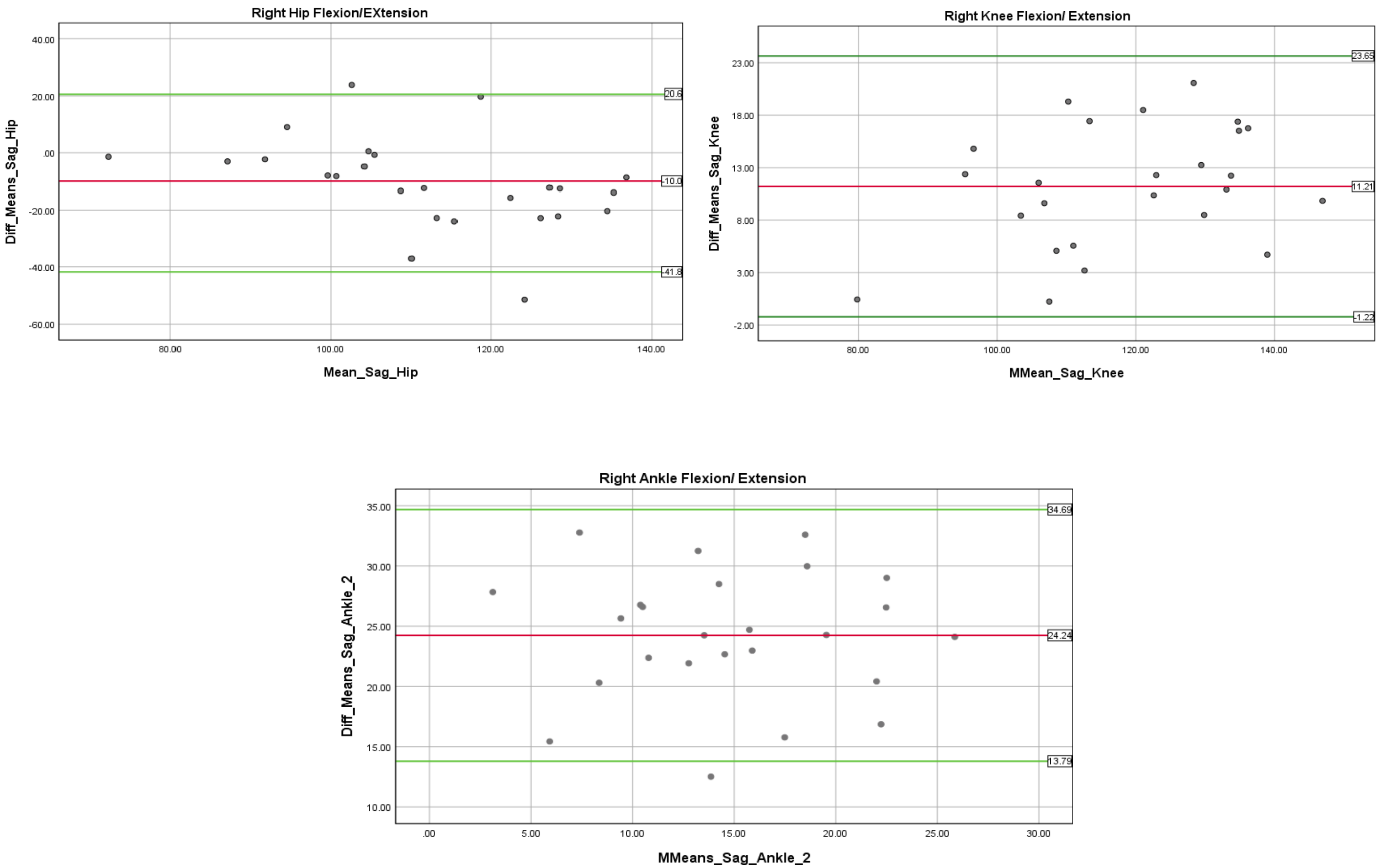


Figure 11. Bland-Altman plots based on 95% limits of agreement, comparing lower limb joint angles at PKF derived from the 3D and 2D movement analysis methods in the sagittal and frontal planes during the DLS task

Key: Solid red line represents the average mean difference between the two methods, while the upper and lower green lines represent the 95% limits of agreement, Diff_Means = Average mean difference, Frn = Frontal plane, MMean= Average means, Sag= Sagittal plane

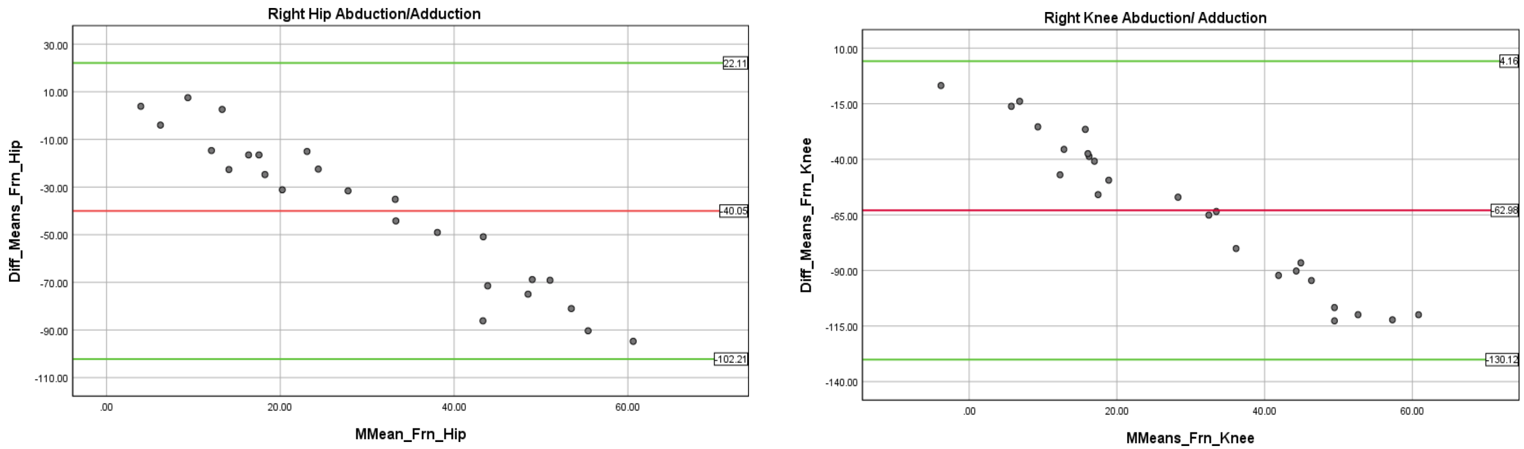


Figure 11. Bland-Altman plots based on 95% limits of agreement, comparing lower limb joint angles at PKF derived from the 3D and 2D movement analysis methods in the sagittal and frontal planes during the DLS task (continuous)

Key: Solid red line represents the average mean difference between the two methods, while the upper and lower green lines represent the 95% limits of agreement, Diff_Means = Average mean difference, Frn = Frontal plane, MMean= Average means, Sag= Sagittal plane

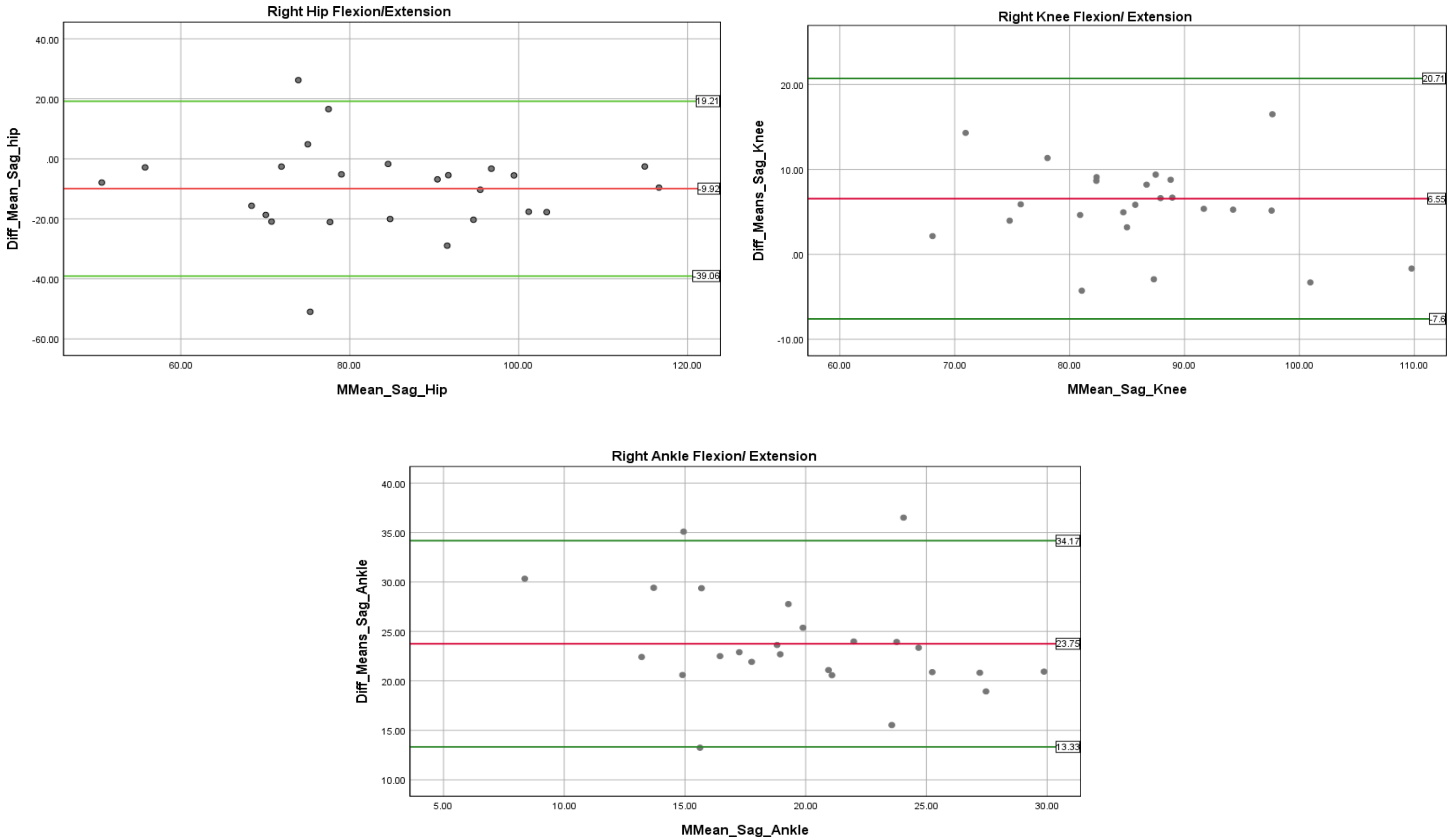


Figure 12. Bland-Altman plots based on 95% limits of agreement, comparing lower limb joint angles at PKF derived from the 3D and 2D movement analysis methods in the sagittal and frontal planes during the SLS task

Key: Solid red line represents the average mean difference between the two methods, while the upper and lower green lines represent the 95% limits of agreement, Diff_Means = Average mean difference, Frn = Frontal plane, MMean= Average means, Sag= Sagittal plane

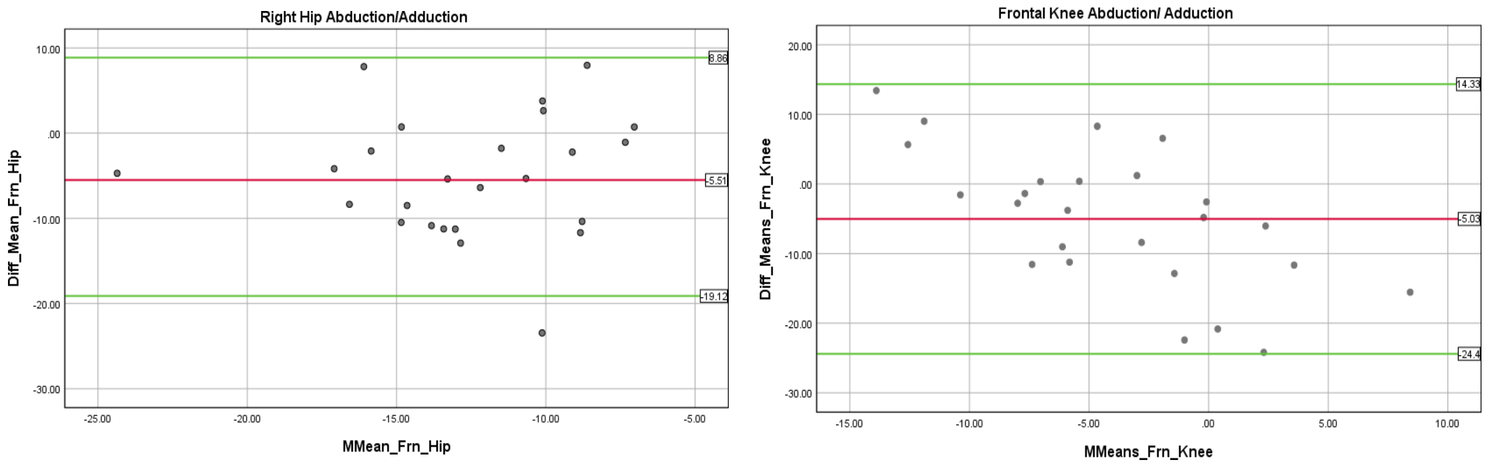


Figure 12. Bland-Altman plots based on 95% limits of agreement, comparing lower limb joint angles at PKF derived from the 3D and 2D movement analysis methods in the sagittal and frontal planes during the SLS task (continuous)

Key: Solid red line represents the average mean difference between the two methods, while the upper and lower green lines represent the 95% limits of agreement, Diff_Means = Average mean difference, Frn = Frontal plane, MMean= Average means, Sag= Sagittal plane

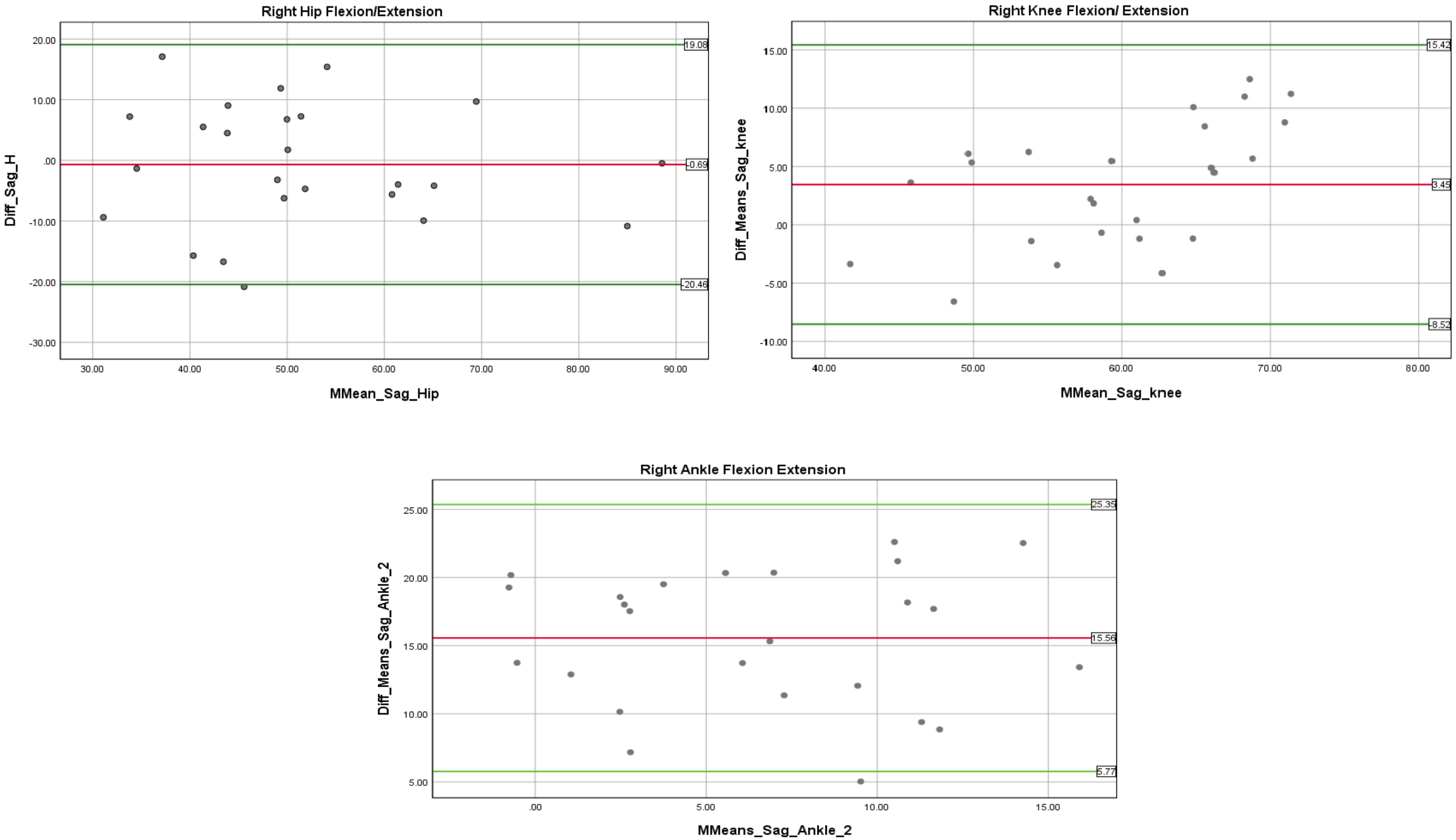


Figure 13. Bland-Altman plots based on 95% limits of agreement, comparing lower limb joint angles at PKF derived from the 3D and 2D movement analysis methods in the sagittal and frontal planes during the SLDH task

Key: Solid red line represents the average mean difference between the two methods, while the upper and lower green lines represent the 95% limits of agreement, Diff_Means = Average mean difference, Frn = Frontal plane, MMean= Average means, Sag= Sagittal plane

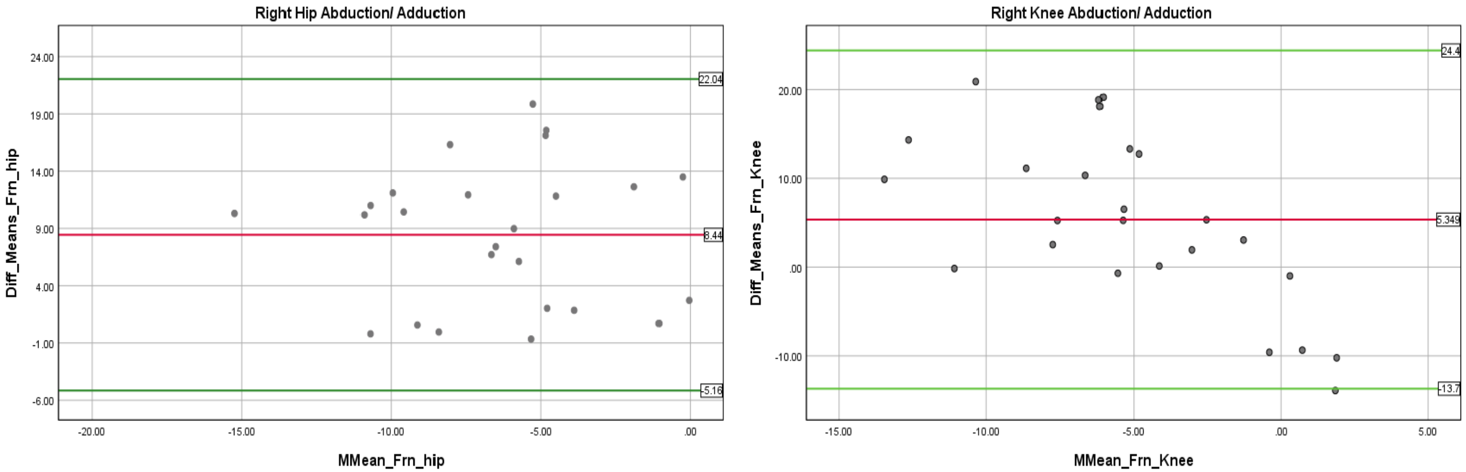


Figure 13. Bland-Altman plots based on 95% limits of agreement, comparing lower limb joint angles at PKF derived from the 3D and 2D movement analysis methods in the sagittal and frontal planes during the SLDH task (continuous)

Key: Solid red line represents the average mean difference between the two methods, while the upper and lower green lines represent the 95% limits of agreement, Diff_Means = Average mean difference, Frn = Frontal plane, MMean= Average means, Sag= Sagittal plane

1.6 Discussion

The aim of this study was to establish whether there is any correlation and agreement between sensor-based 3D movement analysis and 2D video analysis for quantifying lower limb joint angles in the sagittal and frontal planes during functional tasks (DLS, SLS, and SLDH). This is considered crucial to determine if sensor-based 3D movement analysis can play a role in clinical practice.

1.6.1 Summary of the main results

The ICC values for the sagittal angles measured at PKF for hip, knee, and ankle joints exhibited a moderate to excellent correlation between sensor-based 3D and camera-based 2D movement analysis methods during all tasks. However, for the frontal plane angles at PKF, a poor correlation was found between the two methods during all tasks at the hip and knee joints. Despite the correlation found in the sagittal angles, the findings of the paired t-test for almost all angles in the two planes showed statistically significant differences between the means for the joint angles at PKF provided by the two methods, aside from the hip flexion angle during SLDH.

The paired t-test findings were also supported by findings relating to the Bland-Altman plots. The majority of the plotted values were distributed around the average mean difference and within the 95% LoAs. However, a significant magnitude of bias was present, as the zero line was not within the 95% confidence interval for the average mean difference for almost all the joint angles in both planes during all tasks, except for the hip flexion angles during SLDH. Therefore, the findings from the current study rejected the two hypotheses that suggest lower limb joint angles quantified in the sagittal and frontal planes using the 2D and sensor-based 3D movement analysis methods during all tasks will be moderately correlated. It is concluded here that the two movement analysis systems (sensor-based 3D and camera-based 2D) were not comparable when measuring hip, knee, and ankle joint angles, especially in the frontal plane during functional tasks (DLS, SLS, and SLDH). Consequently, the two systems could not be used interchangeably in clinical practice.

Comparing the correlation findings in the sagittal and frontal planes with the previous literature

The findings of the current study agreed with the studies in the literature, which assessed joint angles in the sagittal (Norris and Olson 2011; Krause et al. 2015; Schurr et al. 2017) and frontal planes (Willson and Davis 2008; Scholtes and Salsich 2017; Schurr et al. 2017; Neal et al. 2020) during varied tasks. A study conducted by Schurr et al. (2017) reported less correlation for joint angles provided by a 2D video analysis and 3D movement analysis obtained by an electromagnetic tracking system in the frontal plane compared to those in the sagittal plane during the SLS task. The findings exhibited a significant moderate to strong correlation between the sagittal angles at the hip, knee, and ankle joints ($r = 0.93$, 0.86, and 0.51, respectively). However, there was a poor correlation between the two movement analysis methods in quantifying frontal angular kinematics at similar lower limb joints ($r = 0.28$, 0.03, and 0.39, respectively) (Schurr et al. 2017). These correlation findings were supported by Bland-Altman plots, which revealed small average mean differences for sagittal kinematics (at hip 2.60° and knee 0.74°) and higher values for frontal joint angles (hip 8.72° and knee 6.62°) (Schurr et al. 2017).

This reduced correlation between sensor-based 3D and 2D movement analysis methods when quantifying the lower limb joint angles in the frontal plane compared to angles in the sagittal plane at PKF during functional tasks may be explained by the subjective visual identification of PKF performed by the 2D video player goniometer software. In the current study, this was achieved by slowly forwarding the video episode frame by frame until it reached the lowest position, which typically takes a long period of time to accurately identify. On the other hand, recognising the PKF in the 3D movement analysis software (Xsens MVN Analyze) occurred objectively when observing the knee flexion angle to the point it reached its peak. This could be obvious when identifying PKF from the frontal plane, as it is more challenging than identifying it from the sagittal plane. This issue can be considered a limitation in the process of quantifying joint angles by 2D video analysis, which might result in inaccurate quantification of the joint angles. Therefore, the PKF obtained from the 3D movement analysis system may differ from those identified by the 2D Kinovea software, and thus the lower limb joint angles quantified by the two systems may not be comparable.

On the other hand, two studies demonstrated conflicting results to those in the current study during SLS (Gwynne and Curran 2014; Herrington et al. 2017). Herrington et al. (2017) and Gwynne and Curran (2014) exhibited a strong correlation between the frontal plane angles at PKF for the knee joint provided by the 3D and 2D movement analysis methods during a standardised SLS task ($r = 0.79$ and 0.78, respectively). These conflicting findings might be explained by movements at the hip and knee joints, which are significantly associated with transverse plane movements that could not be captured and quantified using 2D video analysis (Willson and Davis 2008; Ageberg et al. 2010). It has been suggested that the joint angles obtained by the 2D method are not a true representation of the angles obtained by the 3D method, since the 2D method was unable to quantify rotation (Wilson and Davis 2008). This explanation is supported by a study conducted by Ageberg et al. (2010). Ageberg et al. (2010) reported a significant difference in the knee valgus/varus angles among participants in the knee-medial-to-foot position and knee-over-foot position groups using a 2D video analysis (mean angles = -11° vs. -5°, $p < 0.001$, respectively). However, no significant difference was found for the same frontal knee angles among the groups using a 3D motion capture system (-6.1° vs. -5°, respectively). Ageberg et al. (2010) argued that the variability in knee angles provided by the two methods resulted from the greater hip internal rotation movements found in the group with knee-medial-to-foot position, as compared to the knee-over-foot position group. Consequently, when quantifying joint angles using a 2D method, knee flexion may look like knee abduction (out-of-plane error) when the movement is combined with medial rotation of the hip (Jones et al. 2014), particularly when knee flexion exceeds 40° (Cheng and Pearcy 1999). Therefore, Herrington et al. (2017) and Gwynne and Curran (2014) standardised the performance of the SLS task at 45° and 60° of knee flexion, respectively, to avoid the influence of rotational movements associated with frontal plane ones.

In the current study, the participants were not restricted in terms of how they performed the functional tasks. This was to ensure correlation during tasks that are usually performed within the clinical practice with no restrictions. Therefore, this issue of the combination of the transverse plane movements with the frontal plane ones as knee flexion increases could explain the overestimated 2D mean values for frontal angles at hip and knee joints when compared to the 3D angles, especially during the DLS task in the current study. It was observed that the 2D mean knee flexion angles were greater during the DLS than the SLS and SLDH (112.94°, 83.4°, and 58.02°, respectively). Consequently, the 2D frontal angles were found to be overestimated during the DLS task (mean hip abduction/adduction = 50.42° and knee abduction/adduction = -60.37°) as compared to the angles during the SLS and SLDH (mean hip abduction/adduction = -10.03° and -10.68°, and knee abduction/adduction = -1.49° and -7.85°, respectively).

In contrast, the mean values for the 3D frontal angles at hip and knee joints during DLS were 10.37° and -2.61°, respectively. The huge variability between the means for frontal angles provided by the 2D and 3D methods indicates that 2D frontal plane angles may be influenced by an out-of-plane error arising from the combined rotational movements that occurred simultaneously with frontal plane angles. This was supported by Willson and Davis (2008), who reported a poor correlation between the 3D motion capture systems and 2D video analysis when measuring the frontal plane angle of the knee joint during SLS (beyond 60° of knee flexion) ($r = 0.21$, $p = 0.195$). Therefore, this should be considered a significant limitation in terms of the use of 2D video analysis when quantifying frontal plane kinematics during functional tasks that involve a high degree of knee flexion.

Moreover, another contrasting study was conducted by Alahamri et al. (2020). Alahmari et al. (2020) reported a strong correlation between two 3D and 2D systems when quantifying the maximum frontal hip angle ($r = 0.79$) and a moderate correlation for maximum knee angle ($r = 0.42$) during a forward single leg landing (FSLL) task, which is comparable to the task of SLDH examined in the current study. This better correlation may result from the pre-standardised distance between the start point and the force platform (30 cm), which was determined for each participant to jump and land within (Alahmari et al. 2020). In the current study, the participant was asked to transfer themselves to a self-determined maximum distance. This may have affected the frontal plane movements due to the difficulty stabilising the lower limb and keeping balance during the landing phase of the task. Hence, the current study is not comparable with this conflicting study in terms of standardising the performance of the hop tasks (Alahmari et al. 2020), as the current study assessed the correlation during tasks that are usually performed within the clinical practice with no restrictions. Consequently, determining the PKF using a subjective visual approach to 2D movement analysis software could be more challenging, and it may result in variability when selecting precise time frames for PKF between trials in the current study, as compared to a study with conflicting results. Hence, the subjective identification of PKF should be considered a limitation when quantifying joint angular kinematics using a 2D video analysis system.

Another explanation for the reduced correlation between the joint angles obtained by the two movement analysis methods, especially in the frontal plane, is the variation in the frame rates of sensor-based 3D and camera-based 2D movement analysis in the current study (3D frame rates = 60 Hz and 2D frame rates = 30 Hz). It has been suggested that as long as the frame rate is faster, the quality of the episode recorded is improved, and the number of frames is increased, which is important to quantify angles at PKF (Alahmari et al. 2020; Neal et al. 2020). This might therefore influence the accurate selection of the same exact frame of PKF using the two movement analysis methods.

This potential explanation contradicts the findings of a study conducted by Neal et al. (2020). Neal et al. (2020) compared a high frame rate 2D video analysis system using smartphone cameras (240 Hz) with an optoelectronic 3D motion capture system (200 Hz) designed to quantify joint angles in PFPS individuals while running. Surprisingly, the findings exhibited a poor correlation between the angles of knee flexion and hip adduction as provided by the 3D and 2D systems (ICC = 0.42 and 0.06, respectively) (Neal et al. 2020). When comparing the findings of Neal et al. (2020) and those of the current study, Neal et al. (2020) mentioned two limitations in terms of the methods adopted to identify and calculate angles. Neal et al. (2020) used the markerless method to calculate angles at the hip and knee joints. However, in the current study, retroreflective markers were used to optimise the process of identifying bony landmarks during the quantification of angles, as recommended in the previous literature as a way to achieve more consistent findings (Gwynne and Curran 2014; Krause et al. 2015; Schurr et al. 2017; Kingston et al. 2020; Mousavi et al. 2020). Inaccurate results might arise when using the markerless approach, especially when landmarks cannot be identified easily due to adipose tissue and clothing. Moreover, Neal et al. (2020) used a touch screen tablet (10.2-inch screen size), with Hudl techniques applied, to quantify the angles, while the current study used computer-based Kinovea software (24-inch screen size). Utilising a large screen and a computer mouse might afford greater accuracy when analysing 2D videos, as it requires clear observation and identification of the bony landmarks to draw lines between them and form accurate angles. Therefore, the study by Neal et al. (2020) was not found to be comparable with the current study, and thus it is still unclear whether using a 2D video analysis with a higher frame rate frequency would enhance accuracy.

Sensor-based 3D movement analysis system (Xsens MVN Analyze) has an advantage in terms of offering selections of a range of frame rates (60 Hz, 90 Hz, 120 Hz, or 150 Hz) prior to commencing recording and collecting angular kinematic data. However, the frame rates for the 2D video analysis are based on the specifications of the camera used. Therefore, this consideration could limit the use of 2D video analysis within clinical practice, as a camera with a high frame rate may be required.

Overall, the reduced correlation and agreement for sagittal and frontal joint angles provided by the sensor-based 3D and 2D movement analysis methods during tasks was potentially due to the several limitations related to the 2D video analyses. These 2D limitations included subjective identification of the PKF, an inability to quantify the transverse plane movements associated with frontal plane ones, and the reduced frame rates used. Sensor-based 3D movement analysis can potentially eliminate all the limitations associated with the use of a 2D video analysis.

Limitations

Several limitations may have affected the results of this comparison study. The first limitation is that the dominant lower leg was not determined for each participant. Based on Ford et al. (2003), high risk neuromuscular characteristics were very apparent in the dominant leg compared to the non-dominant one. The dominant leg is thus more prone to experiencing excessive frontal plane movements at the knee joint. Potentially, a greater correlation and agreement may be found between the 2D and 3D movement analysis methods when measuring the frontal plane angle at the knee joint for participants exhibiting excessive knee valgus during a landing task. It would be ideal for the dominant limb to be determined and analysed by the two movement analysis methods. However, as long as the two movement analysis methods are used in a consistent and robust manner, the same correlation findings should result.

A further limitation associated with the 2D system used in the current study related to marker identification during the process of joint angle quantification. Some markers were difficult to identify due to the natural biomechanical variability between participants that presented during the performance of the tasks. For instance, excessive trunk flexion was accompanied by the movements of some of the participants during the descending phase of the squatting tasks and during the landing phase of the hopping task. This trunk movement may cover the ASIS markers with the participant's body, which makes them invisible to the researcher when seeking to identify the ASIS markers and measuring hip and knee frontal kinematics using 2D software (Kinovea). Similarly, in some cases, the lateral femoral epicondyle markers were covered by the participants' arms when performing tasks. In order to manage this, the location of the covered marker was estimated by drawing a line bisecting the frontal surface of the thigh (ASIS) and a line bisecting the lateral surface of the thigh (later femoral epicondyle). This alternative method was utilised in the previous literature, and a good correlation was found between 3D and 2D movement analysis methods (Krause et al. 2015; Scholtes and Salsich 2017).

Finally, this study included a sample population of healthy and recreationally active adults recruited in a university setting. Of the 25 subjects, only a small number of female subjects (n = 2) were involved in this study, which may limit the external validity of the findings. It would be nice to test this in a pathological knee sample, but this did not prove to be practically possible. However, as the study mainly aimed to assess the correlation and agreement between the two movement analysis methods when quantifying the angular kinematics, the consistent accurate methods used in the current study to measure angles might result in the same findings. Additionally, the current study was a preparatory early developmental study that afforded the lead researcher the opportunity to practice data collection and analysis and identify challenges associated with both systems. Therefore, it should be acknowledged that this study was not the core component of this PhD thesis.

Clinical implications

Assessing movement patterns in the sagittal and frontal planes is crucial and is considered key when assessing individuals with knee pain. Several limitations, related to the use of a 2D video analysis in comparison to a 3D analysis provided by IMU sensors, restrict its use in clinics. These were highlighted in this study, as the 2D video analysis had limitations in terms of its inability to quantify transverse plane angular kinematics, subjective long-time identification of PKF and quantification of angles, and reduced frame rate. Moreover, the clinical use of 2D video analysis could be restricted due to issues of privacy and consent for video recording participants. It is also important to state that the 3D and 2D systems cannot be used interchangeably to measure angular kinematics, as concluded by this study. Therefore, if physiotherapy clinicians are looking for a more usable comprehensive movement analysis method that includes the sagittal, frontal, and even transverse planes, IMU sensors could be considered as an alternative method to be used within the clinical setting.

Conclusion

The aim of this study was to assess the correlation and agreement between the 3D movement analysis tool obtained by IMU sensors and a 2D video analysis for quantifying lower limb joint angles in the sagittal and frontal planes during functional tasks. The findings of this study suggested that the camera-based 2D movement analysis using the video player goniometer software (Kinovea) was not comparable when compared with the sensor-based 3D movement analysis system using MVN analyze software to quantify lower limb angular kinematics. As the use of a 2D movement analysis method is associated with several fundamental limitations in clinical practice, future research should be further directed to identify how kinematic data provided by sensor-based 3D movement analysis can be presented to clinicians, interpreted by them, and whether such data can impact their clinical decision making.

Appendix C: Rating sheet used in (Phase I) by raters to identify the presence of altered movement patterns and interpret in writing if it is presented

Report number:

Functional Tasks	Planes of movement	Joints	Altered movement pattern (YES or NO)	If YES, what is the altered movement pattern	Consistency (YES or NO)
Walk	Sagittal plane	Hip joint			
		Knee joint			
		Ankle joint			
	Frontal plane	Hip joint			
		Knee joint			
		Ankle joint			
Double Leg Squat	Sagittal plane	Hip joint			
		Knee joint			
		Ankle joint			
	Frontal plane	Hip joint			
		Knee joint			
		Ankle joint			
Stair Ascent	Sagittal plane	Hip joint			
		Knee joint			
		Ankle joint			
	Frontal plane	Hip joint			
		Knee joint			
		Ankle joint			

Appendix D: The sample size required in (Phase I) which is based on Table 2 adapted from Donner and Rotondi (2010)

Table 2: Number of subjects N required to ensure that the expected lower limit of a 95 % one-sided confidence limit for κ is no less than κ_L

			Number of Raters (n)			
κ_0	κ_L	π	2	3	4	5
		0.10	559	373	301	255
0.50	0.40	0.30	264	146	112	95
		0.50	228	120	89	76
		0.10	140	94	76	64
0.60	0.40	0.30	66	37	28	24
		0.50	57	30	23	19
		0.10	463	311	247	207
0.70	0.60	0.30	205	124	99	87
		0.50	174	102	81	73
		0.10	116	78	62	52
0.80	0.60	0.30	52	31	25	22
		0.50	44	26	21	19

Appendix E: Summary of comments on agreement of coding process among the lead researcher (M.F.) and the second reviewer (K.B) (Phase I)

	gait	Double leg squat	Stair ascent
Amount description	General comment, there seems to be an overlap with the theme called 'direction'. Are they the same? We need a definition of both to distinguish how they are different otherwise we will need to combine.		
Amount description	Good but should the word 'altered' be included? I agree it is non-specific but we don't have a code for this	Good but 'increased' is a term that should also be included	This is mixed up with the coding for 'direction'
Amount number	I AGREE	I AGREE	I AGREE
Compensation peak	I AGREE	I AGREE	I AGREE
Compensation ROM	I AGREE	I AGREE	I AGREE
Compensation timing	Check – I think text such as 'early stance' should be coded as 'event phase'?	I AGREE	Check – texts as the following should be coded i.e. alteration in timing, rapid knee adduction, asynchronous wave form, delayed peak
Compensation unspecified	I AGREE	I AGREE	I AGREE Check if text as 'reduced knee flexion stepping on and climbing onto step' unspecified? For this task, would we expect range or peak or timing to be mentioned?
Event cycle	I AGREE	I AGREE	I AGREE

Event phase	Discuss and check as some may be missed out. I think you have coded initial swing phase, mid swing phase and early swing as discrete time points. That is fine if you have consistently done this.	I AGREE	I AGREE – Discuss when a text is a phase or discrete time point.
Event discrete time point	I AGREE	Check the coding and make sure no 'phases' have been included	Discuss – Is 'through step up phase' a phase or DTP? Is 'during step' a phase or DTP?
Events unspecified	I AGREE Check terms such as 'throughout stance' should be coded as 'phase'	Discuss and agree that 'reduced peak flexion is a discrete time point i.e. occurs at maximum squat. (Check coding)	I AGREE
Direction specified	I AGREE	I AGREE	I AGREE
	Please see my previous comment about amount. Does direction refer more to the plane of movement?		
Direction unspecified	Check 'too much' when coupled with flexion is a direction but this is an example of why there is overlap with amount	Should 'too much' be included here? Should the following texts be included? 'Opposite movement', 'maintained hip flexion'	I AGREE

Appendix F: Codes for 'Phase' and 'Discrete time point' categories in theme 'Event' identified in (Phase I)

Category	Proposition	Overground gait	Double-leg squat	Stair ascent
Event (Phase)	During Through Throughout From… till… As	-Stance phase -Early stance -Mid stance phase -Late stance -Initial stance phase -Terminal stance phase -Loading response -Heel strike to swing -Mid to late stance -Mid stance to terminal stance -Mid stance to mid swing -Push off to swing -Swing phase -Early swing -Initial swing -Swing to heel strike -Mid swing phase -Late swing	-Squatting phase -Initial descent phase -Mid descending to mid ascending -From mid descent to late ascent -increasing squat depth -From full flexion back to extension -Through decent and ascent -During ascent -Mid ascent phase -Early ascending phase -at mid of descending till end of squat cycle -during all ascending squat cycle	-Swing -Initial stance phase -Raises and plants foot onto step -Stepping onto and when climbing onto step -Step up phase -Lifting leg onto step -As pushed onto step -During raising leg and initial contact with step -Swinging step and at initial contact through to push into extension -Leg in air to end of push off -Through early stance to swing -Stance phase -Mid stance phase -Late stance -From mid to late cycle -From stance to late swing -Last phase of cycle -Through mid-cycle -Early in cycle

				-Swing phase -Initial swing phase -Mid and late swing phase -Late in cycle -on weight bearing -During step
Event (discrete time point)	at on in	-Initial contact -Heel strike -Initial stance -Early stance -Mid stance -Late stance -Terminal stance -Mid of terminal stance -Toe off -Initial swing -Early swing -Mid swing -Terminal swing -End of loading response -Mid of pre-swing -Mid of terminal swing	-Start of movement -Mid squat position -At full squat depth -At max squat depth -Peak knee flexion -At full squat -At deep squat position -Peak of descending -Start of ascending -Beginning of ascending squat	-Initial contact -Initial weight bearing on step -At Weight acceptance -At contact with step -Foot contact -Foot strike -Foot clearance - At stepping onto step -In Early stance -in Mid stance -at Mid cycle -at Late cycle -At start of SA -Lift off -Toe off -Lifting foot off floor

				-Second foot contact -Double support -peak flexion -full squat depth -Vertical thrust

Appendix G: Physiotherapy clinician guideline which provides an overview of the recruitment and data collection procedures used in (Phase II)

Eligibility Criteria

Inclusion criteria:

- Adults aged 18+ years
- Patients complaining of knee pain for more than 3 months and on most days of the previous month.
- Have activity related joint pain
- Have either no morning joint-related stiffness or morning stiffness that lasts no longer than 30 minutes.

Exclusion Criteria:

- Patients with lower limb pathologies that impair walking and movement
- Lower limbs neurologic deficits
- History of lower limb surgery

Data Collection Procedure

Each participant will have three additional kinematic screening sessions over a period of two months, at two weeks, five weeks, and eight weeks, in addition to their standard rehabilitation. The participants will be asked to perform six tasks in their way (DLS, SLS, jump, stair ascend and descend, and walk). A series of semi-structured interviews will be conducted with the participants following completion of the final screening session.

Contact us for information.

[redacted]

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

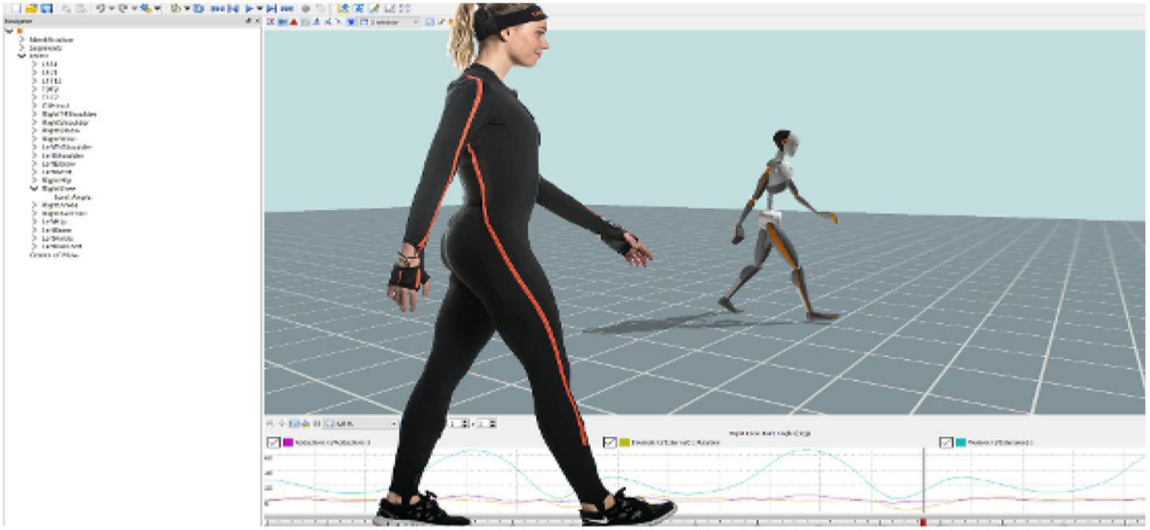
BIOMECHANICS & BIOENGINEERING RESEARCH CENTRE VERSUS ARTHRITIS

SENSOR-BASED MOVEMENT ANALYSIS FEEDBACK TOOLKIT

PHYSIOTHERAPIST GUIDELINE

WHAT IS IT?

The participants will continue to receive their standard physiotherapy care, but in addition will receive sensor-based motion analysis feedback regarding their movement performance over a range of functional tasks.



In these motion analysis feedback sessions, the patient will be asked to perform several functional activities while the researcher collects their kinematic measurements. A report of the kinematic variables will be sent to the physiotherapist following completion of each motion analysis session, in order to guide the physiotherapist, and to target he rehabilitation programme.

Why is it needed?

1. It provides physiotherapist with a precise movement assessment of several joints in different planes of movements while participant is performing dynamic functional tasks

2. It could be an inherent solution for the imitations of employing the traditional observational analysis methods and the laboratory-based motion analysis systems in clinical practice

3. The report generated is used for guiding clinicians with their clinical decision-making in managing and preventing injuries by identifying the alterations of movement patterns and consequently targeting the most effective rehabilitation programme

Recruitment

Physiotherapist screens patients with general knee pain during a self-referred visit to a physiotherapy clinic within CVUHB.

↓

If the patient satisfy the eligibility criteria (next page) for inclusion in this research trial, physiotherapist will discuss the nature of the research, and provide the patient with the related Participant Information Sheet.

↓

Physiotherapist asks the interested patient to attend the follow-up appointment earlier by an hour, and send an email to the researcher (Mohannad Felemban) with a brief summary about the patient condition (first appointment only) and the time for the follow-up appointment.

↓

Following the data collection session, a movement analysis report will be sent to the accessible email for the physiotherapy department in addition to an avatar (on laptop screen) which shows the performance of the patient during the functional tasks will be available.

↓

Physiotherapist shares report (see training information sheet) and avatar with the patient and use it to plan treatment.

Appendix H: Movement analysis feedback report interpretation guideline for physiotherapy clinicians used in (Phase II)

Sensor-Based Movement Analysis Feedback Toolkit

(Report's Interpretation Guideline)

Done by:

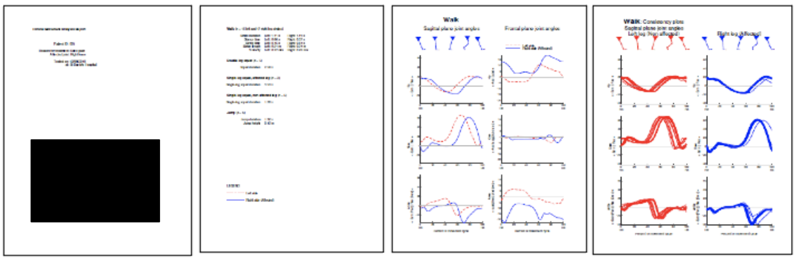
Mohannad Felemban

PhD candidate, Cardiff University

- **Content:**

A clinical movement analysis will be sent to the physiotherapist by the end of each movement analysis session. Each report includes the following information:

- ➢ Patient's details including the side of the affected knee joint and the data and time of the movement analysis session (first page) (graph 1a).
- ➢ Summary of performance measures including temporospatial measures for gait, squat duration for double and single leg squat, step duration for stair ascend and descend, and jump duration and height for jump (second page) (graph 1b).
- ➢ Graphs present the average joint angle waveforms for hip, knee and ankle joints in the sagittal and frontal planes during the movement cycle. Each graph presents the waveform for the affected and non-affected sides (subsequent pages) (graph 1c).
- ➢ Consistency plots show the joint angle waveforms for all movement trial performed before being averaged (separate pages) (graph 1d).



(a) (b) (c) (d)

Graph 1: example of movement analysis report content

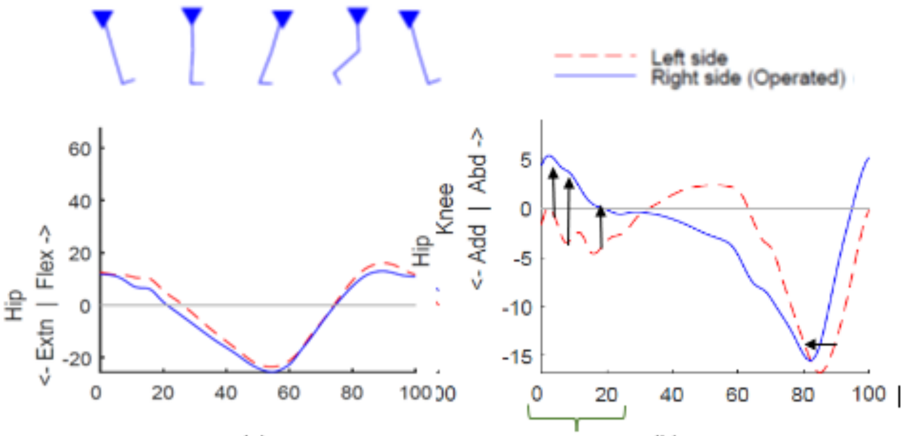
- **Graphs Interpretation:**

The interpretation of the graphs is based on the comparison of the waveforms for the affected and non-affected joint sides. The two waveforms in the graph may be compared according to the three following categories:

- ➢ **Amount:** the size or the magnitude of the compensation strategy. This could be described in text or number (graph 2).
- ➢ **Nature:** The type of the compensation strategy. This could be described as peak, range of motion or timing (graph 2).
- ➢ **Event:** The time when the compensation strategy happened along the movement cycle. This could be described as in the entire movement cycle, the phase or the discrete time point (graph 2).

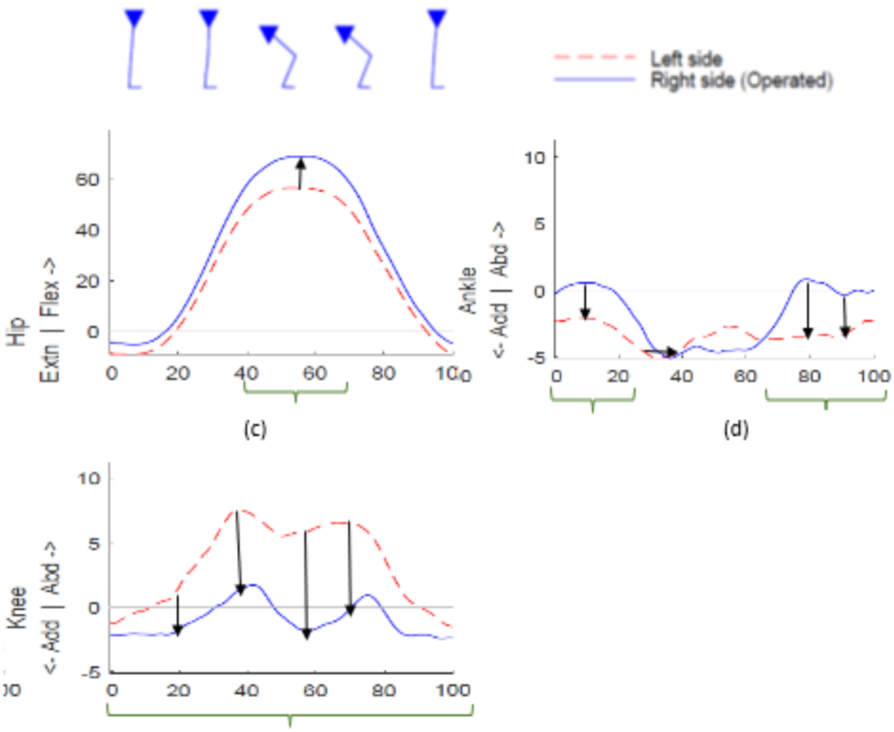
Graph 2: Examples of graphs interpretation during different functional activity tasks

➤ **Walk**



(a) (b)

➤ **Double Leg Squat**



(c) (d)

(e)

- **Amount** ↑ Increase ↓ Decrease → Delay ← Early
- **Event** The phase or cycle when compensation strategy occurred

The point of time when compensation strategy occurred (DTP)

Graphs Interpretation:

	Amount	Side	Nature	Variable	Event
a	No compensation Strategy				
b	-Increase ↑ -Early ←	-Rt -Rt	-ROM -Timing	-Knee abduction -Peak knee adduction	-During early stance phase -At mid swing phase
c	Increase ↑	Rt	Peak (maximum)	Hip flexion	During late descending and early ascending phase
d	-Decrease ↓ -Delay →	-Rt -Rt	-ROM -Timing	-Ankle adduction -Peak ankle adduction	-During early descending and late ascending phase -At late descending prior to maximum squat
e	Decrease ↓	Rt	ROM	Knee abduction	Throughout squat cycle

Appendix I: (a) Patient Information Sheet (PIS), (b) Consent Form (CF), and (c) Permission to contact form given to individuals with knee pain, used in (Phase II)

(a) Patient Information Sheet (PIS)

Insert local header / logo

Biomechanics and Bioengineering Research Center Versus Arthritis

PATIENT INFORMATION SHEET

Assessment of joint function in patients with joint problems using three-dimensional motion analysis techniques

We would like to invite you to take part in a research study.

- Before you decide if you would like to take part it is important for you to understand why the research is being done and what it will involve.
- Please take some time to read the following information sheet carefully and discuss it with friends or relatives if needed.
- It is your decision whether or not to take part.
- Ask a member of the study team if you have any questions about the research.
- If you decide to take part in this research but later change your mind you are free to withdraw at any time. This will not affect any of your NHS care.

Important Information about this Research

- Taking part in this research will not change your NHS treatment in any way.
- This research is part of a series of studies being conducted by the Biomechanics & Bioengineering Research Centre Versus Arthritis (BBRCVersusArthritis) at Cardiff University.
- Participating in this research could involve visits to Cardiff University School of Engineering, or School of Healthcare Sciences, additional to any NHS care.
- During study visits you may be asked to complete some questionnaires.
- We would also like to collect information about your diagnosis and treatment from you and from your medical records
- We do not expect there to be any direct benefit for people who take part in this research
- The information we collect in the research will help improve our understanding of how people with joint problems move.

Page 1 of 10 Version 12.1, 06 September 2019

What is the purpose of this research?
This research is part of a series of studies being carried out by the Centre Researchers, Orthopaedic Surgeons and Physiotherapists.

We are interested in knowing more about how people with joint (e.g. knee) and back problems move when performing normal activities such as walking, standing, bending etc. We aim to investigate how treatment (operation or physiotherapy) changes the way you move and how your movement compares with people without joint or back problems.

We are interested in learning about changes that happen within the affected joints. In order to do this we may ask if you are willing to take part in some of the related Centre studies.

We hope that the information we collect in this research can be used to develop new tools to help orthopaedic surgeons and other health professionals with the diagnosis and management of joint and back problems.

Why am I being asked to take part?
You have been asked to take part because you fall into one, or more, of the following categories:

- Are currently on a waiting list for orthopaedic, physiotherapy or rheumatology treatment
- Have received treatment for a joint or back problem
- Have previously taken part in Centre research.
- Have a joint problem we are interested in looking at with this technique

If you are on a waiting list for surgery, your surgeon has agreed that you may be suitable to take part in this research.

What does taking part involve?
This research is being carried out in a number of different settings. If you decide to take part in the research you will be asked to attend one of the following locations;

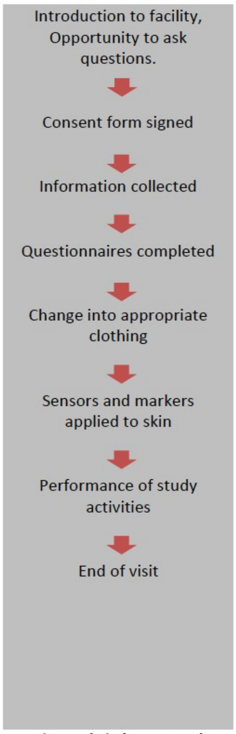
- **The Musculoskeletal Biomechanics Research Facility** (Cardiff University School of Engineering), or;
- **The Research Centre for Clinical Kinaesiology** (Cardiff University School of Healthcare Sciences).
- **A relevant clinical setting such as an NHS clinic**

The number of times you will be asked to attend will depend on your specific joint problem. Patients with back problems may only be asked to attend a single session. If you are waiting for an operation you may be asked to attend a session before your operation and further sessions during your post-operative recovery. You may be asked to attend a maximum of six sessions over a period of five years.

Before any study activities are performed you will be introduced to the research facility. A researcher will talk you through the specific requirements of the study. You will have an opportunity to ask questions about the research and the study setting. Each session will last between 30 minutes and three hours. The length of the visit will depend on the joint and treatment under investigation. After attendance at the session you will be reimbursed for reasonable travel expenses

If you are happy to take part in the study we will ask you to sign a consent form

After you have signed a consent form we will ask you about your joint problem and take some measurements (e.g. height and weight, limb circumference)



You may also be asked to complete some questionnaires and be asked to answer some questions on your joint problem and how it affects daily life.

To prepare for the movements you will be asked to change into **appropriate clothing**. For lower limb problems this is usually loose fitting shorts and t-shirt. Patients with back problems may be asked to wear a sports bra or swimming costume. If you do not have appropriate clothing this can be provided by the researcher. Your modesty and dignity will be respected throughout the visit.

A selection of **reflective markers** will be placed at specific points on your; feet, legs, lower back, spine and arms. These markers are held in place with sticky tape. The markers help the motion capture system track your movements – see pictures on the next page.

For the final part of the visit you will be asked to perform a selection of movements that will be appropriate to your specific joint or back problem.

Throughout the session you will be given the opportunity to rest and take regular breaks. During the session you will not be expected to perform any activities that cause you pain and discomfort.

Throughout the visit you will be asked to perform repeated movements. The number of times each movement is repeated will vary depending on the joint under investigation. These movement tasks may include:

Back	**Hip, Knee and Ankle**	**Shoulder and Elbow**	**Wrist**
Bending	*Walking*	*Lifting light objects*	*Grip*
Stretching	*Up and down stairs*	*Range of motion*	*Range of motion*
Sit to stand	*Sit to stand*	*Reaching for objects*	
	Standing on one leg		
	Up and walk from a chair		

Some of these movements may be performed on a special treadmill. The treadmill is set at floor level and can rotate in multiple directions to replicate uneven ground. In some circumstances these treadmills will be set within a virtual reality environment. When using the treadmill you will be asked to wear a safety harness to prevent falls.

The treadmill is not used for patients awaiting joint replacement.

Depending on the joint being studied; muscle activity, function and joint strength may also be measured. Measuring muscle activity involves the placement of muscle sensors, called electrodes, on the surface of the skin. The location of the sensors will depend on the joint that is being studied. In some circumstances it may be necessary to shave hair from the area where the senor is to be placed. In some cases, muscle function is measured with the use of a small electrical muscle stimulus during certain movements to activate the muscle and produce a change in movement. This may cause a strange feeling but will not be painful. To test joint strength you may be asked push or pull against a resistance. This may involve your limb being strapped into a machine while performing movements.

During the session your movement may also be recorded using standard audio-visual equipment (e.g. video camera). These recordings are used to verify the data collected by the motion capture system. If recordings are used in any presentations or publications, digital masking (removal of features) will be used to ensure that you cannot be identified from the video files.

You may also be asked to perform the following movements as fast as you can without pushing yourself to overexertion and within a short set time: standing and sitting from a chair, standing from a chair and walking, walking on level ground, ascending and descending stairs.

Before you decide if you would like to take part in the research a member of the study team will talk you through the exact requirements for your study visit(s).

Examples of Sensor and Marker placement for Low Back Pain (left picture) and lower limb (right picture)

 Version 12.1, 06 September 2019

What are the potential risks and benefits of taking part?

The reflective markers and sensors are placed with sticky tape or adhesive silicon rubber. The removal of these items may cause some mild discomfort, similar to removing a sticking plaster.

You may experience some temporary pain in the affected joint associated with the study activities. This risk will be limited by allowing breaks during the visit and limiting the activities performed to those which you are comfortable with

There is no intended clinical benefit for people taking part in the study. The information we collect from patients may help us to provide future patients who have joint disease or injury with improved treatment options.

What will happen to my information?

After you have signed a consent form you will be assigned a unique number. from then on, this number will be used to identify you throughout the study.

All electronic data will be held securely on NHS or University computers. Access to this information will be restricted to members of the research team.

As well as the data collected at the study visits we may also collect some routine data from your medical records. This may include information about your operation, diagnosis and treatment, where it is relevant to your participation in this study.

Cardiff University is the sponsor for this study based in the UK. We will be using information from you and your medical records in order to undertake this study and will act as the data controller for this study. This means that we are responsible for looking after your information and using it properly. Cardiff University will keep identifiable information about you for up to 15 years after the study has finished.

Your rights to access, change or move information are limited, as we need to manage your information in specific ways in order for the research to be reliable and accurate. If you withdraw from the study, we will keep the information about what we have already obtained. To safeguard your rights, we will use the minimum personally-identifiable information possible. You can find out about how we use your information by contacting the project lead detailed on the next page.

[redacted]

The NHS will use your name, NHS number and contact details to contact you about the research study, and make sure that relevant information about the study is recorded for your care, and to oversee the quality of the study. Individuals from Cardiff University and regulatory organisations may look at your medical and research records to check the accuracy of the research study. The NHS will pass these details to the Biomechanics and Bioengineering Research Centre (Cardiff University) along with the information collected from you and/or your medical records. The only people in Cardiff University who will have access to information that identifies you will be people who are conducting the research, those who need to contact you about the study or audit the data collection process.

The NHS will keep identifiable information about you from this study for at least 10 years after the study has finished..

With your consent, anonymous data collected in the study may be shared with other institutions, including Universities and commercial organisations.

You will not be identified in any reports, presentations or publications relating to this research.

Other Useful information about this study.

Occasionally, during a research project, new information may become available. If this happens you will be contacted by a member of the research team to explain how this may affect you and your participation in the research.

We do not routinely send a letter to your GP to inform them that you are taking part in this research. However, we would still like to collect the details of your GP for the study. This will only be used to ensure that it is still appropriate to contact you for study follow-up visits.

This research has been reviewed approved by Wales Research Ethics Committee 3 (REC3) and is managed by Cardiff University.

If something goes wrong and you are harmed due to negligence, you may have grounds for legal action. If you wish to make a complaint about the way you were approached or the treatment you have received within the study please contact [redacted] If you feel your complaint is not adequately addressed, you may escalate your complaint by writing to: [redacted]

As well as being asked to take part in this research you may also be asked if you are interested in taking part in some of the other Centre studies.

For each of these studies you will be provided with a further information sheet and have the opportunity to ask questions. For each additional study you will be asked to sign a consent form before and research activity is performed.

What happens next?

This information sheet covers research into a wide range of joint and back problems. The study requirements vary depending on the joint under investigation and the planned treatment.

If you still have questions after reading this information, please contact a member of the research team.

Contact Details:

Centre Manager
[redacted]

NHS Site
INSERT LOCAL NHS CONTACT DETAILS HERE

Project Lead / Contact
INSERT CARDIFF UNIVERSITY PROJECT LEAD DETAILS HERE

Thank you for taking time to read this information sheet

More information about the Biomechanics and Bioengineering Research Centre Versus Arthritis can be found by visiting:
http://www.cardiff.ac.uk/arthritis-biomechanics-bioengineering-centre

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(b) Consent Form (CF)

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

Insert local header / logo

PATIENT CONSENT FORM

Page 1 of 2

Assessment of joint function in patients with joint problems using three dimensional motion analysis techniques

Centre ID: ☐☐☐☐☐ **Project Name:** ______________________

You DO NOT have to sign this document. Please DO NOT sign this document unless you fully understand it. If there is ANYTHING which you do not understand please do not hesitate to ask for a full explanation.

To confirm agreement with each of the statements below, please <u>initial</u> each box and delete where applicable:

1. I confirm that I have read and understand the information sheet dated 06 September 2019 (Version 12.1) for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.. ☐

2. I understand that my participation in the study is voluntary and that I am free to withdraw at any time, without giving any reason, and without my medical care or legal rights being affected but any data collected up to the point of my withdrawal will be kept. ☐

3. I understand that relevant sections of my medical notes and other data routinely collected by the NHS related to my treatment may be looked at by individuals from Cardiff University, from regulatory authorities and from NHS Organisations where it is relevant to my taking part in the research. I give permission for these individuals to have access to my medical records. ☐

4. I agree for my movements to be recorded using audio-visual equipment. I understand that digital masking will be used to ensure my anonymity if the footage is used in any publication or presentation. ☐

BIOMECHANICS & BIOENGINEERING RESEARCH CENTRE
VERSUS ARTHRITIS

Page 9 of 10 Version 12.1, 06 September 2019

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

PATIENT CONSENT FORM

5. I understand and agree that the research team will securely store my identifiable details in order to contact me in future regarding this study (e.g. telephone/text/email). Identifiable details, including a copy of the consent form, will be available only to the research team, other than for purposes of monitoring and audit. ☐

6. I agree to take part in the above study. ☐

Optional

I agree that anonymous information collected during the study may be shared with external collaborators in the UK and abroad, including commercial companies. ☐

I agree to be contacted in the future to ask if I would be interested in taking part in future research into my joint/back problem. ☐

Name of Participant	Date (dd/mmm/yyyy)	Signature
Name of person obtaining consent	Date (dd/mmm/yyyy)	Signature

Original Investigator Site File / Trial Master File, 1 copy for the participant; 1 copy for the patient notes (where applicable), 1 copy researcher

BIOMECHANICS & BIOENGINEERING RESEARCH CENTRE VERSUS ARTHRITIS

(C) Permission to contact form

Insert local header / logo

PERMISSION TO CONTACT FORM
Biomechanics and Bioengineering Research Centre Versus Arthritis (BBRCVersusArthritis)

Versus Arthritis and Cardiff University have set up the Biomechanics and Bioengineering Research Centre Versus Arthritis (BBRCVersusArthritis). The centre is a collaborative partnership between 6 academic departments within Cardiff University, Orthopaedic Consultants, Rheumatology Consultants and Physiotherapists within Cardiff and the Vale University Health Board and Cwm Taf Health Board.

The research team is investigating the function of healthy, arthritic and painful joints/spines to determine how this is influenced by weakness, disease or trauma to inform treatment and rehabilitation. The objectives of the Centre are to look at how we can slow down the progression and possibly improve outcomes for people with arthritis.

For some of our research we need patients who have weakness, disease, suffered trauma or are undergoing surgery to take part. This may range from allowing us to have the tissue removed during surgery that would normally be disposed of after surgery so that we can look for causes of joint diseases, having an extra blood test during routine clinic visits so that we can look for indicators of disease, which may help us to pick up conditions such as osteoarthritis earlier in the future, or visiting a special laboratory to have movements in your joints recorded by special cameras.

If you are interested in taking part in our research and would like to hear more from one of our researchers, please fill in this form. Filling in this form does not mean that you have to take part, and you are free to withdraw from the research at any time, and this will not affect your standard of care and you do not have to give a reason for your withdrawal from the study.

Filling in this form simply gives us permission to talk to your consultant about the reason you are seeing him or her and to contact you to tell you more about the research areas that you may be appropriate for. Please be reassured that your information will be kept confidential if you sign this form.

You may be asked to take part in none, one, several or all of the separate parts of the research. If you do take part in the research, we will ask you to sign a consent form for each separate research project.

You can find out more information about the Centre from our website:
https://www.cardiff.ac.uk/biomechanics-bioengineering-research-centre-versus-arthritis

Page 1 of 2 Version 11 – 25 June 2019

Contact for further information

[redacted]

If you are interested in taking part in the research carried out in the Centre, please fill in the form below and leave it in the box provided, give to a member of you clinical team or a researcher who may be present at clinic. If you would prefer to take the form home and think about it, please complete and send it to the the address above if you decide you wish to be contacted with further information.

Full Name: ______________________________

Date of Birth: ______________________________

Hospital number (if known): ______________________________

Address: ______________________________

____

Postcode ______________________________

Telephone number: ______________________________

Email address: ______________________________

Consultant name (if known): ______________________________

Joint affected: ______________________________

Operation type (if applicable): ______________________________

Operation date (if applicable): ______________________________

I give permission for researchers associated with the Arthritis Research UK Biomechanics and Bioengineering Centre, Cardiff University to talk to my consultant about the reason I am seeing him or her and to look at my medical records to determine if I am suitable to take part in any of the research studies. I understand this does not mean I have to take part in any of the research studies and that I am free to withdraw at anytime.

______________________	______________	______________
Name	Date (dd/mmm/yyyy)	Signature

BIOMECHANICS & BIOENGINEERING RESEARCH CENTRE VERSUS ARTHRITIS

Appendix J: Data collection sheet used in (Phase II)

Knee Pain Clinic Feedback Data Collection sheet v1; Jun 19

Participant ID: ________________

Study Visit No: 1 2 3

Treating Clinician (Physiotherapist):__________________

Department: _________________

Hospital: ____________________

Setup – Xsens (n = 17)

Left foot	Left hand
Left shank	Left forearm
Left thigh	Left arm
Right foot	Left shoulder
Right shank	Right hand
Right thigh	Right forearm
Pelvis	Right arm
Sternum	Right shoulder
Head	

Session Starting Time: [ ]

Pain Level (24 hours): [/10]

Participant Measurements

Name of researcher taking measurements: _________________

Height: [ ] cm **Dominant Leg:** [ ] **Body mass:** [ ] Kg

Make the following measurements on the right side of the body (cm):

Xsens: Foot size		From the back of the heel to the front of the toe.
Xsens: Ankle height		From the floor to the centre of the ankle (lateral malleolus).
Xsens: Knee height		From the floor to the lateral epicondyle.
Xsens: Hip height		From the floor to the greater trochanter.
Xsens: Hip width		From the left ASIS to the right ASIS.
Xsens: Shoulder height		From the floor to the tip of acromion
Xsens: Shoulder width		From the left tip of acromion to the right tip of acromion
Xsens: Arm span		From the top of top of left fingers to the top of right fingers

Sensors Placed By: ______________________

Comments (e.g. placement due to post-operative bandaging, bruising, swelling etc)

____

____

Activity Order:

Activity	**Tick when complete**	**Pain**
1. Static Calibration		
2. Dynamic Calibration		
3. Double leg squat		
4. Single leg squat (Rt + Lt)		
5. Vertical Jump		
6.Walking		
7.Stair ascending and descending		

Date: [ ] Participant ID: [ ]

Knee Pain Clinic Feedback Data Collection sheet v1; Jun 19

Start Time: 　　　　　　End Time:

Trial No.	Activity		Comment (skin marks, NRS)
Trial 1		S F	
Trial 2		S F	
Trial 3		S F	
Trial 4		S F	
Trial 5		S F	
Trial 6		S F	
Trial 7		S F	
Trial 8		S F	
Trial 9		S F	
Trial 10		S F	
Trial 11		S F	
Trial 12		S F	
Trial 13		S F	
Trial 14		S F	
Trial 15		S F	
Trial 16		S F	
Trial 17		S F	
Trial 18		S F	
Trial 19		S F	
Trial 20		S F	
Trial 21		S F	
Trial 22		S F	
Trial 23		S F	
Trial 24		S F	
Trial 25		S F	
Trial 26		S F	
Trial 27		S F	
Trial 28		S F	

Date: 　　　　　　Participant ID:

Knee Pain Clinic Feedback Data Collection sheet v1; Jun 19

Notes:

Date: ______ **Participant ID:** ______

Appendix K: Knee Injury and Osteoarthritis Outcome Score (KOOS) form, used in (Phase II)

KOOS KNEE SURVEY

Today's date: _____/_____/_____ Date of birth: _____/_____/_____

Name: ____

INSTRUCTIONS: This survey asks for your view about your knee. This information will help us keep track of how you feel about your knee and how well you are able to perform your usual activities.
Answer every question by ticking the appropriate box, only one box for each question. If you are unsure about how to answer a question, please give the best answer you can.

Symptoms
These questions should be answered thinking of your knee symptoms during the **last week**.

S1. Do you have swelling in your knee?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S2. Do you feel grinding, hear clicking or any other type of noise when your knee moves?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S3. Does your knee catch or hang up when moving?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S4. Can you straighten your knee fully?

Always	Often	Sometimes	Rarely	Never
☐	☐	☐	☐	☐

S5. Can you bend your knee fully?

Always	Often	Sometimes	Rarely	Never
☐	☐	☐	☐	☐

Stiffness
The following questions concern the amount of joint stiffness you have experienced during the **last week** in your knee. Stiffness is a sensation of restriction or slowness in the ease with which you move your knee joint.

S6. How severe is your knee joint stiffness after first wakening in the morning?

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

S7. How severe is your knee stiffness after sitting, lying or resting **later in the day**?

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Pain

P1. How often do you experience knee pain?

Never	Monthly	Weekly	Daily	Always
☐	☐	☐	☐	☐

What amount of knee pain have you experienced the **last week** during the following activities?

P2. Twisting/pivoting on your knee

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P3. Straightening knee fully

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P4. Bending knee fully

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P5. Walking on flat surface

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P6. Going up or down stairs

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P7. At night while in bed

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P8. Sitting or lying

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P9. Standing upright

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Function, daily living

The following questions concern your physical function. By this we mean your ability to move around and to look after yourself. For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your knee.

A1. Descending stairs

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A2. Ascending stairs

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your knee.

A3. Rising from sitting
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

A4. Standing
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

A5. Bending to floor/pick up an object
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

A6. Walking on flat surface
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

A7. Getting in/out of car
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

A8. Going shopping
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

A9. Putting on socks/stockings
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

A10. Rising from bed
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

A11. Taking off socks/stockings
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

A12. Lying in bed (turning over, maintaining knee position)
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

A13. Getting in/out of bath
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

A14. Sitting
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

A15. Getting on/off toilet
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your knee.

A16. Heavy domestic duties (moving heavy boxes, scrubbing floors, etc)

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A17. Light domestic duties (cooking, dusting, etc)

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Function, sports and recreational activities

The following questions concern your physical function when being active on a higher level. The questions should be answered thinking of what degree of difficulty you have experienced during the **last week** due to your knee.

SP1. Squatting

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP2. Running

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP3. Jumping

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP4. Twisting/pivoting on your injured knee

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP5. Kneeling

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Quality of Life

Q1. How often are you aware of your knee problem?

Never	Monthly	Weekly	Daily	Constantly
☐	☐	☐	☐	☐

Q2. Have you modified your life style to avoid potentially damaging activities to your knee?

Not at all	Mildly	Moderately	Severely	Totally
☐	☐	☐	☐	☐

Q3. How much are you troubled with lack of confidence in your knee?

Not at all	Mildly	Moderately	Severely	Extremely
☐	☐	☐	☐	☐

Q4. In general, how much difficulty do you have with your knee?

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Thank you very much for completing all the questions in this questionnaire.

Appendix L: Patient Information Sheet (PIS), and Consent Form (CF) given to (a) individuals with knee pain and (b) treating clinicians for qualitative interview, used in (Phase II)

(a) Individuals with knee pain PIS and CF

[redacted]

PATIENT INFORMATION SHEET

Qualitative analysis of patient and clinician opinion on experiences, opinions and satisfaction on current and proposed methods of care and treatment

Part one

You are being invited to take part in a research study with Cardiff University's Arthritis Research UK Biomechanics and Bioengineering Centre (ARUKBBC). Before you decide, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. One of our team will go through the information sheet with you. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to participate. Part 1 tells you about the purpose of this study and what will happen to you if you take part. Part 2 gives you more detailed information about the conduct of the study.

What is the purpose of this research?

This research is part of a series of studies being conducted by the Arthritis Research UK Biomechanics and Bioengineering Centre, which uses an interlinking approach to investigate the effects of disease, injury and/or any related treatment on the biomechanics of the joint compared to healthy joints.

The aim of this study is to obtain views of patients with musculoskeletal disorders, via interviews about their experiences, opinions and satisfaction on current and proposed methods of care and treatment.

Why have I been asked to take part in this study?

You have been asked to take part in this study as you have a joint problem that we are interested in. It will allow us to gain your opinion via a recorded interview on the use of new technologies, treatments and advice such as the use of phone apps.

Do I have to take part?

It is up to you to whether or not to take part. If you do decide to take part you will be given this information sheet to keep and after you have had enough time to read through it, be asked to sign a consent form. If you decide to take part, you are still free to withdraw at any time, without giving a reason. However, any data that we may have collected up to the point of withdrawal will be kept for analysis. If you decide not to take part we will remove your data / contact details from our database and it will not affect your care or treatment in the NHS.

What will happen to me if I take part?

If you wish to take part you will be invited to attend one of our research centres in Cardiff University or in a clinic setting in the hospital where you are being treated. You will be interviewed by a Cardiff university researcher. The types of questions asked during interview will include the following:

Interviews conducted before treatment is undertaken for your condition:

A description of your condition
The impact of the condition on your every day life. How you have managed your condition so far
What sources of information have you accessed so far about your condition
Expectations of treatment you will receive
Opinions about using and usefulness of technology for advice about your condition
Experiences of previous treatments/interventions
Opinions about accessing health care using electronic resources Opinions about self-management of musculoskeletal disorders
Opinions about involvement in choice of treatments for a musculoskeletal disorder
Opinions about use of technology in supporting delivery of care Opinions about location of delivery of care

If you have received treatment for your condition you may be asked to attend a further interview and will asked questions that include the following:

An update of your condition
An update on the impact of your condition in every day life
What care and treatment have you received since the pre treatment interview
Opinions about choice of care and treatment
Opinions about treatment meeting your needs and its effectiveness
Opinions about involvement in management of your condition
Opinions about location of delivery of care
Expectations regarding recovery

Opinions about usefulness of technology supporting management of your condition

Interviews should take no longer than 30 / 45 minutes, in most cases it will take less time. The interviews will be recorded on a tape recorder. After the interview the interview will be transcribed and you will receive a copy of this transcription if you wish to have a copy.

During interview(s) you may also be asked to complete some paper based questionnaires called PROMs (Patient Reported Outcome Measure's). This will take around ten minutes to complete.

Will the information I provide be kept confidential?

Your data and interview details / transcription will be kept securely for a minimum of 15 years from the end of the study in accordance with good research practice and data protection regulations imposed by Cardiff University in accordance with the Data Protection Act 1998. All data obtained during the study will remain confidential. Access to data will only be available to the investigators attached to the Arthritis Research UK Biomechanics and Bioengineering Centre at Cardiff University. If new information becomes available, we may invite you to take part in a follow-up study in the future, please indicate on the consent sheet if you do not mind us contacting you. With your permission and consent, we may also invite you to take part in other interlinking studies associated with our research. However, you are under no obligation to take in any other or future studies.

Are there any risks in participating in this research?

We do not anticipate any risks for taking part in interviews.

Are there any benefits in participating in this research?

Being part of this PhD thesis is of no added benefit to you directly. However, the information we collect may help improve care for others in the future.

Are there any disadvantages in participating in this research?

The only disadvantage would be the time taken to take part in the interview(s).

If the information in Part 1 has interested you and you are considering participation, please read the additional information in Part 2 before making a decision.

[redacted]

PATIENT INFORMATION SHEET

Qualitative analysis of patient and clinician opinion on experiences, opinions and satisfaction on current and proposed methods of care and treatment

Part Two

What will happen if I do not want to carry on with the study?

If you decide you would like to withdraw from the study, we will erase all identifiable material. However, any information collected up to that point will be kept and used unless you tell us that you would like your information removed from the project.

What if something goes wrong?

In the rare circumstance that you are harmed by taking part in this PhD thesis, there are no special compensation arrangements. If you are harmed due to someone's negligence, then you may have grounds for a legal action but you may have to pay for it. Regardless of this, if you wish to complain, or have any concerns about any aspect of the way you have been approached or treated during the course of this study, please contact a member of our team the details of which are in the "What if I wish to lodge a complaint?" section below.

Will my taking part in this study be kept confidential?

Once you have consented to take part in the study, you will be assigned a unique identifier which will be linked to your details and will also allow us to track you through the study. All information which is collected about you during the course of the research will be kept strictly confidential. We may share the data we collect with researchers at other institutions including Universities and commercial research organisations, in the UK and aboard. However, any information that leaves the Centre will be anonymous. It will have your name and address removed so that you cannot be recognised from it. In any sort of report we might publish, we will not include information that will make it possible for other people to know your name or identify you in any way. You will simply be referred to by your gender, age and your condition.

Will my GP be informed of my involvement in the study?

We do not routinely send a letter to the GP to inform them of your participation in this research.

What will happen to the results of the research study?

We may wish publish the results of this study in a scientific journal. We may also present the results at a scientific conference or a seminar in a university. We may also publish results on our website. We would be happy to discuss the results of the study with you and send you a copy of the published results. It will not be possible to identify you in any report or publication.

Who is organising and funding the research?

Research staff at the Arthritis Research UK Biomechanics and Bioengineering Centre at Cardiff University and Consultant Orthopaedic Surgeons at the University Hospital of Wales are carrying out the study. The study is part of the Arthritis Research UK Biomechanics and Bioengineering Centre at Cardiff University; it is not funded by commercial sources and runs alongside research in the Cardiff University School of Engineering motion analysis laboratories and Research Centre for Clinical Kinaesiology at Cardiff University School of Healthcare Sciences. Occasionally work associated with these studies may also be supported by commercial companies, we will inform you by sending you a letter when this is the case.

Who has reviewed the study?

This study has been reviewed by Wales Research Ethics Committee 3 (REC 3).

What if I wish to lodge a complaint?

If you wish to make a complaint regarding the way you were approached or treated during the recruitment and/or interviews, please contact the Arthritis Research UK Biomechanics and Bioengineering Centre on Telephone: [redacted] Email: [redacted]
If you feel your complaint is not adequately addressed then you may escalate your complaint by writing to the School Manager of the host school for the Centre: The School Manager, School of Biosciences, Museum Avenue, Cardiff, CF10 3AX. Please ensure you include details of any complaint made so far and correspondence you have so far received.

Contact for further information

[redacted]
Tel: [redacted]
Email: [redacted]

This completes Part 2. Thank you for reading this information sheet.

If you agree to take part in this study then you will be given a copy of the information sheet and a signed consent form to keep.

[redacted]

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

PATIENT CONSENT FORM

Qualitative analysis of patient and clinician opinion on experiences, opinions and satisfaction on current and proposed methods of care and treatment

Study Number

Patient Identification Number for this research:

You DO NOT have to sign this document. Please DO NOT sign this document unless you fully understand it. If there is ANYTHING which you do not understand please do not hesitate to ask for a full explanation.

To confirm agreement with each of the statements below, please initial each box and delete where applicable:

1. I confirm that I have read and understand the information sheet dated 14 April 2017 (Version 1) for the above study and have had the opportunity to ask questions.	
2. I understand that my participation in the interviews is voluntary and that I am free to withdraw at any time, without giving any reason, and without my medical care or legal rights being affected but any data collected up to the point of my withdrawal will be kept.	
3. I understand that my details will be linked to a unique identifier to allow you to follow me through course of the study	
4. You may / may not (please delete as appropriate contact me in the future to ask if I would be interested in participating in a future PhD thesis/survey	
5. I do / do not (please delete as appropriate) agree for you to share my anonymised data with external collaborators in the UK and abroad, including commercial companies	

6. I agree for you to record my interviews on tape recorder and that the interview will be transcribed. I would / would not (please delete as appropriate) like to receive a copy of the transcription. ☐

7. I agree to take part in the above study. ☐

Name of Patient: ____
(Please print)

Signature: _______________________ Date: _________________

I confirm that I have fully explained the experimental protocol and purpose of the study

Name of Researcher: _____________________________________

Signature: ________________________ Date: _________________

Name of person taking consent: ___________________________
(If different from researcher)

Signature: ________________________ Date: __________________

Original Centre file, 1 copy for the patient; 1 copy for the patient notes (if applicable), 1 copy researcher

(a) Physiotherapy clinicians' PIS and CF

[redacted]

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

CLINICIAN INFORMATION SHEET

Qualitative analysis of patient, healthy volunteer and clinician opinion on experiences, opinions and satisfaction on current and proposed methods of care and treatment

Part one

You are being invited to take part in a research study with Cardiff University's Arthritis Research UK Biomechanics and Bioengineering Centre (ARUKBBC). Before you decide, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. One of our team will go through the information sheet with you. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to participate. Part 1 tells you about the purpose of this study and what will happen to you if you take part. Part 2 gives you more detailed information about the conduct of the study.

What is the purpose of this research?

This research is part of a series of studies being conducted by the Arthritis Research UK Biomechanics and Bioengineering Centre, which uses an interlinking approach to investigate the effects of disease, injury and/or any related treatment on the biomechanics of the joint compared to healthy joints.

The aim of this study is to obtain views of patients with musculoskeletal disorders, healthy volunteers and orthopaedic clinicians via interviews about their experiences, opinions and satisfaction on current and proposed methods of care and treatment.

Why have I been asked to take part in this study?

You have been asked to take part in this study as you are a clinician involved in the care and treatment of patients with musculoskeletal disease. It will allow us to gain your opinion via a recorded interview on the use of new technologies, treatments and advice such as the use of phone apps.

Do I have to take part?

It is up to you to whether or not to take part. If you do decide to take part you will be given this information sheet to keep and after you have had enough time to read through it, be asked to sign a consent form. If you decide to take part, you are still free to withdraw at any time, without giving a reason. However, any data that we may have collected up to the point of withdrawal will be kept for analysis. If you decide not to take part we will remove your data / contact details from our database.

What will happen to me if I take part?

If you wish to take part you will be invited to attend one of our research centres in Cardiff University or a researcher will visit your place of work at a time convenient for you. You will be interviewed by a Cardiff university researcher. The types of questions asked during interview will include the following:

Your opinions about choice of treatments for patients
Your opinions about and acceptability of technology and biomechanics feedback. How would this information alter their decision making on treatment selection
Your opinions about location of delivery of care

Interviews should take no longer than 30 / 45 minutes, in most cases it will take less time. The interviews will be recorded on a tape recorder. After the interview the interview will be transcribed and you will receive a copy of this transcription if you wish to have a copy.

Will the information I provide be kept confidential?

Your data and interview details / transcription will be kept securely for a minimum of 15 years from the end of the study in accordance with good research practice and data protection regulations imposed by Cardiff University in accordance with the Data Protection Act 1998. All data obtained during the study will remain confidential. Access to data will only be available to the investigators attached to the Arthritis Research UK Biomechanics and Bioengineering Centre at Cardiff University. If new information becomes available, we may invite you to take part in a follow-up study in the future, please indicate on the consent sheet if you do not mind us contacting you. With your permission and consent, we may also invite you to take part in other interlinking studies associated with our research. However, you are under no obligation to take in any other or future studies.

Are there any risks in participating in this research?

We do not anticipate any risks for taking part in interviews.

Are there any benefits in participating in this research?

Being part of this PhD thesis is of no added benefit to you directly. However, the information we collect may help improve care for patients in the future.

Are there any disadvantages in participating in this research?

The only disadvantage would be the time taken to take part in the interview(s).

If the information in Part 1 has interested you and you are considering participation, please read the additional information in Part 2 before making a decision.

[redacted]

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

CLINICIAN INFORMATION SHEET

Qualitative analysis of patient and clinician opinion on experiences, opinions and satisfaction on current and proposed methods of care and treatment

Part Two

What will happen if I do not want to carry on with the study?

If you decide you would like to withdraw from the study, we will erase all identifiable material. However, any information collected up to that point will be kept and used unless you tell us that you would like your information removed from the project. You may ask for the interview to be stopped at any point during the interview process and the interview will be terminated.

What if something goes wrong?

In the rare circumstance that you are harmed by taking part in this PhD thesis, there are no special compensation arrangements. If you are harmed due to someone's negligence, then you may have grounds for a legal action but you may have to pay for it. Regardless of this, if you wish to complain, or have any concerns about any aspect of the way you have been approached or treated during the course of this study, please contact a member of our team the details of which are in the "What if I wish to lodge a complaint?" section below.

Will my taking part in this study be kept confidential?

Once you have consented to take part in the study, you will be assigned a unique identifier which will be linked to your details and will also allow us to track you through the study. All information which is collected about you during the course of the research will be kept strictly confidential. We may share the data we collect with researchers at other institutions including Universities and commercial research organisations, in the UK and aboard. However, any information that leaves the Centre will be anonymous. It will have your name and address removed so that you cannot be recognised from it. In any sort of report we might publish, we will not include information that will make it possible for other people to know your name or identify you in any way. You will simply be referred to by your gender, age and that you are a healthy volunteer.

Will my GP be informed of my involvement in the study?

We do not routinely send a letter to the GP to inform them of your participation in this research.

What will happen to the results of the research study?

We may wish publish the results of this study in a scientific journal. We may also present the results at a scientific conference or a seminar. We may also publish results on our website. We would be happy to discuss the results of the study with you and send you a copy of the published results. It will not be possible to identify you in any report, presentation or publication.

Who is organising and funding the research?

Research staff at the Arthritis Research UK Biomechanics and Bioengineering Centre at Cardiff University and Consultant Orthopaedic Surgeons at the University Hospital of Wales are carrying out the study. The study is part of the Arthritis Research UK Biomechanics and Bioengineering Centre at Cardiff University; it is not funded by commercial sources and runs alongside research in the Cardiff University School of Engineering motion analysis laboratories and Research Centre for Clinical Kinaesiology at Cardiff University School of Healthcare Sciences. Occasionally work associated with these studies may also be supported by commercial companies, we will inform you by sending you a letter when this is the case.

Who has reviewed the study?

This study has been reviewed by Wales Research Ethics Committee 3 (REC 3).

What if I wish to lodge a complaint?

If you wish to make a complaint regarding the way you were approached or treated during the recruitment and/or interviews, please contact the [redacted] on Telephone: [redacted] Email: [redacted] If you feel your complaint is not adequately addressed then you may escalate your complaint by writing to the School Manager of the host school for the Centre: [redacted] Please ensure you include details of any complaint made so far and correspondence you have so far received.

Contact for further information

[redacted]

Tel: [redacted]

Email [redacted]

This completes Part 2. Thank you for reading this information sheet.

If you agree to take part in this study then you will be given a copy of the information sheet and a signed consent form to keep.

[redacted]

CLINICIAN CONSENT FORM

Qualitative analysis of patient and clinician opinion on experiences, opinions and satisfaction on current and proposed methods of care and treatment

Study Number

Participant Identification Number for this research:

You DO NOT have to sign this document. Please DO NOT sign this document unless you fully understand it. If there is ANYTHING which you do not understand please do not hesitate to ask for a full explanation.

To confirm agreement with each of the statements below, please initial each box and delete where applicable:

1. I confirm that I have read and understand the information sheet dated 14 April 2017 (Version 1) for the above study and have had the opportunity to ask questions. ☐

2. I understand that my participation in the interview is voluntary and that I am free to withdraw at any time, without giving any reason, but any data collected up to the point of my withdrawal will be kept. ☐

3. I understand that my details will be linked to a unique identifier to allow you to follow me through course of the study ☐

4. You may / may not (please delete as appropriate) contact me in the future to ask if I would be interested in participating in a future PhD thesis/survey ☐

5. I do / do not (please delete as appropriate) agree for you to share my anonymised data with external collaborators in the UK and abroad, including commercial companies ☐

6. I agree for you to record my interviews on tape recorder and that the interview will be transcribed. I would / would not (please delete as appropriate) like to receive a copy of the transcription. ☐

7. I agree to take part in the above study. ☐

Name of Clinician: ____
(please print)

Position Held: ____
(Please print)

Signature:________________________________Date: ____________________

I confirm that I have fully explained the protocol and purpose of the study

Name of Researcher: ____

Signature:________________________________Date: ____________________

Name of person taking consent: ____________________________________(If different from researcher)

Signature:________________________________Date: ____________________

Original Centre file, 1 copy for the clincian, 1 copy researcher

Appendix M: Interview topic guide for (a) individuals with knee pain and (b) treating clinicians, used in (Phase II)

(a) Interview Topic Guide for individuals with knee pain

➢ Introductory questions

1. Can you tell me about sports and exercise you do regularly?
    - How long do you spend daily?
    - What types of sport do you play?
    - If no, can you tell me about your everyday activities? For how long?

2. Can you tell me about your knee problem?
    - How long have you had this problem?
    - How does this affect your everyday life?

3. Can you tell me what physiotherapy you have received?
    - How long have you had physio?
    - What types?
    - What physio (exercises) have you done at home?

➢ "Intervention coherence: The extent to which the participant understands the intervention and how it works" (Sekhon et al. 2017, p. 8)

4. Can you tell me about how the sensors-based movement analysis and the feedback report were incorporated into your physiotherapy treatment?

➢ "Affective attitude: How an individual feels about the Intervention" (Sekhon et al. 2017, p 8)

5. What were your initial impressions of using the sensors-based movement analysis and the feedback report as part of your physiotherapy? (Prompt; Like/ dislike, want to change or improve)

➢ "Burden: The perceived amount of effort that is required to participate in the intervention" (Sekhon et al. 2017, p. 8)

6. In your opinion, how easy or difficult was it to understand the feedback report that was discussed with you by your treating clinician?

- How this feedback report could be improved (i.e. training, format of feedback)
- How would you prefer the feedback report data to be presented to you? (Prompt; 1:1 Physio & discussion, electronically/digitally, hardcopy)

7. How did you experience the data collection sessions?
    - Timing (Length, Frequency (How often), Total time (data collection session + treatment session)
    - Flow of the session
    - Exercise performed

8. Have you experienced any challenges that need to take into account? (Any risk).
    - How these challenges could be encountered?

➢ "Perceived effectiveness: The extent to which the intervention is perceived as likely to achieve its purpose" (Sekhon et al. 2017, p. 8)

9. In your opinion, how these sensor-based movement analysis and feedback report could assist with your physiotherapy care within the clinic? (Prompt: motivation, monitoring, personalising, targeting, etc)
    - Do you think your treatment was changed based on the sensor-based movement analysis and feedback report received? To what extent? How did it help? (i.e. personalised, tailored, objective)

10. What do you think about using this movement analysis feedback intervention through all NHS settings?

➢ Closing questions

11. What would be your take-home message from the experience of using sensor-based movement analysis and feedback reports alongside your usual physiotherapy care?

12. Is there anything you want to add concerning sensors, feedback or data collection session?

(b) Interview Topic Guide for treating clinicians

- Introductory Questions:

1. Could you please tell me how do you normally analyse your patient's movements in clinic? (i.e. Observation, camera, phone or tablet)

2. Have you used any types of movement analysis technologies in clinical setting previously?

- Movement Analysis Sessions:

1. How did you experience the flow of the movement analysis session and the treatment session?

2. What do you think of the movement analysis sessions in terms of timing and frequency?
   - Do you think 30 to 45 minutes suitable for a movement analysis session?

3. In your opinion, when should the movement analysis sessions take place? (Prompt; Sufficient time to read, analyse and interpret feedback report),
   - Do you think you got a sufficient time to read, analyse and interpret feedback report?

4. How many movement analysis sessions should be included during patient's treatment course?

5. What do you think of the exercise tasks analysed in these sessions? (i.e. DLS, SLS, jump, walk, SA, SD)
   - Is there any exercise you want to change or add?

6. From your perspective, who should run these movement analysis sessions using sensor technology? (physios)
   - What qualification should this person have?

- Feedback Report:

1. How did you experience the process of accessing, understanding, and interpreting the feedback report with patients?

2. What did you like and found useful about this feedback report? (Prompt; Features, format)

3. What did not you like and want to change or improve about the feedback report?

4. What do you think of the content of the feedback report (i.e. temporo-spatial parameters, movement waveform graphs, consistency plot)
   - Are there any additional contents needed?

5. Did you fully understand the feedback reports provided and be able to discuss it with your patients?
   - What part do you think you did not understand most? Why?

6. How would you like the feedback report to be provided to you? (Prompt; Hardcopy, electronically)

➢ Impact:

1. How do you think this sensor-based movement analysis and feedback report could inform clinical practice?

2. From your experience that you have had, what impact (positive or negative) have you had from integrating the movement analysis feedback into your practice? (Prompt; Effectiveness, productivity, time)

3. What do you think about using this movement analysis feedback intervention through all NHS settings?

➢ Closing questions:

1. Have you experienced any challenges that need to take into account?

2. Is there anything you want to add concerning equipment, feedback report or movement analysis sessions?

Appendix N: (a) Example of coded data and the associated codes taken from transcript of an individual with knee pain (Nancy, P005) (Phase II)

Participant #	Line #	Text	Codes
P005	77-80	I did most of them at home. There was one that he said about using the knee extension at the gym. So I have access to the gym at my university as well so I did that one there. But most of them I could do at home.	Patient's compliance toward exercises prescribed
P005	85-89	Yes, so obviously attended that at the start of each session and then [clinician] had a look at the avatar which I was able to note some movement patterns and things and kind of adjusted by his recommendations and exercises that he gave me. He also would email me across reports with all the graphs as well so I could have a look.	Understanding session process – how the tool works
P005	92-93	Erm I think like the avatar was really useful, being able to like see like your movement pattern	Positive perception about the visualisation of the feedback (avatar)
P005	93-94	kind of increases your awareness of how you move I think.	Perceived impact - Increased patient's awareness of movement
P005	94-95	I think that would be quite a useful thing for probably most people using physiotherapy.	Positive perception about implementing movement analysis feedback tool within physiotherapy clinics
P005	97-100	Yeah, I can imagine like a kind of, like a programme where you can almost like hook it up to your TV and even like an exercise or something and the sensors could pick up on how you move and how to sort of improve your form and, I think that would be quite useful.	Using movement analysis feedback tool outside physiotherapy clinic (Home)
P005	103-105	I really liked the being able to see it in the avatar, because I'd be like you can just swirl it round, see exactly how you move in different angles which you can't always do normally.	Positive perception about the visualisation of the feedback (avatar) Explanation
P005	105-106	So I think that was really useful to actually see how like your sort of joints and everything move.	Perceived impact – Increased patient's awareness of movement
P005	106-108	The task that [clinician] like emailed across, that was useful, just a bit complicated and hard to understand what those meant.	Understanding of the feedback report (negative perception)
P005	108-109	But seeing the avatar and adjusting like the recommended movements was probably the most useful I think.	Personal preferences of the feedback type received
P005	112-113	I guess that was the only thing really about the graph because they were quite complicated, I didn't really understand what a lot of them meant.	Understanding of the feedback report (negative perception) Explanation

P005	117	So no I think it was fine.	No negatives about the movement analysis feedback tool (sensor technology)
P005	122-123	Erm yeah I mean obviously like in hospital and stuff people were kind of looking and watching, erm but that doesn't really bother me much.	Psychosocial effect of wearing sensor technology
P005	128-130	I guess kind of just continuing how I've been doing now where like using the sensors to sort of pick up on different movement happens and informing the kind of recommendations there	Benefits – tailoring treatment
P005	130-133	but also in the last session where we looked back and sort of compared like from the first session to now you can then sort of gave a good erm sense of like how, if you are getting better and how.	Benefits – monitoring progress among sessions (comparing between sessions)
P005	134-135	so you think err, this has helped clinicians in planning treatment? RES: Yeah, I think so. Say both clinicians and the patient though.	Benefits – tailoring treatment (Positive response)
P005	140-143	I think to be fair where like you're kind of given recommended exercises to do between sessions, if like you had sensors, like he said to use at home but to track you, it gives that accountability and probably make you more likely to do the exercises.	Benefits – motivation (to perform exercises)
P005	144-146	Alright, so do you think your treatment will change following your experience of using the technology? RES: Yeah, I hope so	Perceived impact of the tool (treatment changed) positive response
P005	149-153	I mean I think it kind of like relies a lot on physio knowledge and understanding to pick up on things that came out of the sensors. Obviously they know a lot more than me but then like being able to relay that information and point out bits on like the avatar of like how my hip was dropping in certain movements and things like that. I think it would have been harder for me to understand that if you were to sort of explain it in words	Perceived impact of the tool (treatment changed based on clinician's knowledge and understanding)
P005	161-163	Yes, so I think like the avatar like maybe the clips were really good to be able to see it, but the graphs are just a bit complicated. Like there's a lot of like little graphs a lot of I didn't really know what I was looking at.	Personal preferences of the feedback type received
P005	166	Yeah, it was just a bit complicated, I didn't really know what the lines meant.	Understanding the content of the feedback report (waveform graphs)
P005	168-170	I think probably just to make it more simple, maybe just have like one or two graphs for each exercise, and or maybe even like to explain like what the graphs mean a bit.	Suggestions for improving reports - fewer number of graphs/ training
P005	171-173	Mmm alright, so do you think err if we try to train the patients to understand these graphs is useful? RES: Yeah, definitely.	Suggestions for improving reports - Positive response for the need of training patients on how to read feedback reports

P005	175-179	I mean the graph was alright but maybe like, for me like I am quite visual, maybe seeing the avatar erm even if it was like stills from it where like you could actually see the visual presentation of like the movement where like things could be like improved, so like my hip dropping, seeing that in picture helps more than the graph.	Personal preferences of the feedback type received (Explanation)
P005	183-187	I guess I prefer probably email because it is just sort of easy, you can kind of go back and forth. But I think also maybe a hard copy sometimes that you could then talk about with your physio. Like if you had a longer session you could go through it and maybe they could explain better what it means.	Personal preferences of the format of the feedback report (both, electronic and hard copies) (Explanation)
P005	188-190	Alright, good, so now what do you think about using this technology through all NHS settings? RES: I think it's a really good idea	Positive perception of implementing movement analysis tool in physiotherapy clinical practice (spread/ rolling out)
P005	192-193	Yeah, I think like definitely most patients. I can't think of any off the top of my head that maybe would not benefit.	Relevancy of using movement analysis tool with different conditions
P005	201-202	Erm obviously the first one was longer for taking like all the measurements but then after that it was a lot quicker. It was fine.	Practicality - Positive perception of the timing of movement analysis sessions
P005	201-202	Erm obviously the first one was longer for taking like all the measurements but then after that it was a lot quicker.	Practicality – Understanding about timing of the first movement analysis session compared to subsequent ones
P005	203-206	Yeah, and so do you think that long and that need to be a bit short, a bit shorter? RES: Yeah, probably but if it was to be used erm like more regularly or with most people, obviously it would just impact the time of appointments.	Practicality – Negative perception about the timing of movement analysis sessions (explanation)
P005	208-210	I think that's quite good to be fair because it was kind of sort of when I needed to see the physio. It wasn't too short that it was like too repetitive, it was kind of every like 3-4 weeks at a time.	Practicality - Positive perception of the frequency of movement analysis sessions
P005	211-213	So do you think 3 sessions err over the treatment course is a good number? RES: Erm, yeah I think so, I think it probably depends on the type of knee problem to be fair as well.	Practicality – frequency of movement analysis sessions based on condition
P005	216	After the first session it was the same exercises so you do get familiar with it.	Practicality – Understanding about timing of the first movement analysis session compared to subsequent ones (familiarisation)
P005	214-215	how about the flow of the session? RES: Yeah, it was fine, it was good, like I knew what was coming	Practicality – positive reception of the flow of movement analysis sessions

P005	217-218	how about the exercise [unclear: 0:20:05]. RES: Yeah, they were all fine	Practicality – positive perception on the exercises included in the movement analysis sessions
P005	218-221	on my second session I think it was I couldn't do the single leg squat because my knee was really sore, it was quite painful that day. So that one obviously was a bit painful but that was the only time I couldn't do it.	Practicality – Challenges of the types of the exercises included (example SLS)
P005	222-225	do you recommend any exercise to be included or to be taken into consideration in future? RES: I would say maybe running because for me that was kind of what started the injury, so I think that would have been interesting to see.	Practicality – suggestions to include more exercises (running) (Explanation)
P005	226-227	have you experienced an challenges that need to take into account? RES: No.	No Challenges have been faced
P005	229-230	any risk? RES: No, not that I can think of.	No risks have been noticed
P005	233-235	I think just that the sensors were useful to inform both myself and my physio of kind of what the problems were then to give him an idea of how to fix it	Benefits – Identifying altered movement patterns
P005	235	then helped me to sort of understand more as well.	Perceived impact of the tool - Increased patient’s knowledge about knee pain problem

(b) Example of coded data and the associated codes taken from transcript of treating clinician (Clinician, PH001) (Phase II)

Participant ID	Line #	Text extracts	Codes
PH001	57-59	Erm well the patient had it every time that they came in, erm I think because I wasn't seeing him that frequently because the department was very busy, erm like I thought the frequency was good.	Practicality – frequency (positive perception)
PH001	57-58	I think because I wasn't seeing him that frequently because the department was very busy, erm like I thought the frequency was good.	Practicality – frequency (Challenges) – busyness of department
PH001	59-66	I think if I'd probably been seeing him every two, it would have been helpful for me to see them one time I think in between personally, like one time with you and then a monthly review was good but I think for me it would have been good to do an extra appointment at 2 weeks in between but due to circumstances I wasn't able to do that anyway. But I don't want to feel like I needed to have your analysis on a two-weekly basis but I feel like in the start I could have seen him a bit more frequently.	Practicality – Flow (personal preferences) - monthly bases of combined sessions (treatment + movement analysis) with a solely physio session in between "2 weeks"
PH001	68-75	Because I feel like it would have been good to like, obviously the video information about the analysis at the end of the session, I feel like it would have been good to have a session just with him and me where I was able to like utilise that a bit more before you then re-did it the next time if you see what I mean. INT: Hmm mmm, yeah. RES: I feel like there could have been an appointment in between which would have been helpful.	Practicality – Flow (personal preferences) – Split sessions in different days (monthly bases of combined sessions (treatment + movement analysis) with solely physio session in between "2 weeks"
PH001	77-80	Yes, I thought it was really helpful, I mean obviously it takes more time, there's only certain patients who can do that time, not everyone has got the time to be able to come and spend an extra half an hour per appointment to be able to use the analysis.	Practicality – timing (suitability) for patients (negative perception)
PH001	82-85	but then added to my understanding of his movement patterns further, with some of the other patterns of motion that were going on so it was quite interesting seeing him shifting side to side when he was doing I think a squat.	Benefits – Add more depth (objectivity) (example)
PH001	80-86	But it kind of, I guess it confirmed my thought processes and getting round to what I was looking at when I was watching him move but then added to my understanding of his movement patterns further, with some of the other patterns of motion that were going on so it was quite	Benefits – Add more depth (objectivity) - confirm decision + identify other compensations

		interesting seeing him shifting side to side when he was doing I think a squat. So just kind of gave extra information perhaps my naked eye didn't see.	
PH001	89-90	Yes, I mean you got everything I would have, that I required when you did the data collection.	Feedback report & avatar – (comprehensive data included)
PH001	90-92	I think he obviously found the benefit and he found it really helpful and really interesting to understand his movement a bit more. So I think he also not just, the benefit for him as well.	Benefits – for patient to increase awareness of movement
PH001	99-102	Well obviously it takes, I think at the start, I do feel like it takes time for biomechanical changes to occur, you know when you're trying to get muscles firing better, quicker that kind of thing. I don't think it needs to be too frequently, maybe like.	Practicality – frequency (understanding about adequate time needed between movement analysis sessions) biomechanical changes
PH001	106-107	So I guess I probably would have maybe like every, I don't know, like 6-8 weeks is maybe better.	Practicality – frequency (understanding about adequate time needed between movement analysis sessions)
PH001	102-108	I guess it depends on how often you can or you want to or sometimes in the NHS it's fitting in when you can see them again. So with him I probably would have wanted to see him more frequently but I couldn't because of the patient did not have enough space, times convenient for him. So I guess I probably would have maybe like every, I don't know, like 6-8 weeks is maybe better. I guess it depends, I guess it completely depends on how often you're managing to be able to see them.	Practicality – frequency (Challenges) - busyness of department
PH001	111-116	I guess perhaps the other thing is that if you were doing it with a patient, the first time we did it we had the information right at the end and I had given him all the plan of stuff to do, it wasn't a new patient, it was the first follow up appointment - was it, I can't remember actually. No it was a first appointment wasn't it? I feel like I needed to implement that I knew that information soon afterwards. Whereas I couldn't see him for a month.	Practicality – timing (negative perception) - (no sufficient time for describing exercises based on report's findings)
PH001	117-120	So I think the NHS restricts you in terms of like how quickly you can make a benefit of that information and to be able to like perhaps get that information and then see him afterwards for a period of time would have been helpful.	Practicality – frequency (Challenges) - busyness of department
PH001	120-123	At the end of the appointment. Because I'd given him stuff to do while you were analysing the information but actually there was more stuff I could have sent him away with given that information if you see what I mean?	Practicality – timing (negative perception) - (no sufficient time for describing exercises based on report's findings)

PH001	126-129	I don't know, I guess if we, do we go on the premise that they get 6 appointments which is roughly what they always say in the NHS. I mean it never happens but erm, I would probably think like one at the beginning, one, or two in the middle and one at the end.	Practicality – frequency (personal preferences) – spread of movement analysis sessions over treatment course and their numbers
PH001	133-134	one in the middle to motivate them to see that there are changes, to motivate them to continue to do what they are doing	Benefits – motivation for patients
PH001	135	then one at the end to analyse the overall changes perhaps.	Benefits – monitoring progress
PH001	133-136	Yeah, maybe, one at the beginning, one in the middle to motivate them to see that there are changes, to motivate them to continue to do what they are doing and then one at the end to analyse the overall changes perhaps. I don't know, if that's what other people think.	Practicality – frequency (personal preferences) – spread of movement analysis sessions over treatment course and their numbers (explanation) (motivation and monitoring)
PH001	137-140	what do you think of the exercise tasks analysed in these sessions? We've analysed double leg squats, single led squat, jump, walk, stairs ascending and descending? RES: Yes, well all functional tasks that are required for day-to-day activities.	Practicality – exercises included (positive perception)
PH001	140-145	I guess if you were looking at an older patient you might want to do like sit to stand or something like that. So that might depend on the age range of people that you are seeing. Because like a 60-year old- some 60 year olds are playing tennis, might be jumping, other 60 year olds might be quite sedentary and just sit and stand or something like that.	Practicality – exercises included (future suggestions) – include exercises based on age
PH001	151-154	Erm like I said to you earlier, like you see a patient at the start I think was it, was fine and then I think then obviously you've done all the movement testing and then I see the patient and then at the end you've got the analysis.	Understanding process – whole session (movement analysis + treatment session) (describe what happened)
PH001	154-163	Like I said to you ideally I would see them after that to then modify my treatment plan based on that. But I couldn't do that until the next appointment which I see as perhaps a wasted opportunity to get him going with stuff earlier. Certain things, and then like obviously you're there the second time, where I haven't given him stuff to do from the findings from the first time so wasn't really expecting those changes to have occurred necessarily. Obviously some of them but I didn't give them everything that we found. The rehab based on everything - and perhaps if we had the data analysed first before I do an objective assessment it might make me look at other things at that point if you see what I mean?	Practicality – timing (negative perception) - (no sufficient time for describing exercises based on report's findings)
PH001	168-172	I guess it depends how you're looking at it I guess from a time perspective. Might struggle to do that, certainly not going to get the funding to be able to spend an hour and a half with each of	Practicality – person should run movement analysis sessions (Challenges)

		our patients. It almost needs some sort of, someone technically minded to be able to do that for us I guess.	factors impact clinician to run sessions - time & training
PH001	174-181	I don't know how scientific or difficult it is to create that report. I don't know whether you just press buttons or whether you physically have to analyse things yourself. I am not really sure how you went about doing the analysis, whether it's quite simple or whether it was complicated. But if it's simple then maybe some sort of physio technical instructor could do it, otherwise it might need to be someone like yourself that is a research person technically minded, I am not sure.	Practicality – person should run movement analysis sessions (Challenges) factors impact clinician to run session - based on level of difficulty
PH001	181-184	I think in reality if we had, in an ideal world we'd have enough time to be able to do it ourselves as physios if we were suitably trained. INT: Hmm mmm. RES: But I am not sure that we have got enough time.	Practicality – person should run movement analysis sessions (Challenges) factors impact clinician to run session - time
PH001	192-193	Erm, yeah but I thought it was really, we obviously went through it verbally together, looked at the videos and the report.	Understanding process for interpreting feedback findings (describe what happened)
PH001	193-197	I thought it was interesting to see the difference between the left and right side for example on the stair ascend and descend. And how like he spent less time on his affected side in comparison to non-affected side with activities, so single leg squatting and you know going up and down stairs.	Feedback report – report's findings (positive perception about waveform graphs) example
PH001	197-200	I found that quite interesting how he wanted to, you know you can see it when people are doing things but like this just kind of confirmed more that actually you're spending less time on that leg. That was really interesting to see.	Feedback report – report's findings (positive perception about waveform graphs)
PH001	198-206	you know you can see it when people are doing things but like this just kind of confirmed more that actually you're spending less time on that leg. That was really interesting to see. Erm and really good to have a look at whether, the wave forms, I am not really sure what you call them. Having a look at the difference between the left and right side in terms of how much the valgus there is, how much varus at the knee, how much pronation on the ankle and how much flexion extension there is to how it changes with biomechanics when he's walking. Because of the anterior knee pain that he experiences.	Feedback report – Understanding waveform graphs – compare between the two legs by looking at time and ROM
PH001	215-221	Erm I like the fact that they give you a report, they give you a side to side difference, I thought that was really helpful. To know how [unclear: 0:15:52] I guess. Erm and like I said to you I really like being able to see how much abduction and adduction there is during the gait cycle of the hip and how much valgus and varus at the knee, how much flexion extension there is because you	Feedback report – (visualisation) – comparing movements ROM

		can then, particularly with valgus and varus abduction adduction you can then kind of, and how much pronation and supranation,	
PH001	217-221	Erm and like I said to you I really like being able to see how much abduction and adduction there is during the gait cycle of the hip and how much valgus and varus at the knee, how much flexion extension there is because you can then, particularly with valgus and varus abduction adduction you can then kind of, and how much pronation and supranation,	Feedback report – (comprehensive data) – presenting all joints at different planes
PH001	227-229	Erm, no like I said I guess it is just timing. It's difficult because it takes you time to obviously analyse the results and the patient, we don't want to keep the patient waiting any longer	Practicality – timing (negative perception) - (no sufficient time for analysing report's findings)
PH001	229-235	I think instead of being able to then deliver a programme immediately off the back of it, on top of the stuff I've already given them I guess you just need to see them a big quicker next time. So want to see them maybe within a week to implement the findings from the report sooner rather than leaving it a month and then you at that point see them again anyway which means they are not going to have made necessary changes because you haven't addressed all the findings.	Practicality – frequency (personal preferences) – Split sessions in different days (monthly bases of combined sessions (treatment + movement analysis) with solely physio session in between "2 weeks"
PH001	240-246	No, I don't think the consistency plot showed us that much if I remember rightly. They were a little bit generally inconsistent bilaterally so not necessarily sure that they added that much. I remember when we, with the previous research when I looked at those, erm they did make a difference, they were helpful with the ACL injuries I think but I don't know they were necessarily that helpful with this particular patient for some reason. And they were fairly consistent both sides, like it didn't give us much information.	Feedback report – Content (consistency plot) negative perception (not added value) based on previous experience
PH001	250-251	I guess if you spent time going through that with a patient that's going to be motivating for him as well.	Benefits – motivation for patients
PH001	247-251	But I found the other stuff helpful, also like the interesting to look at the difference between the first and the second appointment as well, in terms of have there been any improvements. And there were changes, so that was helpful to see. I guess if you spent time going through that with a patient that's going to be motivating for him as well.	Feedback report – Content (difference between sessions graphs) positive perception (monitoring progress & motivation)
PH001	253-256	But I guess probably the factor to consider are things like making sure that he comes again in the same trainers, like because things like that can make a difference to err outcome can't they, they have got to really factor that in and consider that but it might be something for consideration.	Practicality – equipment – using same trainers across sessions

PH001	259	Erm well you were there so went through it with me so that was helpful.	Feedback report – discussing findings with person ran the session (positive perception)
PH001	259-260	I'd previously look at them before. Erm, so have an understanding of them anyway.	Feedback reports – understanding findings (positive response based on previous experience)
PH001	261-264	Erm I like the videos, I think they are really nice, the avatars. They are really helpful to have a visual on what is going on. I think for me that is the quickest way of understanding what is going on and seeing differences rather than erm,	Avatar – visualisation comparing movements (positive perception)
PH001	264-266	I'd prefer those, they are the quickest way of getting the information into my brain I guess rather than the graphs take a little bit more time to look at but they are still helpful. Just more time-consuming.	Feedback report & avatar - Personal preference about the feedback form received (time)
PH001	272-275	The, I've got the movement analysis report but I think the avatar videos, the zip files. INT: Yeah. RES: I couldn't access them. I'd already seen them with you anyway.	Avatar – Access (challenges) struggling to access videos via university OneDrive shared
PH001	278-279	Yes. Again, yes because you can't send it via WeTransfer, it's probably too big, and you can't probably Dropboxs it, it's too big.	Avatar – Access (challenges) unable to send videos online
PH001	281-283	I mean I'd seen them with you anyway, so it wasn't a problem but like I said they are - because we send it by Microsoft Office, I do have Microsoft Office but I am not really sure why I couldn't access it.	Avatar – Access (challenges) struggling to access videos via university OneDrive shared
PH001	286-289	Erm, the email for the like graphs and things was fine but maybe like you said like a memory stick or CD with the avatar on would be helpful I guess. INT: Yeah, okay so you prefer to be electronically, more than to be a hard copy? RES: Yeah. It will be too much paper. Not good for the environment.	Feedback forms – format (personal preferences of having digital format)
PH001	295-303	Erm well obviously the information that we found in the movement analysis report, erm, enabled me to give the patient more - it helped me to assess the patient more appropriately, finding the biomechanical movement patterns that are occurring during the avatar and using the graph and you an analyse that better which means that you can then give better, assess them more appropriately and assess the observations based on that, based on more scientific kind of data rather than erm just opt for grading and objective and like observation of movement. Erm bit more scientific and got numbers and graphs that are attached to it which is nice.	Benefits – Add more depth (objectivity) identifying compensation strategies specifically

PH001	303-311	it means that you might be able to get your patient better quicker because you've got a lot more information at the start. Because with physio appointments obviously we get 45 minutes so by the time you build a clinical picture of what's going on based on erm assessing certain areas and progressing and assessing a few more areas, so working through your [unclear: 0:23:29]. Whereas with this you get a lot more information quicker so it means that you hopefully to get the patient better, you'd be able to provide them with a better treatment plan earlier.	Perceived impact – save clinician's time (reduce frequency of sessions over time of treatment course)
PH001	315-317	I found it fairly easy to do, erm it's not particularly time-consuming, erm I found it helpful, like I said to assess certain areas of the body once they had that information.	Usefulness – easy to use, useful (positive perception)
PH001	317-322	I went into more depth around certain things like for example looking at hips in more detail because he was over-pronating. Erm, so those sorts of things. I can't remember whether or not he had an earlier like err toe off on that side I am not sure but we did a lot of stretching around the ankle which I can't recall if that's the reason why erm but I think he might have been tight in his calves.	Benefits – add more depth (objectivity) - identifying compensation strategies
PH001	323-324	I didn't find it was too impactful on me as a person in the physio department.	Perceived impact – limited impact on clinician!
PH001	322-326	So it has a good benefit on the patient in terms of what he was given from a rehab perspective. I didn't find it was too impactful on me as a person in the physio department. It seemed to enhance the rehab process for him. Erm and it wasn't too time consuming for him.	Perceived impact – physiotherapy treatment (tailoring treatment)
PH001	332-338	Well obviously a bit, it does take slightly more time so erm in terms of you're going to have to reflect on the report or spend time with you looking for tasks so that does take time. And in a setting where I wasn't able to have that time because obviously I was helping with the research, I gave myself a little bit of extra time to be able to do that. You know you have to rely then on patients DNA'ing or you having admin time to be able to do that in other words.	Practicality – timing (negative perception) - (no sufficient time for analysing report's findings) (negative)
PH001	341-344	Erm like I said it's just working out who would be the person to do the analysis of it and being given enough time to then spend time with the person analysing it or on your own to be able to read the information.	Practicality – person should run movement analysis sessions (Challenges) – time factor needed
PH001	344-348	You'd need obviously some training as a physio to understand and interpret the information that you're giving them and if we are the ones actually using the machine, using the equipment, then we obviously would need training for that too and adequate time to be able to implement it.	Practicality – person should run movement analysis sessions (Challenges) - training and time needed to interpret findings and to create reports
PH001	259-361	have you experienced any challenges that we need to take into account? RES: Erm, no. I don't think so.	No other challenges have been faced

Appendix O: All initial codes identified from participants interviews (individuals with knee pain and clinicians) (188 codes) (Phase II)

All initial codes identified		
- Positive perception prior experience of the movement analysis tool - Positive perception about implementing the movement analysis tool in physiotherapy clinical practice (spread / rolling out) - Identifying altered movement patterns specifically and objectively - Tailoring treatment (to prescribe exercises) - (suitability) average timing of sessions positive perception - Understanding about the importance of the first movement analysis session (baseline) - Limited time for analysing feedback report) – negative perception -Limited time for analysing feedback report and sharing findings at the same session (negative perception - Too much data within report) - Perceived impact of the tool - on physiotherapy treatment (changed) - Perceived impact of the tool - on physiotherapy treatment (partially changed) - Negative perception about understanding feedback report - Importance of discussing the feedback results with clinician to increase understanding	- Limitations of paper-based format - colours on paper-based - Limitations of paper-based format - too many papers to be printed and attached in patient's file particularly if it is focused on specific joint - Perceived impact on exercise performance (Correcting the way of exercising) - Perceived impact - improve function - Understanding the use of waveform graphs – compare between the two legs - Understanding the use of waveform graphs – to look at movements at different joints and planes - Understanding the use of waveform graphs – to look at movements across time points - Positive perception during the experience of movement analysis feedback session – understanding may affect perception - Psychosocial effect of wearing sensor technology - Positive perception - enjoyability of wearing sensors - Early appointments (department closed) - Compliance (patient's lateness) - Identifying altered movement patterns specifically and objectively (Example) - Adds more depth to treatment – objectivity - Adjusting follow up session time	- Identify compensation strategies specifically and objectively - Confirm clinician's decision made - Benefits – motivation (to perform exercises) - Advantages of electronic format) – to send to patients with a summary - Suggestions to make interpretation of consistency graphs easier by adding number or colour - Altered movement pattern identified using observational assessment during functional activities by clinician - Limited time for analysing feedback report and sharing findings at the same session (negative perception - additional exercises based on report's findings need to be prescribed) - Uncertain perception during the experience of movement analysis feedback session - Factors impact clinician to run sessions - based on level of difficulty - Suggestion to include advanced type of exercises gradually based on patient's condition - Suggestion to include exercises based on patient's goal (sport) - Suggestion to include exercises based on age

- Personal preferences to set movement analysis sessions based on patient's condition (NOT predefined) - personal preferences to set movement analysis sessions based on a mutual decision between clinician and patient (NOT predefined) - Limited recruitments of patients - Positive perception about straps used - Feedback report gives comprehensive data - Feedback report gives comprehensive data (presenting all joints at different planes) - Negative perception about the jacket size used - Negative perception about the synchronisation of avatar - Increased pt familiarization throughout sessions reduce time taken - Understanding about timing of the first movement analysis session compared to subsequent ones (time for taking measurements) -Report's Format (personal preferences) paper-based based on facilities within NHS - Report's Format (personal preferences) electronic (environment) -Positive perception about exercises -Positive perception about exercises for this cohort of patients - Struggling to access videos via university OneDrive shared - Unable to send videos online	- Findings of feedback report were not discussed with patient at the same session because of time shortage - Positive perception about the visualisation of the feedback - Understanding of the knee problem - Understanding about knee condition and the effect of rehabilitation - Personal preferences to set movement analysis sessions based on patient's request (NOT predefined) - Positive response about exercises included in the movement analysis sessions - Positive perception about exercises included in the movement analysis sessions (comprehensive exercises) - Understanding the use of difference between sessions graphs - monitoring progress & motivation - Understanding the use of difference between sessions graphs - monitoring progress - Positive perception about the perceived impact - No negatives have been noticed for using the tool - Suggestion of digital version from report - Suggestion of digital version from report (looking at avatar and feedback report at same time) - Perceived impact (Increased patient's awareness of movement) - Perceived impact (Increased patient's knowledge about knee problem) - Experience and familiarisation to increase understanding of report	- Positive perception about exercises included in the movement analysis sessions (Instructions given during movement analysis sessions) - Patient struggle to keep static during calibration - Understanding of time required between movement analysis sessions (monitor changes) - Jacket size (not fit well) - Using same trainers across sessions - Negative perception about Timing of movement analysis session - Benefits for clinicians to see more patients - Positive response about equipment used - Psychosocial effect of wearing sensor technology - Benefits – monitoring progress (compare between sessions) - Tailoring treatment - Report's findings discussion is required to increase understanding - Positive perception about discussing the feedback results with clinician - Set an adequate time between sessions to analyse and interpret findings - Suggestion to send materials to patient about procedures of movement analysis session to improve familiarisation - Personal preferences of the most suitable person to discuss findings of the reports with - Understanding about adequate time needed between sessions (biomechanical change)

- Sessions should be spread along the time of the whole physiotherapy treatment course - Number of sessions based on condition - Number of sessions based on clinician - Positive perception about the visualisation of the feedback) (avatar) (enjoyability) - Positive perception about using report as reference - Uncertain perception about movement analysis tool during his experience of wearing sensors and performing activities - Negative perception about movement analysis tool during his experience of wearing sensors and performing activities - Factors impact clinician to run sessions - time & training needed - Factors impact clinician to run sessions - time needed - Increase clinician's understanding of movements - Add more depth to assessment and treatment through confirm decision, identify other compensations objectively and increase clinician's understanding of movements - Tailoring treatment (to prescribe exercises) - Benefits – Tailoring treatment (Description of exercise prescribed by clinician) - Understanding of feedback report (positive response) - Benefit for clinicians to reduce the frequency of sessions with patient over time of treatment course - Benefit for clinicians reduce time of follow up sessions - Increase patient's awareness of movements	- Training needed for clinician to increase understanding of report - Understanding process – movement analysis session - Uncertain perception prior experience of the movement analysis tool - Positive perception prior experience of the movement analysis tool (novel) - Positive perception about frequency of sessions - Negative perception about spread of sessions - Use report to assess patient's movement during high-speed tasks - Use report as reference - Use report for visualisation (comparing ROM) - Using movement analysis feedback tool outside physiotherapy clinic (Home) - Benefits – enhance engagement (to look at results) - Positive perception about the perceived impact - Understanding the use of consistency plot negative perception (NOT added value) - Comparing the findings of these plots for this cohort against a previous experienced cohort - Positive perception about using avatar and report - Patient's excitement about having movement analysis sessions - Understanding the use of temporo-spatial data – correlating data with observational analysis - Understanding the use of waveform graphs – compare between the two legs by looking at time and ROM	- Time needed between movement analysis sessions - Suggestion to include more activities - Suggestion to consult clinician about the exercise required prior to the movement analysis session - Busyness of department (availability) may impact number of sessions - More sessions- Continuing the movement analysis sessions along physiotherapy treatment course - Improve patient's motivation and adherence toward exercises - Concern about cost of software and hardware - Increase patient's motivation to treatment - To monitor progress among sessions (comparing between sessions) - Perceived impact of the tool (treatment changed based on clinician's knowledge and understanding - Personal preferences to spread movement analysis sessions over treatment course and their numbers - Sufficient time for clinician to analyse and interpret feedback reports is required - Pain with some types of exercises - Suggestion to use very high-quality computer - Suggestion for a well preparation may reduce technical issues - Positive perception about controlling - watching and replaying avatar - Lack of patient's understanding of findings - Lack of familiarisation - Personal preferences of the feedback type received

- Increased pt knowledge and awareness about movements - Positive perception about Feedback report (easy to use) - Understanding the use of waveform graphs – to look at difference - Understanding the use of waveform graphs – help in discussion with pt - Personal preference of report's format (Electronic format) - Personal preference of report's format (Both format) - Personal preferences of split sessions in different days (based on patient's interest) - Personal preferences of extra solely physio session in between two analysis sessions - Understanding longer first session because consent and measurements taken - Understanding longer first session because patient's familiarisation over sessions - Providing patient with a summary of the findings of the feedback report feedback reports with patient to increase understanding - Understanding exercises' level of challenges - Understanding the importance of analysing movement during functional tasks - Suggestion about more discussing the findings of the	- Tailoring treatment (Positive response) - Tailoring treatment (inform prescription) - Suggestion of digital version from report (markers, comments, highlights) - Suggestion of digital version from report (easy access for patient and clinician) (motivation for patient) - Positive perception about report's presentation - Positive perception about Frequency of movement analysis sessions - Difficult to set number of sessions - Familiarisation to increase understanding of report - Training needed for clinician to increase understanding of report (training methods) - Number of physiotherapy sessions patient received with clinician - Positive perception about timing for setting sensors and conducting the movement analysis sessions - Positive response about Timing of movement analysis session - Personal preferences paper-based format based on facilities within NHS - Personal preferences of electronic format (environment) - Positive perception about flow of movement analysis session and treatment session	- Personal preferences to set movement analysis sessions based on patient's progress (NOT predefined) - Positive perception about Timing of movement analysis session - Personal preference about the feedback form received (avatar rather than report) - Positive perception about the visualisation of the avatar (comparing movements) - Personal preferences for the most suitable person to interpret feedback report - Suitability of timing for patients (negative perception) - Technology process (slow) - Relevancy of using the tool with different conditions - Understanding process – whole session (movement analysis + treatment session) - Understanding process – interpreting feedback report - Understanding the importance of consistency plot - (to see how consistent the movements across trials are) - Practicality - Recruitment rate (limited) - Interpreting consistency plot - outlier waveforms - Confirm clinician's decision - Inform clinician's decision - Pain with activity tasks - Attaching avatar videos with the feedback reports - Personal preference of having sequential sessions at same day

Appendix P: Refining of all initial codes identified from participants interviews (individuals with knee pain and clinicians) which have same meaning but were named differently (Phase II)

Initial codes	Refined codes	Initial codes	Refined codes
- Positive perception prior experience of the movement analysis tool - Uncertain perception prior experience of the movement analysis tool - Positive perception prior experience of the movement analysis tool (novel)	Perception prior experience	- Confirm clinician's decision - Confirm clinician's decision made - Inform clinician's decision	Inform clinician's decision
- Positive perception about the perceived impact - No negatives have been noticed for using the tool - Positive perception about using avatar and report - Patient's excitement about having movement analysis sessions	Perception post experience	- Benefits – motivation (to perform exercises) -Improve patient's motivation and adherence toward exercises -increase patient's motivation to treatment	Improve pt motivation
- Identifying altered movement patterns specifically and objectively - Identifying altered movement patterns specifically and objectively (Example) - Adds more depth to treatment – objectivity -Identify compensation strategies specifically and objectively - Add more depth to assessment and treatment through confirm decision, identify other compensations objectively and increase clinician's understanding of movements	Identifying altered movement patterns specifically and objectively	- Uncertain perception about movement analysis tool during his experience of wearing sensors and performing activities - Negative perception about movement analysis tool during his experience of wearing sensors and performing activities - Uncertain perception during the experience of movement analysis feedback session - Positive perception during the experience of movement analysis feedback session – understanding may affect perception - Psychosocial effect of wearing sensor technology (perception) - Positive perception - enjoyability of wearing sensors	Perception during experience
- Tailoring treatment (to prescribe exercises) - Benefits – Tailoring treatment (Description of exercise prescribed by clinician)	Tailoring treatment	- To monitor progress among sessions (comparing between sessions) - Benefits – monitoring progress (compare between sessions)	Monitoring progress

- Tailoring treatment (Positive response) - Tailoring treatment (inform prescription) - tailoring treatment			
- Perceived impact of the tool - on physiotherapy treatment (changed) - Perceived impact of the tool - on physiotherapy treatment (partially changed) - Perceived impact of the tool (treatment changed based on clinician's knowledge and understanding -Positive perception about the perceived impact	Perceived impact of movement analysis tool	- Perceived impact (Increased patient's awareness of movement) - Perceived impact (Increased patient's knowledge about knee problem) - Increase patient's awareness of movements - Increased pt knowledge and awareness about movements	Increase patient knowledge and awareness of movements
- Positive response about exercises included in the movement analysis sessions - Positive perception about exercises included in the movement analysis sessions (comprehensive exercises) - Positive perception about exercises included in the movement analysis sessions (Instructions given during movement analysis sessions) -positive perception about exercises -positive perception about exercises for this cohort of patients	Perceptions about exercises included	- Pain with some types of exercises - Pain with activity tasks	Pain with exercises included
- Understanding of feedback report (positive response) -Positive perception about Feedback report (easy to use) -Negative perception about understanding feedback report	Perceptions about understanding feedback report	- Personal preferences of the feedback type received - Personal preference about the feedback form received (avatar rather than report)	Personal preferences of the feedback type received
- Personal preferences of the most suitable person to discuss findings of the reports with	Personal preferences of	- Importance of discussing the feedback results with clinician to increase understanding	Report's findings discussion is

- personal preferences for the most suitable person to interpret feedback report and share findings	the most suitable person to discuss findings with	- Report’s findings discussion is required to increase understanding - Positive perception about discussing the feedback results with clinician - Suggestion about more discussing the findings of the feedback reports with patient to increase understanding	required to increase understanding
- Personal preference of report’s format (Electronic format) - Personal preference of report’s format (Both format) -Report’s Format (personal preferences) paper-based based on facilities within NHS - Report’s Format (personal preferences) electronic (environment) - Personal preferences paper-based format based on facilities within NHS - Personal preferences of electronic format (environment)	Personal preferences of report’s format	- Positive perception about the visualisation of the feedback - Positive perception about the visualisation of the feedback) (avatar) (enjoyability) -use report for visualisation (comparing ROM) - positive perception about the visualisation of the avatar (comparing movements)	Visualisation
-Limited time for analysing feedback report) – negative perception -Limited time for analysing feedback report and sharing findings at the same session (negative perception - Too much data within report) -Limited time for analysing feedback report and sharing findings at the same session (negative perception - additional exercises based on report’s findings need to be prescribed) - Findings of feedback report were not discussed with patient at the same session because of time shortage	Limited Timing for analysing report and sharing findings	- Positive perception about Timing of movement analysis session - Positive perception about timing for setting sensors and conducting the movement analysis sessions - Positive response about Timing of movement analysis session -(suitability) average timing of sessions positive perception -Suitability of timing for patients (negative perception) - Negative perception about Timing of movement analysis session	Perceptions about timing
- Increased pt familiarization throughout sessions reduce time taken	Lack of familiarisation	- Feedback report gives comprehensive data - Feedback report gives comprehensive data (presenting all joints at different planes)	Comprehensive findings

- Lack of familiarization			
- positive perception about Frequency of movement analysis sessions -positive perception about frequency of sessions -negative perception about spread of sessions	Perceptions about frequency and spread	- Perceived impact on exercise performance (Correcting the way of exercising) - Perceived impact - improve function	Improve function and exercise technique
- Positive perception about using report as reference -use report as reference	Used report as reference	- Practicality - Recruitment rate (limited) - Limited recruitments of patients	Limited recruitments of patients

Appendix Q: All the refined codes grouped into initial categories (Phase II)

Categories	**Perception of prior, during and post experience of using movement analysis tool in clinical practice**	**Category – Implementing movement analysis tool in clinical practice**	**Category – Using movement analysis tool outside clinic**	**Category – Understanding process of movement analysis session**
Refined codes	-Perception prior experience -Perception during experience -Perception post experience	- Positive perception about implementing the movement analysis tool in physiotherapy clinical practice (spread / rolling out) - Relevancy of using the tool with different conditions	- Using movement analysis feedback tool outside physiotherapy clinic (Home)	- Understanding process – movement analysis session - Understanding process – whole session (movement analysis + treatment session) - Understanding process – interpreting feedback report
Categories	**Category – Add more depth to physiotherapy assessment and treatment**	**Category – Increased clinician's efficiency**	**Category – Increase patient understanding and awareness of movements**	**Category – Improve motivation and adherence toward exercises and function**
Refined codes	-Identifying altered movement patterns objectively -Increase clinician's understanding of movements -Inform clinician's decision -Tailoring treatment -Monitoring progress	- Benefit for clinicians to reduce the frequency of sessions with patient over time of treatment course - Benefit for clinicians reduce time of follow up sessions - Benefits for clinicians to see more patients	-Increase patient knowledge and awareness of movements	-Improve function and exercise technique -Enhance engagement (to look at results) -Improve pt motivation
Categories	**Category – Perceptions about understanding feedback report**	**Category – Features of movement analysis feedback report**	**Category – Perception about report's format**	**Category – Personal preferences of report's format**
Refined codes	-Perceptions about understanding feedback report	-Visualisation -Used report as reference	- Positive perception about report's presentation	-Personal preferences of report's format

		-Use report to assess patient's movement during high-speed tasks -Comprehensive findings		
Categories	**Category – Aadvantages of electronic format**	**Category – Limitationss of paper-based format**	**Category – Future suggestions of report's format**	**Category – Challenges and features of avatar videos**
Refined codes	-Aadvantages of electronic format – to send to patients with a summary	-Limitations of paper-based format - colours on paper-based -Limitations of paper-based format - too many papers to be printed and attached in patient's file particularly if it is focused on specific joint	- Suggestion of digital version from report - Suggestion of digital version from report (looking at avatar and feedback report at same time) - Suggestion of digital version from report (markers, comments, highlights) - Suggestion of digital version from report (easy access for patient and clinician) (motivation for patient)	- Struggling to access videos via university OneDrive shared - Unable to send videos online -Positive perception about controlling - watching and replaying avatar -Visualisation
Categories	**Category – Understanding the use of difference between sessions graphs**	**Category – Understanding the use of temporo-spatial data**	**Category – Understanding the use of waveform graphs**	**Category – Understanding the use of consistency plots**
Refined codes	- Understanding the use of difference between sessions graphs - monitoring progress & motivation - Understanding the use of difference between sessions graphs - monitoring progress	- Understanding the use of temporo-spatial data – correlating data with observational analysis	- Understanding the use of waveform graphs – to look at difference - Understanding the use of waveform graphs – help in discussion with pt - Understanding the use of waveform graphs – compare between the two legs by looking at time and ROM	- Understanding the use of consistency plot negative perception (NOT added value) - Comparing the findings of these plots for this cohort against a previous experienced cohort - Understanding the importance of consistency plot - (to see how

			- Understanding the use of waveform graphs – compare between the two legs - Understanding the use of waveform graphs – to look at movements at different joints and planes - Understanding the use of waveform graphs – to look at movements across time points	consistent the movements across trials are) - Interpreting consistency plot - outlier waveforms -Suggestions to make interpretation of consistency graphs easier by adding number or colour
Categories	**Category – Suggestions to increase understanding of report**	**Category – Personal preferences of the feedback type received**	**Category – Personal preferences of the most suitable person to discuss findings with**	**Category – Perceptions about timing of movement analysis session**
Refined codes	- Report's findings discussion is required to increase understanding - Sufficient time for clinician to analyse and interpret feedback reports is required - Providing patient with a summary of the findings of the feedback report - Attaching avatar videos with the feedback reports - Experience and familiarisation to increase understanding of report - Training needed for clinician to increase understanding of report - Familiarisation to increase understanding of report	-Personal preferences of the feedback type received	-Personal preferences of the most suitable person to discuss findings with	-Perceptions about timing

	- Training needed for clinician to increase understanding of report (training methods)			
Categories	**Category – Suggestions to eliminate challenges of session's timing**	**Category – Challenges of movement analysis session's timing**	**Category – Timing for analysing report and sharing findings**	**Category – Timing of first and subsequent movement analysis sessions**
Refined codes	-Set an adequate time between sessions to analyse and interpret findings -Suggestion to send materials to patient about procedures of movement analysis session to improve familiarisation -Suggestion to use very high-quality computer -Suggestion for a well preparation may reduce technical issues	-Early appointments (department closed) -Compliance (patient's lateness) -Technology process (slow) -Lack of patient's understanding of findings -Lack of familiarisation	-Limited time for analysing feedback report and sharing findings at the same session - Adjusting follow up session time	- Understanding about timing of the first movement analysis session compared to subsequent ones (time for taking measurements) - Understanding longer first session because consent and measurements taken - Understanding longer first session because patient's familiarisation over sessions
Categories	**Category –Perceptions about frequency and spread**	**Category – Time between movement analysis sessions**	**Category – Personal preferences of sessions' frequency and spread**	**Category – Perceptions about flow**
Refined codes	-Perceptions about frequency and spread	- Understanding of time required between movement analysis sessions (monitor changes) - Understanding about the importance of the first movement analysis session (baseline)	- Difficult to set number of sessions- More sessions- Continuing the movement analysis sessions along physiotherapy treatment course - Sessions should be spread along the time of the whole physiotherapy treatment course	- Positive perception about flow of movement analysis session and treatment session

		- Understanding about adequate time needed between sessions (biomechanical change) - Time needed between movement analysis sessions	-Personal preferences to spread movement analysis sessions over treatment course and their numbers - Number of sessions based on condition - Number of sessions based on clinician - Personal preferences to set movement analysis sessions based on patient's condition (NOT predefined) - Personal preferences to set movement analysis sessions based on a mutual decision between clinician and patient (NOT predefined) - Personal preferences to set movement analysis sessions based on patient's progress (NOT predefined) - Personal preferences to set movement analysis sessions based on patient's request (NOT predefined)	
Categories	**Category – Personal preferences of sessions' flow**	**Category – Challenge of splitting sessions**	**Category – Perceptions about exercises included**	**Category – Importance of exercises**
Refined codes	- Personal preference of having sequential sessions at same day - Personal preferences of split sessions in different days (based on patient's interest)	- Busyness of department (availability) may impact number of sessions	-Perceptions about exercises included	- Understanding exercises' level of challenges - Understanding the importance of analysing movement during functional tasks

	- Personal preferences of extra solely physio session in between two analysis sessions			
Categories	**Category – Suggestions to include more exercises**	**Category – Challenges of exercises**	**Category – Perceptions about equipment used**	**Category – Effect of using equipment on patients**
Refined codes	- Suggestion to include more activities - Suggestion to consult clinician about the exercise required prior to the movement analysis session - Suggestion to include advanced type of exercises gradually based on patient's condition - Suggestion to include exercises based on patient's goal (sport) - Suggestion to include exercises based on age	- Pain with exercises included	- positive response about equipment used - Positive perception about straps used - Negative perception about the jacket size used - Jacket size (not fit well) - Negative perception about the synchronisation of avatar	- Psychosocial effect of wearing sensor technology
Categories	**Category – Suggestions about equipment**	**Category – Challenges of equipment used (cost)**	**Category – Factors required for clinician to run movement analysis session**	**Category – Challenges during session (Calibration)**
Refined codes	- Using same trainers across sessions	- Concern about cost of software and hardware	- Factors impact clinician to run sessions - time & training needed - Factors impact clinician to run sessions - time needed	- Patient struggle to keep static during calibration

			- Factors impact clinician to run sessions - based on level of difficulty	
Categories	**Category – Patients' recruitment**	**Category – Perceived impact of movement analysis tool**		
Refined codes	- Limited recruitments of patients	- Perceived impact of the tool - on physiotherapy treatment (changed) - Perceived impact of the tool - on physiotherapy treatment (partially changed) - Perceived impact of the tool (treatment changed based on clinician's knowledge and understanding -Positive perception about the perceived impact		

Appendix R: An overview of the potential themes identified and assigned by applying colour codes for each (Phase II)

Changing perceptions about the movement analysis feedback toolkit prior, during, and post-experience
Perceived impact of the movement analysis feedback toolkit
Mechanism of perceived benefits from the tool
Usability of the movement analysis feedback report
Practicality of the movement analysis session
Understanding the process of movement analysis session
Miscellaneous theme

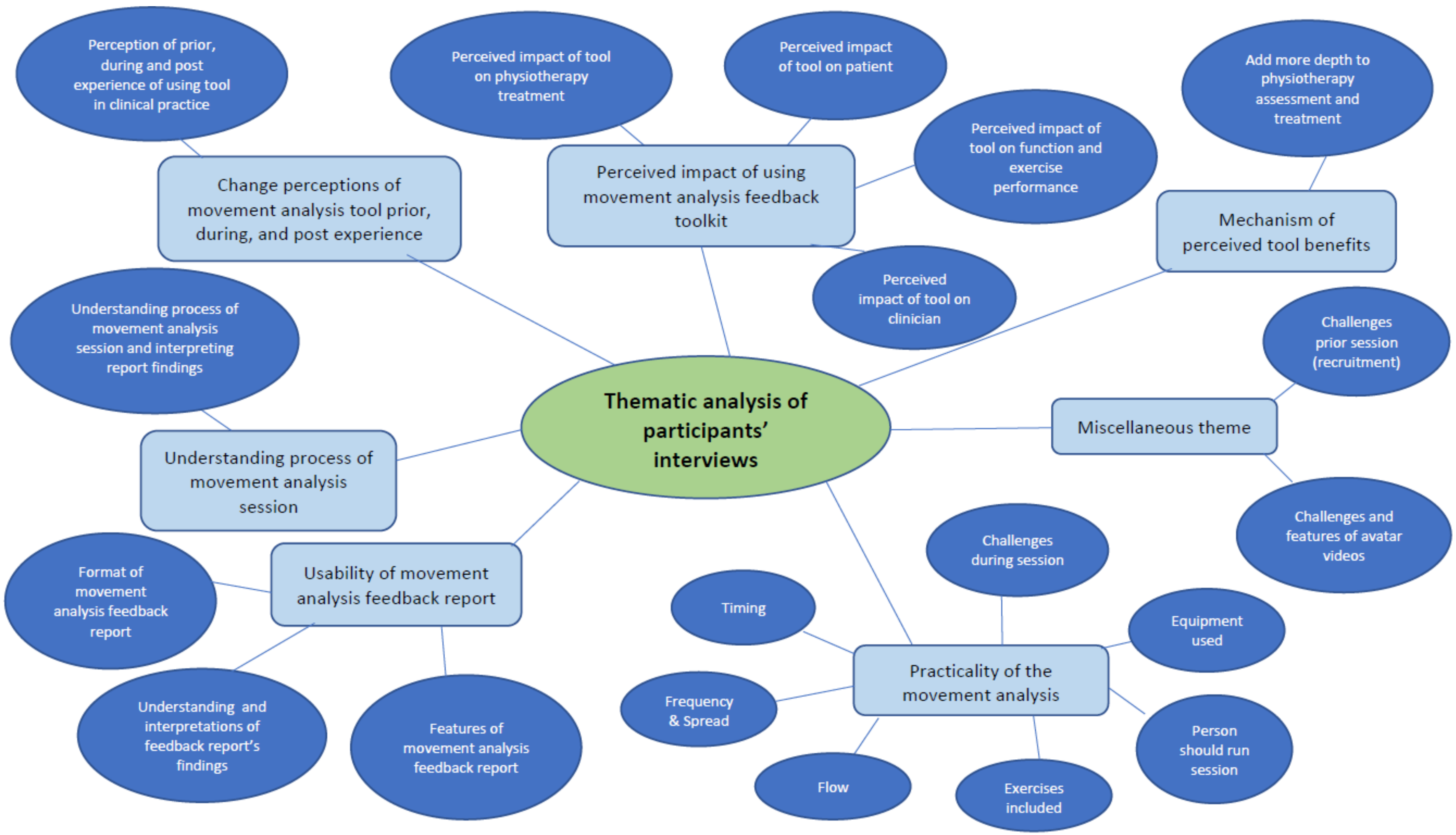
Appendix S: Sorting all the categories into potential sub-themes and themes (Phase II)

Theme - Perceived impact of the movement analysis feedback toolkit				
Subthemes	*Perceived impact of movement analysis tool on physiotherapy treatment*	*Perceived impact of movement analysis tool on individual*	*Perceived impact of movement analysis tool on function and exercise performance*	*Perceived impact of movement analysis tool on clinician*
Categories	-Perceived impact of movement analysis tool	-Increase individual knowledge and awareness of movements	-Improve motivation and adherence toward exercises and function	-Increased clinician's efficiency
Theme - Mechanism of perceived benefits from the tool				
Subthemes	*Add more depth to physiotherapy assessment and treatment*			
Categories	-Identifying altered movement patterns objectively -Inform clinician's decision -Tailoring treatment -Monitoring progress -Improve motivation and adherence toward exercises and function			
Theme - Usability of the movement analysis feedback report				
Subthemes	*Understanding and interpretations of feedback report's findings*	*Format of movement analysis feedback report*	*Features of feedback report*	
Categories	-Perceptions about understanding feedback report -Understanding the use of temporo-spatial data -Understanding the use of waveform graphs -Understanding the use of consistency plots -Understanding the use of difference between sessions graphs	-Perception about report's format -Personal preferences of report's format -Advantages of electronic format -Limitations of paper-based format -Future suggestions of report's format	-Visualisation -Used as reference -Assessing movement during high-speed tasks -Comprehensive findings	

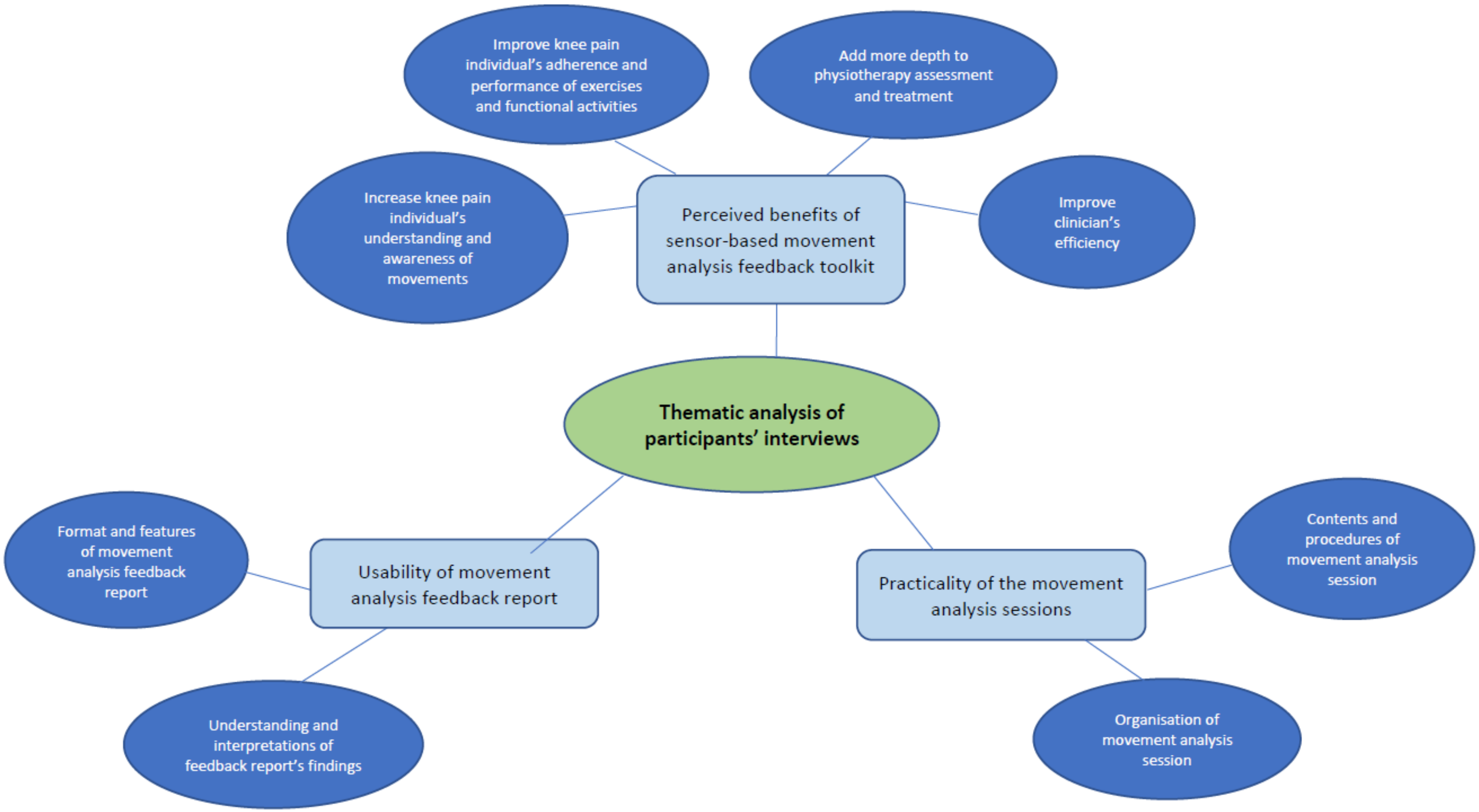
	-Personal preferences of the feedback type received -Personal preferences of the most suitable person to discuss findings with -Suggestions to increase understanding of report			
Theme - Practicality of the movement analysis session				
Subthemes	*Timing of movement analysis sessions*	*Frequency and spread of movement analysis sessions*	*Flow of movement analysis sessions*	*Exercises included in movement analysis session*
Categories	-Perceptions about timing -Challenges of movement analysis session's timing -Timing for analysing report and sharing findings -Timing of first and subsequent movement analysis sessions -Suggestions to eliminate challenges of session's timing	-Perceptions about frequency and spread -Personal preferences of sessions' frequency and spread -Time between movement analysis sessions	-Perceptions about flow -Personal preferences of sessions' flow -Challenge of splitting sessions	-Perceptions about exercises included -Suggestions to include more exercises -Challenges of exercises -Importance of exercises
Subthemes	*Equipment used in movement analysis session*	*Person should run movement analysis session*	*Challenges during session*	
Categories	-Perceptions about equipment used -Effect of using equipment on individuals -Suggestions about equipment -Challenges of equipment used (cost)	-Factors required for clinician to run movement analysis session	-Challenges during session (Calibration)	
Theme - Understanding the process of movement analysis session				
Subthemes	*Understanding process of movement analysis session and interpreting report findings*			
Categories	-Understanding process of movement analysis session and interpreting report findings			
Theme – Change perceptions about the movement analysis feedback toolkit prior, during, and post experience				

Subthemes	*Perception of prior, during and post experience of using movement analysis tool in clinical practice*			
Categories	-Perception prior experience -Perception during experience -Perception post experience			
Theme - Miscellaneous theme				
Subthemes	*Challenges and features of avatar videos*	*Challenges prior session (recruitment)*		
Categories	-Struggling to access videos via university OneDrive shared -Unable to send videos online -Positive perception about controlling - watching and replaying avatar -Visualisation	-Individuals' recruitment		

Appendix T: Initial thematic map created for the analysis of participants' (individuals with knee pain and clinicians) interview transcripts (Phase II)



Appendix W: Final thematic map created for the analysis of the participants' (individuals with knee pain and clinicians) interview transcripts (Phase II)



Appendix X: A summary of the physiotherapy treatments documented by treating clinicians in their physiotherapy notes following the movement analysis sessions for all individuals with knee pain (Phase II)

Individuals		Session 1	Session 2	Session 3
George (001)	**Altered movement patterns documented**		Alterations at hip and ankle	
	Physiotherapy treatments	- Gluteal muscles strengthening exercise from side lying with hip abduction - Quadriceps strengthening exercises (Inner-range) -Hamstrings strengthening exercise from 90/90 lying position -Squat functional exercise -Balance SLS functional exercise	- Squat functional exercise (discussed improving symmetry with the timing) - Squat functional exercise without heels raise -As squat with heel lifting was observed: • Gastrocnemius and soleus muscles stretching exercises (3x30 seconds)	-Continue with gastrocnemius and soleus stretching exercise -Gastrocnemius and soleus strengthening exercise 'Eccentric heel drop exercise' (Rt) (3x15 twice a day) - Squat functional exercise (discussed movement technique to increase hip flexion, keep heels flat, and increase foreword trunk lean) (1x15 reps)
Dora (002)	**Altered movement patterns documented**	-Alterations at hip, ankle and stiffening at knee -Good sagittal plane, but poor frontal plane movements		
	Physiotherapy treatments	-Trunk and lumber stabilisation exercises 'neutral spine exercise' -Balance exercises - progressive strengthening exercises for lower limb muscles programme		

		- Squat and lunge functional exercises (discussed movement technique to correct performance)		
David (003)	**Altered movement patterns documented**	Alterations at ankle (frontal plane)		
	Physiotherapy treatments	- Squat functional exercise (discussed movement technique to increase hip and knee flexion) - Gastrocnemius strengthening exercise (3 x 12 reps) -Soleus strengthening exercise (3 x 6 reps)	- Single leg sit to stand functional exercise (CKC exercise) - Quadriceps strengthening exercises 'Static' - Iliopsoas and quadriceps strengthening exercises 'Straight leg raise exercise' - Quadriceps, hamstrings and gluteal muscles strengthening exercises 'Leg press exercise' (with increase reps) -Advised to be seen by podiatrist (shoes insole)	
Nell (004)	**Altered movement patterns documented**	-Alterations at hip and knee (sagittal plane) (reduced) during single leg squat and stairs ascend and descend -Reduce balance control and proprioception during single leg squat		
	Physiotherapy treatments	-Balance and proprioceptive exercises in single leg - Quadriceps strengthening exercises		

		‘Knee extension’ - Quadriceps, hamstrings and gluteal muscles strengthening exercises ‘Leg press exercise’ (with increase repetitions) -Bicycle exercise with 20 kgs for Rt and Lt legs - As increased load on the right-side leg was observed: • Squat functional exercise (discussed improving symmetry between legs)		
Nancy (005)	**Altered movement patterns documented**	-Alterations at hip and knee (frontal plane) - reduced neuromuscular control		
	Physiotherapy treatments	- Gluteal muscles strengthening exercise from side lying with hip abduction using Thera band -Perform running between sessions	-Mobilisation therapy (Caudal glides in 30 of flexion for patellofemoral joint) - Quadriceps strengthening exercises ‘OKC exercise’ (3x12 reps with 15 kgs) - to increase endurance - Gluteal muscles strengthening exercise ‘Pelvic drop exercise’ (Rt) -Hip flexors stretching exercise (3x20 secs) - Quadriceps stretching exercise (3x30 secs)	- Gluteal muscles strengthening exercise ‘Pelvic drop exercise’ (Rt) (3x15 reps) - Quadriceps strengthening exercises ‘on single leg’ (one rep max, with 14 kgs on (Rt) and 21Kgs on (Lt)) -Side plank (targeting gluteal muscles) -Advised to perform running with wider steps

Joe (006)	**Altered movement patterns documented**	-Shift to Lt side during landing and jumping (Rt hip restriction) -Increased valgus on Lt knee	-Alterations at hip (increase hip flexion (Lt)) and at knee (reduced knee flexion) -Alterations at ankle (increased Pronation (Lt)) and at hip (increased abducting) during gait	
	Physiotherapy treatments	- Deep hip medial rotators stretching exercise (in position of Hip and knee 90/90) -Adductor muscles stretching exercise - Gluteal muscles strengthening exercise 'Hip thrust' - Gluteal muscles strengthening exercise 'Frog pumps' -Sumo squat functional exercise	- Iliotibial band tightness reduction (Rt) 'using foam roll' -Continue with previous strengthening, stretching and functional exercises	

Abbreviations: CKC= Close kinetic chain, Kg= Kilogram, Lt= Left side, OKC= Open kinetic chain, Reps= Reptations, Rt= Right side, Secs= Seconds, SLS= Single leg squat