Exploring the Utility of Individualised IMU-Based Movement Analysis in People with Chronic Knee Pain to Inform Physiotherapy Practice

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Abstract

Background: This study aims to explore kinematic differences in individuals with chronic knee pain (CKP) compared to healthy individuals and test the usability of an inertial measurement unit (IMU) movement analysis reporting tool for physiotherapists treating CKP.

Methods: In Part 1, kinematic movement patterns were measured using IMUs and compared within CKP and healthy individuals for the hip, knee, and ankle joints in the sagittal and frontal planes during a variety of tasks. The waveform data for each participant was analysed descriptively, with common trends being identified using a standardised reporting template that provides a structured clinical interpretation (SCI) of waveform data. Alongside this, a standard quantitative analysis (SQA) of discrete time points for all activities in both the frontal and sagittal planes was investigated for the lower limb joint angle. For the knee pain group, the painful limb (KPPL) was compared to the non-painful limb (KPNPL), and for the healthy group, the dominant limb (HDL) was compared to the non-dominant limb (HNDL).

In Part 2, a quantitative evaluation of the usability of an electronic movement analysis reporting tool for IMU data was tested via the think-aloud (TA) method and the system usability scale questionnaire (SUS). Physiotherapists interacted with the electronic reporting tool virtually and were asked to interpret movement analysis reports. The system's usability was measured using six usability metrics: efficiency, effectiveness, memorability, problems, errors, and overall ease of use.

Results: In Part 1, altered kinematic movement strategies were highlighted in both groups. The SCI revealed the complexity and individual variation of altered movement patterns, with additional information regarding the timing, nature, and amount of the alteration within the waveform graphs across joints for all activities and planes.

Using gait as an example, **in the sagittal plane,** the SCI of gait waveforms for the hip, knee and ankle depicted 17 different movement patterns in the KPPL compared to the KPNPL and 19 in the HDL compared to the HNDL across individuals. Among both SCI and SQA, alterations related to the ankle were identified within CKP individuals and the healthy group. CKP individuals displayed reduced knee flexion during the stance phase and limited ankle plantarflexion during the swing phase. Notably, there were considerable individual variations within the CKP group.

In the frontal plane, the SCI of gait waveforms for the hip, knee and ankle depicted 31 lower-limb movement alterations in the KPPL compared to the KPNPL and 33 in the HDL compared to the HNDL. Among both SCI and SQA, diverse movement alterations were observed in both CKP and healthy participants, with no significant differences identified either within the CKP group or between CKP and healthy individuals. Averaged data revealed a notable decrease in the knee adduction angle at heel strike between the KPPL of the CKP group and the HDL in the healthy group.

In part 2, the mean time spent completing the usability evaluation was 33.31 minutes. The gait report had the highest completion rate (95%) and was the most effective and efficient report. Regarding errors, a total of 76 errors were made while interpreting the reports. The system demonstrated good memorability between reports with less time spent on the repeated task (01:53 minutes for the repeated task vs. 04:04 minutes for the first time). The overall system usability was 63.33%, indicating borderline to good usability.

Conclusion: Using the standardised template, movement alterations were identified across the hip, knee, and ankle joints in the sagittal and frontal planes over a range of activities. This provided additional information at the individual level compared to that gained through the discrete analysis. Therefore, it might be advantageous to provide physiotherapists with waveform kinematic data to inform therapeutic exercise prescription, movement re-education, and monitoring progress. The results of the usability study informed modifications to the online kinematic reporting tool to reduce problems and errors using the reporting tool and improve its use for physiotherapists treating CKP individuals.

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Glossary of abbreviations

CKP	Chronic knee pain
MSK	Musculoskeletal
GP	General practitioner
PT	physiotherapy
RCT	Randomised control trial
ITB	Iliotibial band syndrome
PFPS	Patellofemoral pain syndrome
ACL	Anterior cruciate ligament
TKA	Total knee arthroplasty
ICC	Interclass correlation coefficient
CMC	Coefficient of multiple comparisons
SIT	Strength inhibition theory
cm	Centimeters
m	meters
Kg	Kilograms
BMI	Body Mass Index
3D	Three dimensional
2D	Two dimensional
HD	High definition
RMSE	Root mean squared error
FB	Feedback
EMG	Electromyography
HS	Heel strike
IC	Initial contact
PKF	Peak Knee Flexion
ROM	Range of Motion
KOOS	Knee injury and osteoarthritis outcome score
NPRS	Numeric pain rating scale
QoL	Quality of life
PROMs	Patient reported outcome measures
SUS	System usability scale questionnaire
uMARS	User version of the Mobile application rating scale
OARSI	Osteoarthritis research society international
ADL	Activity of daily living
SPM	Statistic parametric mapping
GRF	Ground reaction force
KFM	Knee flexion moment
OA	Osteoarthritis
TFOA	Tibiofemoral osteoarthritis
PFOA	Patellofemoral osteoarthritis
DKV	Dynamic knee valgus
SD	Standard deviation
KPPL	Knee Pain Painful Limb
KPNPL	Knee Pain Non-Painful Limb

HDL	Healthy Dominant Limb
HNDL	Healthy Non-Dominant Limb
COD	Change of direction
DGA	Dynamic gait assessment
OG	Overground walking
TM	Treadmill walking
SLS	Single Leg Squat
DLS	Double Leg Squat
SA	Stair Ascent
SD	Stair Descent
VJ	Vertical Jump
IMU	Inertial Measurements unit
MTw	Wireless motion trackers
SCI	Structured clinical interpretation of kinematic data
SQA	Standard quantitative analysis of kinematic data
TA	Think-aloud
PIS	Participant’s information sheet
UI	User interface
CR	Completion rate

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Chapter 1: Introduction

1.1 Background

Chronic knee pain (CKP) has no clear definition and is often linked to underlying conditions such as osteoarthritis (OA). It has been a topic of debate whether it should be regarded as a disease (Treede et al. 2019), with efforts having been made to identify and classify it as a distinct clinical entity (Sluka 2016). CKP is persistent or recurring knee pain that lasts for at least a month to three months or longer which can affect a person’s daily activities, mobility and quality of life (Treede et al. 2019). Definitions of CKP vary depending on the context and research criteria. The current study regards CKP as a distinct clinical condition with its own characteristics and mechanisms, rather than a symptom of another issue. In the current thesis, CKP is considered to last for at least a month and is not caused by injury or surgery.

Chronic knee pain is one of the most common musculoskeletal (MSK) clinic presentations in the UK (Keenan et al. 2006; Ingham et al. 2011; Fejer and Ruhe 2012) and the tenth most common reason for visiting a general practitioner (GP) (Hing et al. 2005). Based on population-level data, up to 10% of people have CKP and lower limb pain resulting in impairment and even more people may present with CKP in combination with other MSK pain problems (Kusnezov et al. 2016). This figure may be underestimated due to the significant number of people who do not present to healthcare professionals and instead self-manage with analgesics (Pal et al. 2016).

Chronic knee pain is costly for healthcare systems to treat. For instance, in a UK population-based study of 5,752 individuals with CKP, the lifetime cumulative proportion indicates that CKP was the reason for almost 13% of all GP visits and accounted for 6.8% of all referrals made to secondary care. Based on the findings of Vos et al. (2016), the global prevalence of CKP conditions such as knee OA was estimated to be approximately 200 million individuals in 2015. Furthermore, this figure indicates a notable increase of approximately one-third over the course of the previous decade (Vos et al. 2016). In 2017, missed working days as a result of OA cost £2.58 billion and by 2030 it is estimated that this cost will have increased to

£3.43 billion (Versus Arthritis 2021). Therefore, reliably identifying the most appropriate management strategies to alleviate this burden is of great importance.

One of the available treatment options is physiotherapy (PT) (Jones et al. 2015; Willy et al. 2019; Buchbinder et al. 2014). According to the National Institute for Health and Clinical Excellence (NICE) (NICE 2022) and the American College of Rheumatology (ACR) (Kolasinski et al. 2020), exercises are the primary PT interventions for managing CKP conditions such as OA. According to a recent systematic review and network meta-analysis of existing Cochrane reviews on the management of OA, PT and exercise constitute the fundamental approaches for managing CKP (Smedslund et al. 2022). Nevertheless, the authors of the review indicated that therapeutic exercise has only a moderate effect in terms of alleviating pain among those with CKP (Smedslund et al. 2022). Owing to the variability of exercise regimens in terms of the type of exercise, training intensity, population characteristics, outcome measures, and knee problems, the formulation of what constitutes sufficient and efficacious treatment is variable (Manojlović et al. 2021; Rocha et al. 2020).

Another recent systematic review and meta-analysis of 91 randomised controlled trials (RCTs) conducted using a sample of people with various CKP conditions indicated a small positive overall effect of therapeutic exercise on pain and function (Holden et al. 2023). This small effect of exercise was attributable to the fact that therapeutic exercise prescription for CKP conditions like OA is multi-dimensional and complicated, which explains the suboptimal delivery of exercise in clinical practice and the variability in management outcomes (Holden et al. 2023). Therefore, the authors provided several suggestions that were in accordance with previous recommendations such as the need to individualise the exercises based on comprehensive assessment, treatment and follow-up, as well as considering the type and amount of exercise (Holden et al. 2023; Osthoff et al. 2018). Experts in the review indicated that exercises should be selected in a way that directly addresses the individual’s impairments and functional limitations (Holden et al. 2023).

It has been proposed in previous research that people with CKP commonly present with altered movement patterns (Kobsar et al. 2015; Watari et al. 2016) which could explain the limited effectiveness of exercise when treating CKP. Thus, further therapeutic benefits might be achieved by addressing movement alterations as a means of individualising treatment and enhancing the benefits of exercise (Willy et al. 2012; Roper et al. 2016). It has been proposed that the mechanism of action of altered movement patterns is that they serve as a mechanism for pain protection (Hodges and Tucker 2011). The chronicity of pain may then lead to the continuity of such altered movement patterns, consequently augmenting the intensity of pain and further restricting movement (Hodges 2011). Pain may modify motor function from muscular activation to movement avoidance, which consequently manifests as movement alterations (Roland 1986; Lund et al.1991; Hodges and Tucker 2011). How chronic pain affects people differs for every individual and each type of pain condition (Sluka 2016) due to peripheral and central nervous system changes causing pain sensitisation, persistence and resistance to guideline-based PT (O’Leary et al. 2018; Fingleton et al. 2015). This again emphasises the importance of individualised responses and analysis of altered movement patterns (Sluka 2016). Analysis of altered movement patterns may entail kinematic analysis using motion capture systems during functional tasks, thereby offering invaluable insight into an individual's movement patterns (Bolink et al. 2012; Nakagawa et al. 2013).

Numerous studies have assessed functional activities to determine how people with CKP move (Bolink et al. 2012; Nakagawa et al. 2012; Ismailidis et al. 2020; van der Straaten et al. 2020). This has been achieved using various motion capture systems to evaluate activities such as gait, double leg squats (DLS), single leg squats (SLS), vertical jumps (VJ), stair ascent (SA) and stair descent (SD) which are essential functional activities that present diverse problems for those with CKP. Hence, tailored management can provide the optimum rehabilitation technique for each individual's needs (Kobsar et al. 2015; Watari et al. 2016).

Lower limb kinematic patterns are evaluated most objectively using laboratory-based optoelectronic three-dimensional (3D) motion capture systems (Ford et al. 2003; Boling and Padua 2013; Nakagawa et al. 2013; Jones et al. 2014). These systems are considered to be the gold standard for analysing movement kinematics and kinetics in all planes during limited functional tasks within controlled environments (Sigward et al. 2011; Munro et al. 2012). However, their limitations include being complex to use, their high cost, the need for sophisticated user training, and the time required to collect and analyse the data (Dingenen et al. 2014; Schurr et al. 2017). In addition, they are difficult to transport and use both within and outside of clinical settings (Schurr et al. 2017).

These systems are often not easily accessible to physiotherapists and, therefore, a portable movement analysis system that is capable of quantifying kinematics in all planes of motion during dynamic activities and that is accessible for physiotherapists in clinical settings is needed. Inertial measurement units (IMUs) offer advantages relative to optoelectronic 3D motion capture systems in terms of their portability, size and the space that is needed. IMUs can monitor movement in all planes during functional activities such as walking and stair climbing.

Al-Amri et al. (2018) evaluated the validity and reliability of the IMU-based movement analysis system during three functional tasks (gait, squatting and jumping). Their results indicated excellent inter-rater reliability for the sagittal plane and at all lower extremity joints during the three functional tasks (ICC > 0.75) but their results demonstrated fair-to-excellent intra-rater reliability across the frontal and transverse planes of movement (ICC = 0.40 – 1.00) (Al-Amri et al. 2018). Additionally, the within-session reliability was fair-to-excellent for lower limb kinematics in all planes when walking and squatting (ICC > 0.60), yet the transverse plane demonstrated reduced within-session reliability which ranged from poor-to-excellent (Al-Amri et al. 2018). The validity of the hip, knee and ankle joint angles was found to be excellent in the sagittal plane for all three tasks. In the frontal and transverse planes, the validity was deemed to be acceptable for the squat and jump activities across the joints. The overall findings of the study indicated that IMUs have the potential to be utilised by physiotherapists when quantifying lower-limb joint angles in clinically related movements (Al-Amri et al. 2018).

Thus, IMU sensors provide a good alternative to the gold-standard optoelectronic 3D motion capture technology for the clinical setting (Cuesta-Vargas et al. 2010). However, movement analysis using IMU’s is complicated because it provides significant amounts of kinematic data in three planes of movement (sagittal, frontal and transverse) across multiple joints concurrently.

Motion capture systems, including IMUs, generate movement analysis reports that physiotherapists can use to identify altered movement patterns, make decisions and create customised therapy plans. These reports often include more than 50-line graphs when bilateral data from the ankle, knee and hip are included, which would prove challenging for most experienced physiotherapists. There is a paucity of literature regarding how physiotherapists interpret movement analysis reports. According to Skaggs et al. (2000), interpreting movement analysis reports involves two elements: identifying the presence of movement alteration and interpreting the alteration. To establish consistent interpretation and therapeutic decision-making, physiotherapists must possess skills in both components (Skaggs et al. 2000). Some movement analysis studies focus on identifying movement alterations (Nieuwenhuys et al. 2017; Wang et al. 2019; Button et al. 2022; Brunnekreef et al. 2005), whereas others focus on how to interpret them (Button et al. 2022; Fellin et al. 2010; Crenshaw and Richards 2006; Manal and Stanhope 2004). No uniform method exists for both components of identifying and interpreting the data.

1.2 Research gap

Accurate movement analysis is challenging due to the difficulties associated with data collection in laboratory settings, as noted above. The methods of interpreting and reporting the acquired data needs to be investigated because the kinematic data is usually presented in the movement analysis reports as averaged data calculated at discrete time points over the movement cycle which makes it difficult for physiotherapists to provide individualised assessments and treatment plans. Additionally, the way in which these kinematic data are interpreted is typically subjective and lacks standardisation, thereby potentially leading to variability, including variable treatment (Skaggs et al. 2000). Holden et al. (2023) emphasised the need to develop user-friendly online tools to help physiotherapists deliver the best possible practice with individualised assessment and management for those experiencing CKP conditions.

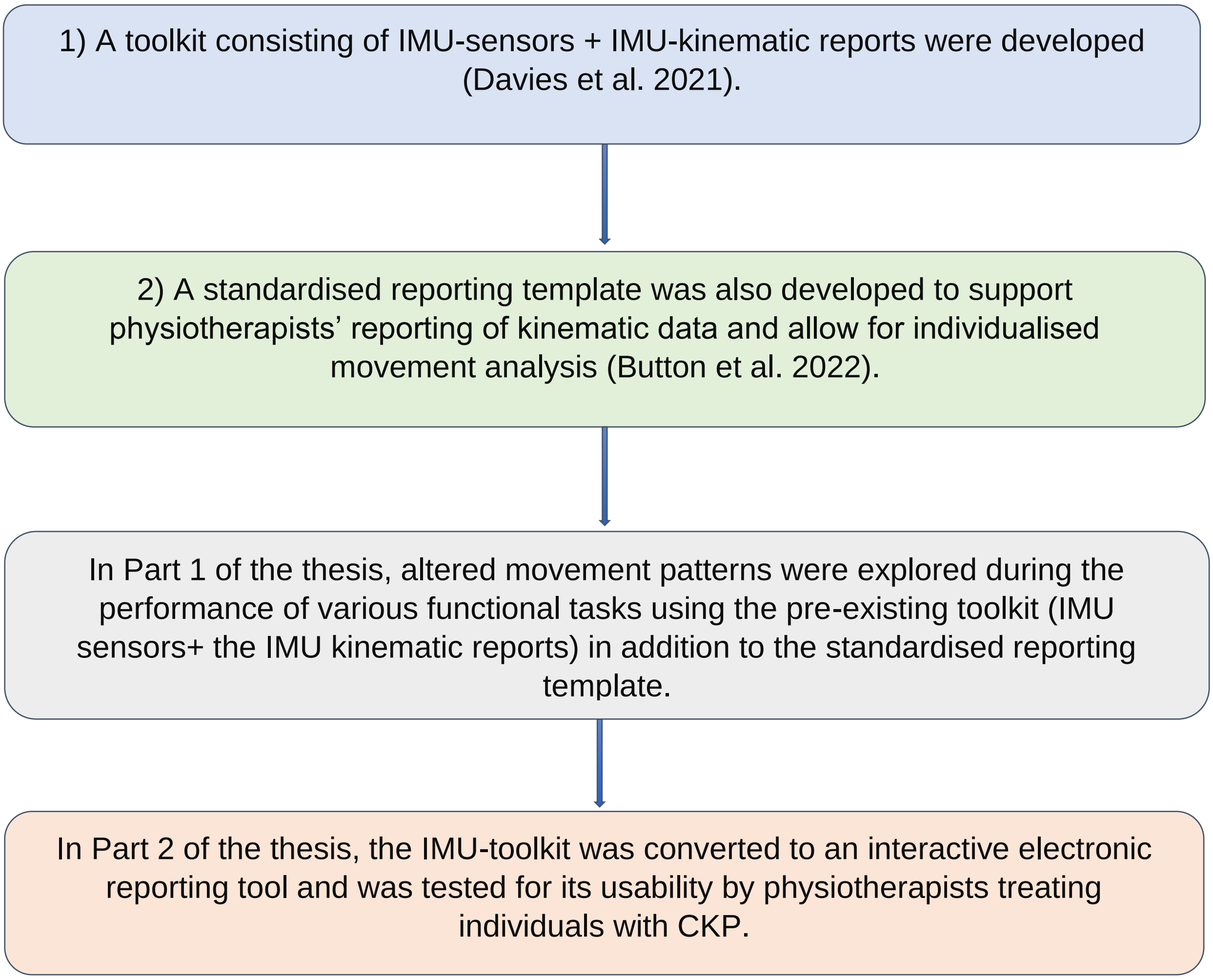
In previous research, a toolkit incorporating IMUs and convenient, rapid and accessible movement analysis kinematic reports that represent kinematic data (temporo-spatial and joint angle waveforms) acquired from IMU sensors for joints in the lower limbs (e.g., hip, knee and ankle) and the sagittal and frontal planes during a variety of functional tasks (gait, DLS, SLS, VJ, SA and SD) was developed (Appendix A) (Davies et al. 2021). The kinematic data reported in these reports can be interpreted by physiotherapists and patients to guide therapeutic decision-making, inform treatment planning and monitor progress, as recommended by Holden et al. (2023).

A standardised template for enhancing the consistency of reporting kinematic waveform data was also developed (Button et al. 2022). The template can be used by inexperienced physiotherapists (Zhou et al. 2021) and allows for individualised interpretation of the whole movement cycle, whilst facilitating the identification and description of movement alterations in a consistent manner. It is believed that this descriptive analysis of waveform data using the template helps to uncover individual nuances in movement patterns that were not apparent when averaging out the data at discrete time points.

Therefore, there are two parts to the current PhD thesis: part one utilises the IMU reporting toolkit (IMU sensors and the IMU kinematic reports) along with the standardised reporting template to assist in the interpretation of movement analysis data and allow for individualised movement analysis for individuals with CKP during various functional tasks. Part two converts the reporting toolkit developed by Button et al. (2022) into an interactive electronic reporting tool. Additionally, in order to fully realise the potential of this electronic reporting tool in clinical practice, it is essential to ensure its usability. Therefore, part two incorporates a usability study. This usability study is important to ensure the user-friendliness and practicability of the electronic reporting tool (see Figure 1 for better understanding of how the pre-developed tools were used in the two parts of the thesis). It is believed that by conducting this usability study, it will be possible to make movement analysis and interpretation easier whilst saving time and offering an approach that is more user-friendly for physiotherapists treating individuals with CKP. As such, this will address the need for practical and user-friendly tools in the field. Accordingly, the aim of the current thesis is:

1.3 Thesis Aim

The overall aim of the current PhD thesis is to explore the utility of individualised IMU-based clinical movement analysis for people with CKP.



1) A toolkit consisting of IMU-sensors + IMU-kinematic reports were developed (Davies et al. 2021).

2) A standardised reporting template was also developed to support physiotherapists' reporting of kinematic data and allow for individualised movement analysis (Button et al. 2022).

In Part 1 of the thesis, altered movement patterns were explored during the performance of various functional tasks using the pre-existing toolkit (IMU sensors+ the IMU kinematic reports) in addition to the standardised reporting template.

In Part 2 of the thesis, the IMU-toolkit was converted to an interactive electronic reporting tool and was tested for its usability by physiotherapists treating individuals with CKP.

Figure 1: Flow diagram representing the pre-developed tools utilised in the current PhD thesis

1.4 Structure of the current PhD thesis

The introduction chapter concludes by outlining the structure of the current study which is organised into a total of nine chapters. Chapter One has introduced the research topic, including the background information, the need for the research and its aim.

Chapter Two presents the literature review which provides the knowledge base regarding the condition of CKP (including its definition, epidemiology, cost, prognosis and conservative management). The chapter also identifies gaps in the existing evidence regarding movement analysis for patients with CKP using various motion capture technologies and reflects on how movement analysis data have been interpreted and reported.

Chapter Three presents the method for the first part of the current study. This study identifies differences in kinematics in patients with CKP and healthy people using kinematic reports from IMU sensors and the standardised reporting template. The study applies two approaches to analyse the kinematic data which are also introduced in this chapter.

Chapter Four provides the results to part one of the current thesis, including the demographic data and study data.

Chapter Five presents the discussion for part one. This includes a summary of the main findings, an interpretation of the results, the strengths and limitations, methodological considerations, clinical implications, and finally the conclusion.

Chapter Six describes the methods for part two of the current thesis which concerns the usability of the electronic version of the reporting tool. This chapter also presents the data analysis for the usability evaluation in addition to the associated ethical considerations.

Chapter Seven explains the results for the usability study and this is followed by Chapter Eight which interprets the findings for part two of the current thesis, the strengths and limitations, and the future research and development in this area.

Chapter Nine concludes with a summary of the whole study. This includes the contribution to the existing body of knowledge, a summary of the strengths and limitations, as well as consideration of the clinical implications of this research.

1.5 Impact of the COVID-19 pandemic on the current PhD thesis

The inability to access resources, facilities, and participants due to COVID-19 restrictions has had a profound impact on this PhD thesis. It was therefore decided to modify the research design for the two parts of this PhD thesis.

The COVID-19 pandemic has significantly impacted Part 1 of the thesis, which involved the attachment of IMU sensors to individuals with and without CKP. Participant accessibility and safety concerns arose, with potential participants expressing hesitancy due to the close physical interactions required for sensor attachment, which had led some participants to cancel their scheduled appointments. It was impossible to conduct the study utilising virtual methods due to the necessity of sensors’ attachment to participants’ bodies. Overcoming these challenges involved modifications to the research timeline for data collection and analysis, revised participant recruitment strategies, and enhanced safety protocols to maintain the integrity of the study and prioritise the well-being of all involved parties.

To address these challenges, a critical adaptation was also made to the plan for Part 2 of the study. Initially designed as a mixed-method study design with face-to-face interviews and including both physiotherapists and individuals with CKP. The researcher reconfigured the study into an online usability study conducted via Zoom, involving only physiotherapists treating individuals with CKP. It is essential to note that no new movement analysis data were collected, as it was not feasible under the prevailing circumstances. The study was decided to be conducted using a quantitative approach for testing the usability and to be a small formative quantitative usability study, utilising the think-aloud method and system usability scale questionnaire. Conducting the study using these two approaches proved to be a rigorous design.

Chapter 2: Literature review

2.1 Introduction

This chapter provides a narrative review of CKP which is one of the main causes of MSK presentation in clinics. This includes its definition, epidemiology, costs, prognosis and conservative management. Following that, an overview of the importance of movement analysis and the mechanism underpinning pain and movement alterations is demonstrated. This is followed by a review of the various motion capture technologies used for movement analysis. Then there is a demonstration of the altered movement patterns associated with CKP using different motion capture technologies during a variety of functional activities. This is critically reviewed to identify the gap in the literature. Finally, the literature concerned with the reporting and interpretation of movement analysis data is also critically reviewed. The chapter concludes by summarising the research evidence gap which leads onto the research question and aims of the current thesis.

2.2 Chronic knee pain

2.2.1 Definition

The knee joint is one of the most common sites for MSK disorders (Keenan et al. 2006; Ingham et al. 2011; Fejer and Ruhe 2012) and knee symptoms are the tenth most frequent reason for MSK presentations in clinics (Hing et al. 2005). While acute knee pain usually arises from injury or surgery, CKP can result from degenerative processes such as OA, overuse or unmanaged injury to the muscles, tendons or ligaments (Albright et al. 2001).

Chronic knee pain presently lacks a standardised definition. While it is frequently linked with underlying conditions such as OA, there is an ongoing debate as to whether CKP ought to be regarded as an autonomous disease entity (Treede et al. 2019). The notion of chronic pain as a disease has attracted renewed interest in recent times, with endeavours aimed at acknowledging and categorising it as a separate clinical entity (Sluka 2016). CKP refers to persistent or recurrent pain in the knee joint that lasts for an extended period, typically three months or longer and can significantly impact a person's daily activities, mobility and quality of life (Treede et al. 2019). Many different timeframes have been presented in the literature regarding the interpretation of CKP. For example, it was defined as recurrent pain in or around the knee that has increased pain symptoms for at least a month (O'Reilly et al. 1996; Ingham et al. 2011). Some researchers have characterised CKP as a chronic condition that often lacks a specific underlying cause and can affect adults of all ages. In individuals aged 45 years and over, CKP may serve as an indicator of knee OA or other related disorders (Altman et al. 1986).

Chronic knee pain is complex and can be brought about by changes in pain modulatory pathways (Neogi et al. 2009; Duncan et al. 2007) such as inflammation, nerve sensitisation and the release of pain mediators which contribute to the development and persistence of pain (Neogi 2013) or structural changes such as knee OA including cartilage degradation, bone remodelling and synovial inflammation which can contribute to pain generation and progression (Felson 2009). This indicates that CKP can have multiple underlying mechanisms and contributors, thereby making its understanding and management challenging.

In summary, the definition of CKP can vary depending on the context and research criteria used. As for the population included in this LR and in the studies for the current research, CKP includes adults with any CKP condition that lasts for at least a month such as OA, patellofemoral pain syndrome (PFPS) and patellar tendinopathy. This LR will not include any knee conditions associated with injuries or surgery such as anterior cruciate ligament injuries (ACL), total knee arthroplasty (TKA), infection or inflammation.

2.2.2 Epidemiology

Estimates of the epidemiological aspects of CKP vary across studies and this can be attributed to the dissimilarities in the categorisation of the underlying causes and definitions of pain (Rothermich et al. 2015). Fejer and Ruhe (2012) conducted a systematic literature review to investigate the prevalence of undefined MSK CKP in the senior population (60+ years) using various self-reporting outcome measures. The estimations ranged from 6% to 63.4%. It was hypothesised that this substantial difference in prevalence estimates resulted from the diverse knee pain criteria utilised across the research (Fejer and Ruhe 2012).

Based on US population-level data for the period from 2006 to 2012, the Defense Medical Epidemiology Database was utilised to identify military active-duty service members who had been diagnosed with CKP (Kusnezov et al. 2015). The study indicated that up to 10% of the population experienced chronicity of knee pain and lower limb pain resulting in disability. Furthermore, an even greater number of individuals may present with knee pain, either alone or in conjunction with other MSK pain conditions (Kusnezov et al. 2015). In 2015, it was estimated that nearly 200 million individuals across the globe experienced CKP conditions such as OA, marking an increase of one-third over the previous decade (Vos et al. 2016). Research suggests that such epidemiological studies may underestimate the true prevalence of knee pain at the community level due to those who do not present to healthcare providers, such as those who self-manage with analgesics (Pal et al. 2016).

Herquelot et al. (2015) utilised two surveys (one at baseline and another at two years for follow-up) to ascertain the prevalence of CKP among a representative sample of the working population in France, with an emphasis on personal and occupational risk factors. At follow-up, 122 (7.5%) of the 1,616 individuals who did not report CKP at baseline had developed CKP. It was anticipated that the prevalence of CKP would be 19.6 per 1,000 years of employment (95% confidence interval: 16.5–23.5). After adjusting for age and body mass index (BMI), a significant correlation was found between incident CKP and kneeling >2 hours per day for males [OR 1.8 (1.0–2.0)] and handling loads >4 kg [odds ratio (OR) 2.1 (1.2–3.6) for males, OR 2.3 (1.1–5.0) for females].

Herquelot et al. (2015) emphasised the significant prevalence of CKP in the working population and the relevance of occupational variables in its occurrence, especially kneeling and lifting. However, due to the limitations of the two-phase design, it was not possible to assess potential fluctuations in the knee pain condition. For example, knee pain could have occurred prior to the administration of the baseline questionnaire, during the period between the baseline and follow-up questionnaires, or in the lost-to-follow-up group in greater proportions.

2.2.3 Cost of CKP

Chronic knee pain places a significant financial cost on healthcare systems. It accounts for approximately 13% of all adult visits to GPs and 6.8% of secondary care referrals over the course of a lifetime (Webb et al. 2004). Some CKP conditions such as OA present a significant challenge for the National Health Service (NHS) in the UK, with 3 million GP consultations and 115,000 hospital admissions attributed to this condition in the year 2000 alone (Webb et al. 2004). According to practitioners, approximately one million adults seek medical care annually due to symptoms associated with CKP conditions, thereby making it a prominent factor driving healthcare utilisation (Royal College of General Practitioners 2006). The anticipated cost of lost working days due to OA in 2017 was £2.58 billion and this is projected to rise to £3.43 billion by 2030 (Jordan et al. 2014).

2.2.4 Prognosis of CKP

A prospective cohort study by Rathleff et al. (2019) was conducted over five years to investigate the prognosis of CKP in adolescents and assess its influence on health, care-seeking and career decisions. Among a sample of 2,200 adolescents aged 15–19 years, along with 252 controls without knee pain, 504 reported at least monthly knee discomfort and were prospectively tracked in this cohort research. At follow-up, 358 (71.0%) of the participants in the knee pain group and 182 (72.2%) participants in the control group replied. Notably, 40.5% (CI: 35.4% to 45.6%) of the 358 in the CKP group experienced regular and severe knee pain five years later, compared to 13.2% (CI: 8.2% to 18.2%) of the control group (Rathleff et al. 2019).

Those in the knee pain group who were still experiencing knee pain recorded a worse physical condition in the knee injury and osteoarthritis outcome scores (KOOS) (13 points worse on KOOS function and 30 points worse on KOOS sport/recreation), they had ceased or reduced their participation in sport due to knee pain (60%) and reported poorer sleep quality, knee-related and overall quality of life (Rathleff et al. 2019). In terms of health behaviours, those with ongoing knee pain reported more visits to the doctor. One-third frequently used painkillers and 15% (95% CI: 12% to 20%) reported that knee pain influenced their employment or career choice. Moreover, four out of ten adolescents with knee pain continued to experience regular and significant knee pain five years later which was severe enough to influence their health, health behaviours and job decisions (Rathleff et al. 2019).

To conclude, according to epidemiological research, CKP burdens older people and its economic cost to healthcare systems is significant. Long-term prognosis studies indicate that many people continue to experience severe pain which affects their health, daily activities and quality of life. The appropriate CKP management options can alleviate pain, enhance outcomes and reduce the burden on individuals and healthcare systems. Thus, the following section discusses the conservative management of the condition.

2.3 Conservative management of CKP

The following section focuses on the non-surgical and non-pharmacological management of CKP conditions.

2.3.1 Physiotherapy and exercise

The literature supports the use of conservative management techniques such as PT for CKP conditions (Jones et al. 2015; Willy et al. 2019; Buchbinder et al. 2014). The goal of PT is usually to alleviate knee pain and improve functional abilities (Juhl et al. 2014; DeVita et al. 2018). Jones et al. (2015) support conservative treatments for two of the most common causes of CKP conditions (namely OA and PFPS), reporting that PT and exercises are the foundations for the effective management of these conditions.

The mechanism of action of exercises in alleviating pain and improving function in CKP conditions is multifactorial and involves various physiological and biomechanical processes. For example, exercise programmes which target the muscles surrounding the knee joint, such as the quadriceps, hamstrings and hip muscles can improve muscle strength and stability (Fransen et al. 2015). Stronger muscles help to support and stabilise the knee joint, thereby reducing stress on the joint and alleviating pain (Fransen et al. 2015; Bennell et al. 2012a). Appropriate exercises can help to stimulate the cartilage within the knee joint (Zeng et al. 2021). Controlled loading of the joint through exercises such as walking or low-impact activities promotes cartilage adaptation and remodelling by increasing the cartilage oligomeric protein and accelerating the growth of damaged cartilage (Roos and Dahlberg 2005; Zeng et al. 2021).

Exercise can stimulate the release of endogenous pain-relieving substances such as endorphins which can help to reduce the perception of pain. Moreover, exercise may induce neuroplastic changes, enhance pain modulation and improve pain tolerance (Naugle et al. 2012; Geneen et al. 2017). Exercise can also promote the production and circulation of synovial fluid which acts as a lubricant within the knee joint (DeVita et al. 2018). Improved lubrication helps to reduce friction between joint surfaces, thereby leading to smoother movement, less pain and improved joint function (Henriksen et al. 2014; DeVita et al. 2018). Lastly, exercise has the potential to facilitate weight loss or weight management, a factor of particular significance for individuals experiencing CKP (Li et al. 2019). Excess body weight places an increased burden on the knee joints, thereby intensifying both pain and functional limitations. Regular exercise combined with a balanced diet can help to achieve and maintain a healthy weight, thereby reducing the load on the knee joint and improving symptoms (Messier et al. 2004; Bliddal et al. 2014).

Physiotherapists have employed a variety of exercise treatment programmes to help people with CKP (e.g., exercise therapy, knee taping and orthotic devices) (Zhang et al. 2008; Hochberg et al. 2012; Willy et al. 2019). However, programmes such as stretching and strengthening exercises were found to be more efficient in terms of alleviating pain and improving function than alternative passive interventions such as ultrasound therapy, electrical stimulation, knee taping, cryotherapy, heat and orthotic devices (Bennell et al. 2012a; Zhang et al. 2008; Hochberg et al. 2012; Willy et al. 2019).

Three recent systematic reviews investigated the types and effects of exercises performed for knee pain conditions and introduced multiple exercise options: strength training, balance training, aerobic exercises, neuromuscular and proprioception training, and aquatic and conventional exercise (Manojlović et al. 2021; Raposo et al. 2021; Rocha et al. 2020). Strength training exercises have a more beneficial effect on pain than on function (Rocha et al. 2020). Manojlović et al. (2021) suggested the addition of hip strengthening exercises to knee exercises because this was found to provide better outcomes than only knee exercises for people with PFPS.

The reviews of Manojlović et al. (2021) and Rocha et al. (2020) had several flaws, including the lack of a clear description of the treatments (number of repetitions, sets, etc.), the load employed and exercise progression which makes it difficult to develop an adequate physical training programme. Rocha et al. (2020) also alluded to the fact that for strength training, most of the reviewed studies lack the use of a gold standard tool for measuring muscle strength, such as a Biodex dynamometer, which makes quantitative analysis of this variable difficult (Rocha et al. 2020).

A recent systematic review and meta-analysis investigating the effects of therapeutic exercise on knee and hip OA suggests that therapeutic exercise has a modest yet beneficial impact on pain reduction and improvement in physical function when compared to non-exercise control groups (Holden et al. 2023). The limited impact of exercises can be attributed to the complex and multifaceted nature of the therapeutic exercise prescription for CKP conditions such as OA. This complexity helps to explain why the implementation of exercise in clinical practice is often inadequate and why there is heterogeneity in the outcomes of care (Holden et al. 2023). Another recent systematic review and network meta-analysis of existing Cochrane reviews for the treatment of OA pain reported that exercise is the core treatment for CKP but it was found to have only a moderate effect in terms of alleviating pain in individuals with CKP (Smedslund et al. 2022).

According to NICE (NICE 2022) and the American College of Rheumatology (ACR) (Kolasinski et al. 2020), exercises are the primary non-pharmacological interventions for the management of OA. However, the ACR guidelines also acknowledge the moderate effect of exercise in alleviating pain and improving function in CKP conditions such as OA.

In summary, PT and exercise are recommended treatments for CKP and have been found to be effective in alleviating pain and improving function. However, the impact of exercise varies and there is a lack of clear guidelines regarding exercise protocols such as repetitions, sets and progression, thereby making it challenging to replicate effective treatment plans. Research shows that exercise therapy only moderately alleviates pain and enhances function for those experiencing CKP but individual responses to exercise may vary. Accordingly, it is essential to understand CKP, including its mechanisms and effects on individuals’ movement.

2.4 Movement alterations

It appears that various exercise interventions did not result in successful treatment outcomes for some people with CKP (Ferber et al. 2015; Kobsar et al. 2015). According to Kobsar et al. (2015) and Watari et al. (2016), the limited effectiveness of some exercise interventions in terms of their ability to reduce pain and improve function may be due to movement alterations during functional performance. Therefore, one possible approach is to look at movement alterations as a means to enhance the comprehensiveness of evaluating individuals with CKP. It has been suggested that pain can cause a variety of motor alterations, ranging from minor changes in muscle activity to movement avoidance (Roland 1986; Lund et al.1991; Hodges and Tucker 2011). As a result, altered movement patterns may be evident among those people with CKP and act as a pain-protective mechanism (Hodges and Tucker 2011). Due to pain chronicity, these altered movement patterns may last for a long time, resulting in further pain and movement restrictions (Hodges 2011). Thus, it is critical for physiotherapists to recognise the movement patterns linked to knee pain to tailor treatment to meet patients’ needs and track their progress. This could be achieved by understanding the underlying mechanisms of pain and movement alterations and how targeting movement alterations would enhance treatment and this is detailed below.

2.4.1 Pain and movement alterations

Pain is important for protecting the body's tissues from damage and stimulating the motor system (Boyer 2018). Nociceptive afferents in the knee joint and surrounding tissues signal the central nervous system when there is a threat of damage (Hunter et al. 2008). This leads to the motor system adapting to remove noxious stimuli and prevent further injury to the knee's tissues (Hodges 2011). It is worthy of note that pain is highly variable among individuals. For instance, knee pain may serve as the initial signal for the onset of OA. Nevertheless, the perception of pain can exhibit significant variability in patients afflicted with OA. This is evidenced by the fact that the degree of knee pain and the severity of radiographic changes of OA are not strongly correlated (Sluka 2016). Thus, alteration in the movement of individuals suffering from pain is variable. Understanding the relationship between pain and motor response can explain how the body adapts to knee joint pain.

Clinically, a broad spectrum of motor adaptations in response to pain are frequently observed, ranging from subtle alterations during tasks to complete avoidance of painful movements (Hodges and Smeets 2015). Pain is a normal protective response but prolonged or dysfunctional adaptations may lead to disability and chronicity (Merkle et al. 2020). In contrast, movement is frequently utilised to alleviate pain and enhance function. Understanding the relationship between pain and movement can direct rehabilitative approaches to recovery while avoiding any adverse long-term effects (Hodges and Tucker 2011). This section investigates the theories, associations and evidence relating to pain and movement.

Various hypotheses have been suggested to clarify the association between pain and typical motor adaptations. Vicious Cycle Theory was proposed by Roland (1986) and suggests that pain leads to a sustained increase in muscle activity (both agonist and antagonist) which further perpetuates pain and dysfunction. Some studies have supported this theory, while others have criticised it, showing reduced muscle activity in relation to pain in certain cases (Zedka et al. 1999; Falla et al. 2007). Muscle relaxants for MSK pain, for example, have been suggested as a potential intervention to disrupt the cycle of muscle tension and alleviate pain. Nevertheless, there are notable where researchers have rejected this hypothesis. For example, Zeller et al. (2003) conducted a study on individuals with PFPS and found that those people exhibited altered muscle activation patterns. In this study, females presented with increased muscle activity compared to males who presented with delayed and reduced activity in the vastus medialis obliquus muscle, a key stabiliser of the patella (Zeller et al. 2003). These findings contradicted the idea of sustained muscle activation proposed by Vicious Cycle Theory and instead suggested that muscle timing and coordination issues may contribute to knee pain.

In contrast, Strength Inhibition Theory (SIT) proposes that pain inhibits peak muscle force and leads to generalised muscle inhibition (Merkle et al. 2020). Evidence supporting this theory has been demonstrated through the experimental induction of knee pain (infrapatellar fat pad injection of hypertonic saline), resulting in reduced peak torque generation for knee flexion and extension but this largely recovers once the pain has been resolved (Henriksen et al. 2011).

Meanwhile, the Theory of Pain Adaptation proposes that motor responses may be both facilitated and inhibited in relation to the painful area, thus integrating certain aspects of both Vicious Cycle Theory and SIT. The alterations in muscular activity induced by pain may constrain motion, resulting in diminished force, magnitude, velocity and displacement as a means of preventing further tissue damage and augmenting recovery (Lund et al. 1991). Nonetheless, several clinical studies of pain have observed that according to Pain Adaptation Theory, pain results in restricted movement in comparison to pain-free controls (Svensson and Graven-Nielsen 2001; van Dieën et al. 2003; Moseley and Hodges 2005).

It is proposed that the agonist muscles, which are primarily responsible for painful movement, exhibit inhibitory activity, whereas the antagonist muscles, which restrict the painful movement, demonstrate sustained increases in activity (Lund et al. 1991). However, there is no consensus in the literature regarding the recruitment of agonist and antagonist muscles in response to pain. For example, some studies indicate that voluntary jaw movements, trunk movements and neck movements were inhibited in the agonist muscles due to pain, which is in accordance with the predictions associated with the theory of pain adaptations (Svensson et al. 1996; Zedka et al. 1999; Falla et al. 2007). Furthermore, pain during dynamic movements of the jaw and leg resulted in increased facilitation of antagonist muscle activity (Stohler et al. 1988; Mongini et al. 1989; Lund et al. 1991; Graven-Nielsen et al. 1997). However, other studies reported that low back pain and jaw pain can lead to alterations in muscle activity among both agonist and antagonist muscle groups (van Dieën et al. 2003; Murray and Peck 2007). Consequently, Hodges et al. (2006) postulated that pain arising during voluntary movements results in a redistribution of muscle activation among multiple agonist and antagonist muscles based on the individual's condition, as opposed to the stereotypically predicted activation of a single muscle group.

Protective Response Theory is represented in Figure 2 which characterises the wide-ranging variability observed in the response of the neuromuscular system to pain. The model aims to provide clarification on aspects of this variability that could not be fully explained by other theories. One of the central premises of this theory is that the short-term neuromuscular adaptations which occur in response to pain are intended to protect the afflicted or threatened body part. This theory has a distinctiveness that sets it apart from the previous three theories in that it is not a direct pain-motor response theory in the strictest sense; rather, it posits that the overarching objective of any motor response to pain is the protection of the organism.

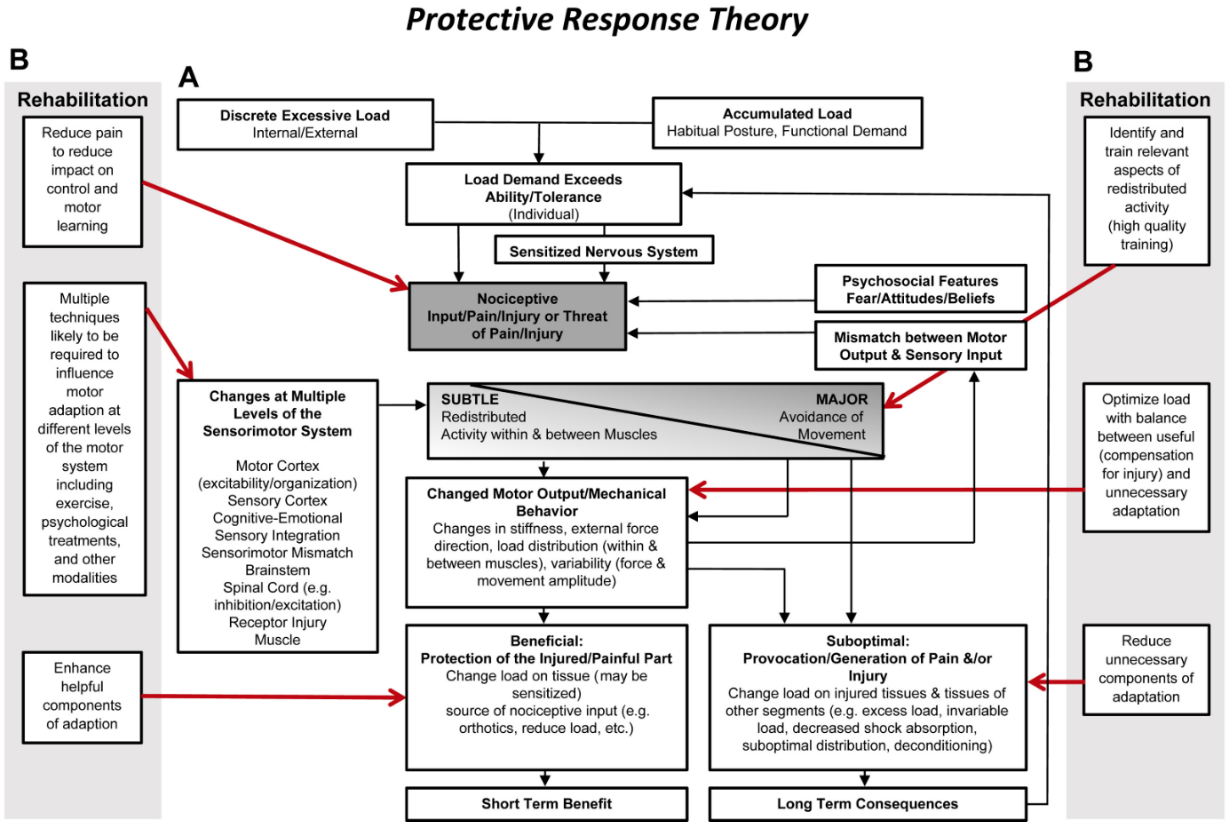


Figure 2: Protective response theory with (A) motor adaptations to pain; and (B) rehabilitative implications. Such adaptations in motor responses may result in diverse outcomes which can either be advantageous or maladaptive, thereby presenting significant intervention implications. Adapted from Merkle et al. (2020)

According to this theory, pain or the perceived threat of tissue injury can cause a wide range of motor behaviour adaptations (Hodges and Tucker 2011). These adaptations can vary from minor changes in muscle activation within a single muscle or among multiple muscles to alterations in body movement within single or multiple joints, or even complete movement restriction (Hodges and Tucker 2011). The theory suggests that these motor behaviour changes may initially provide short-term benefits by protecting the affected body tissue and promoting healing. However, these short-term protective benefits may have negative long-term consequences (Butera et al. 2016). They can reduce an individual's functional level and increase the risk of further pain due to decreased movement and increased load on other areas (Hodges and Tucker 2011; Merkle et al. 2020). This is due to a reduction in movement variability and an increase in load on the same tissue structures (Hodges and Tucker 2011; Merkle et al. 2020).

The theory proposes that unresolved altered movement patterns resulting from chronic pain contribute to the development and maintenance of pain over time (Hodges 2011). An empirical study validating this theory found that back pain led to increased spinal stability as a protective motor adaptation behaviour. The study also observed inconsistent and non-stereotypical patterns of muscle activity and movement between participants, thereby indicating an individualised-specific response in the form of motor adaptation behaviours (Hodges et al. 2013).

Protective Response Theory suggests that individual variability in motor adaptations to pain can be influenced by biopsychosocial factors, affecting neuromuscular responses at various levels of the nervous system (Hodges and Tucker 2011; Merkle et al. 2020). These adaptations are not simply changes in motor cortex excitability but involve more complex modifications in motor planning and coordination, particularly in load distribution on the painful structure. In chronic pain conditions, central mechanisms play a significant role and unresolved movement alterations can persist even after pain resolution and tissue healing, becoming secondary and dysfunctional alterations (MacDonald et al. 2009; Hodges and Tucker 2011).

This theory has important implications for rehabilitation. It emphasises the need for a balanced approach to managing pain, considering both the protective responses and the potential negative consequences of prolonged or excessive pain-related behaviours. Simply addressing pain through pharmaceutical therapies may not be sufficient for chronic MSK conditions where central mechanisms are involved (Hodges and Tucker 2011; Merkle et al. 2020). Physiotherapists need to identify and address the movement alterations that potentially contribute to the condition and develop individualised treatment plans to restore optimal motor control (Hodges 2011). Treatment interventions targeting the higher levels of the motor system responsible for motor planning and coordination may be necessary. Movement retraining with individualised feedback to enhance motor learning and acquire new movement patterns can significantly improve physical function (Noehren et al. 2011; Willy et al. 2012; Roper et al. 2016).

In summary, the relationships between pain and the movement system are complex and often highly variable. The theories suggest that pain can lead to various motor adaptations, including increased or decreased muscle activity, altered movement patterns and restricted motion. These adaptations are influenced by both peripheral and central mechanisms and can have short-term protective benefits but may result in long-term functional limitations and increased levels of pain.

While pain theories provide different perspectives, the actual mechanisms and responses can vary depending on the individual and specific pain condition, which emphasises the importance of individualised responses and the analysis of altered movement patterns in understanding and managing chronic pain. By considering the individual's pain experience and movement alterations, individualised movement assessment can make a significant contribution. It allows for a thorough evaluation of the specific motor adaptations, altered movement patterns and dysfunctional load distribution that contribute to the individual's pain and functional limitations. This assessment can involve kinematic analysis using motion capture systems during functional tasks, providing valuable insight into an individual's movement patterns and identifying areas of impairment. Therefore, the next section elaborates on the various motion capture systems that can be utilised for movement analysis.

2.5 Movement analysis using motion capture systems

Movement analysis is a crucial aspect when examining a person's joint kinematics whilst performing functional tasks in a PT clinical setting. It is useful for assisting in clinical decision-making while managing MSK problems. Human motion analysis allows for the identification of movement abnormalities in the form of altered kinematic, kinetic or electromyographic (EMG) patterns which can then be used to assess neuromusculoskeletal conditions, assist with subsequent treatment planning, and/or gauge the success of treatments across a range of patient populations (Kobsar et al. 2015; Watari et al. 2016). This can result in individualised management that has the potential to offer the best rehabilitation approach to meet each person's specific needs (Kobsar et al. 2015; Watari et al. 2016). To achieve this, it is necessary to give physiotherapists access to movement analysis technologies to accurately assess kinematics in clinical practice.

Movement analysis requires the movements of the body or body parts in the three anatomical planes to be precisely characterised. Movement analysis has used various techniques to quantify this motion. These techniques include visual observation, camera-based video recordings and optoelectronic 3D systems. Laboratory-based optoelectronic 3D motion capture devices are the most widely used in research settings and can apply objective techniques when evaluating complex lower limb kinematic patterns (Ford et al. 2003; Boling and Padua 2013; Nakagawa et al. 2013; Jones et al. 2014). These systems are regarded as the gold standard for assessing movement kinematics and kinetics in all planes of motion during the execution of various functional tasks (Sigward et al. 2011; Munro et al. 2012). The key limitation associated with 3D optoelectronic systems is that they are not portable or simple to utilise either within or outside the laboratory setting (Dingenen et al. 2014; Schurr et al. 2017). This may restrict the widespread application of movement analysis systems in the context of daily clinical practice.

Other limitations associated with 3D optoelectronic motion capture systems include the complexity of the setup, the need for advanced user training, the high financial cost of the equipment, and the length of time needed to collect and analyse the data produced by the system (Schurr et al. 2017). Consequently, portable, objective clinical movement analysis methods that do not require expensive equipment and that can be used in clinics are preferable.

A camera-based two-dimensional (2D) movement analysis method was studied as an alternative to the gold-standard optoelectronic 3D motion capture devices (Herrington et al. 2017; Alahmari et al. 2020; Neal et al. 2020). Although the 2D movement analysis method is reliable for measuring kinematics (Kingston et al. 2020), the results of most studies were inconsistent regarding the method’s validity for quantifying kinematics (Neal et al. 2020; Willson and Davis 2008; Scholtes and Salsich 2017; Gwynne and Curran. 2014; Herrington et al. 2017). The 2D system also has several drawbacks which may limit its clinical applicability when assessing movement in all planes during challenging functional tasks. Among these limitations is its inability to evaluate dynamic, complicated movements over the transverse plane (Malfait et al. 2014) and the subjectivity involved in data processing (Payton and Hudson 2017). As a result, a reliable and valid movement analysis technique that is capable of measuring kinematics in all planes of motion during dynamic and complicated activities in clinical settings is required. The following sections cover the alternative movement analysis techniques used to support movement analysis in clinical settings.

2.5.1 Three-dimensional inertial measurement units

The drawbacks demonstrated by other motion capture systems in the previous section highlight a demand for additional technologies and methods to effectively and accurately assess movements in the context of clinical practice. IMUs are one of the more recent techniques that have become increasingly prevalent in recent years to objectively and clinically analyse subject's movement and deliver feedback (Kobsar and Ferber 2018; van der Straaten et al. 2019). Thus, IMUs were identified as the best option for the current study to realise the aim of utilising a clinically available tool for movement analysis.

IMUs are ambulatory motion tracking systems that utilise fully wireless, small, body-worn sensors allowing participants extra freedom of movement with less preparation time than the alternative 3D optoelectronics (Tao et al. 2012; Cuesta-Vargas et al. 2010). The IMU system is a combination of three-axis accelerometers, three-axis gyroscopes and three-axis magnetometers (Shull et al. 2014). Each of these alone offers certain benefits and disadvantages. Accelerometers and gyroscopes, for instance, are used to measure accelerations and angular velocities (Shull et al. 2014) but they can be affected by the surrounding gravitational forces and are prone to drift errors when integrated to determine position, orientation and absolute angles from angular velocity data (Zijlstra and Aminian 2007).

Magnetometers sense changes in segment orientation relative to the strongest (north) magnetic field; hence, they are highly sensitive modalities that can be affected by the local magnetic field and surrounding ferromagnetic materials which can lead to signal distortion (Shull et al. 2014; Zijlstra and Aminian 2007). However, by integrating the information provided by accelerometers, gyroscopes and magnetometers using a sensor fusion technique, an accurate assessment of the position and orientation of each body segment is then produced (Luinge et al. 1999; Mayagoitia et al. 2002) and different kinematic parameters such as spatio-temporal parameters, body orientation, joint angles, body posture, as well as range of motion (ROM) can be obtained (Wang et al. 2017).

IMUs can be applied on different body parts (upper limbs, back, lower limbs) and measure specific motion repeatedly both within and outside clinical settings, providing quantitative data in addition to the 3D body map (avatar) (Kobsar and Ferber 2018; Chen et al. 2015). IMUs offer some benefits over optoelectronic systems. For instance, kinematics can be evaluated on larger patient populations in a non-controlled environment. When compared with 2D systems, IMU sensors are able to measure joint angles in all three planes of motion (including the transverse plane) when performing challenging dynamic activities (Cuesta-Vargas et al. 2010). With IMU sensors, the problem of applying many markers with optoelectronic 3D motion analysis methods can be avoided because IMUs do not require them.

In comparison to previous clinical movement analysis techniques, the advantages of IMUs for measuring kinematics point to the need of take additional measures and test them in a real-world setting. However, it is crucial to study the literature pertaining to the validity and reliability of IMUs as a technique to quantify joint kinematics during various functional activities before using this promising option in clinical practice. The validity and reliability of IMU sensors is demonstrated in the following section.

2.5.1.1 Validity of the IMU-based movement analysis method

Numerous studies have recognised IMU sensors as a tool for measuring angular kinematics for lower extremity joints during the execution of multiple functional tasks, focusing primarily on ascertaining the validity of IMUs (Favre et al. 2008; Zhang et al.

2013a; Palermo et al. 2014; Lebel et al. 2017; Al-Amri et al. 2018; Karatsidis et al. 2018; Teufl et al. 2018; van der Straaten et al. 2019).

Teufl et al. (2018) compared an IMU's validity to the 3D motion capture of angular kinematics at the lower limb joint in the three planes of movement during gait. For kinematics in the sagittal plane, the results of the coefficient for multiple correlation (CMC) produced an excellent correlation (CMC = 0.99 - 1). The validity results for the 3D IMU kinematics in the sagittal plane were consistent with prior validation studies using gait exercises (good-to-excellent agreement, CMC = 0.71 – 1.00), with acceptable root mean squared error (RMSE) values for nearly all kinematic measures (< 5.7°) (Favre et al. 2008; Zhang et al. 2013a; Palermo et al. 2014; Lebel et al. 2017; AlAmri et al. 2018; Karatsidis et al. 2018).

Numerous studies have assessed the validity of angular kinematics obtained using IMUs during a variety of functional activities, including stair ascent (Bergmann et al. 2009; Zhang et al. 2013a), running (Jakob et al. 2013; Nüesch et al. 2017), squatting (Robert-Lachaine et al. 2017; Al-Amri et al. 2018; Lebel et al. 2017), jumping (Jakob et al. 2013; Al-Amri et al. 2018; Teufl et al. 2018) and sit to stand (Lebel et al. 2017). While squatting, the IMUs-based movement analysis system has a good-to-excellent correlation with minor RMSE scores for all joints in the three planes of movement (CMC > 0.71), especially for the sagittal and frontal kinematics (Robert-Lachaine et al. 2017; Al-Amri et al. 2018; Teufl et al. 2018).

Additionally, the sagittal plane kinematics of jumping demonstrated excellent agreement between the sensors and the 3D optoelectronic motion capture system (CMC > 0.90) (Jakob et al. 2013; Al-Amri et al. 2018; Teufl et al. 2018). During the stair ascending task, the results indicated excellent agreement (Bergmann et al. 2009; Zhang et al. 2013a). Karatsidis et al. (2018) also observed excellent correlation between the IMUs and the 3D optoelectronic systems (CMC = 0.95 - 0.99) with RMSE values of less than 5.7° for all sagittal kinematics at the hip, knee and ankle joints.

The validity results for the frontal and transverse kinematics provided by IMU-based and 3D optoelectronic movement analysis systems were good (ranging from moderate-to-excellent agreement, CMC = 0.50 - 0.96) but they were less significant than the results for sagittal kinematics documented in the majority of the literature (Favre et al. 2008; Zhang et al. 2013a; Palermo et al. 2014; Lebel et al. 2017; Al-Amri et al. 2018; Karatsidis et al. 2018). In Zhang et al.'s (2013a) study, the frontal and transverse plane kinematics during gait and stair negotiation indicated lower correlation than the sagittal plane (CMC ranged from 0.5 to 0.85) during walking and stair ascent and descent (Zhang et al. 2013a). This was also identified in Karatsidis et al.'s (2018) study which showed that during gait, the kinematics in the frontal and transverse planes had a lower agreement than in the sagittal plane (CMC = 0.68–0.91) and a higher RMSE (4.1–9.7°) (Karatsidis et al. 2018). A strength of Karatsidis et al.'s (2018) study is that the kinematics were collected when participants were completing walking tasks at various speeds (comfortable, rapid and slow) for better standardisation. The small sample size in this study (11 healthy adults aged 28 ± 4 years) may have reduced the generalisability of the results to other cohorts, such as older people, while also affecting the confidence of the data by increasing the probability for type II errors. Additionally, there was a lack of clarity regarding how the systems simultaneously collected kinematics.

Teufl et al. (2018) demonstrated good-to-excellent agreement (CMC = 0.88–0.99) for lower limb kinematics in the frontal and transverse planes. The RMSE and range of motion error (ROME) scores, which were less than 2.40° and 1.6°, respectively, for the kinematics assessments of all joints confirmed these correlation findings (Teufl et al. 2018). Additionally, the Bland and Altman plots indicated a tight limit of agreement for all kinematics in all planes and minor average mean difference values (ranging from -0.3° to 0.9°) (Teufl et al. 2018). In their study, rigid marker clusters placed directly on sensors to measure angular kinematics utilising 3D optoelectronic technology enhanced this investigation (Teufl et al. 2018). These kinds of markers and the use of this methodology could potentially reduce the error between the two systems caused by soft tissue artefacts, thereby improving the accuracy of the agreement findings. More specifically, the quantity of soft tissue artefacts was distributed evenly between the two systems (Teufl et al. 2018).

The fact that lower limb joints' ranges of motion in the frontal and transverse planes are smaller than those in the sagittal plane may help to explain the lower validity findings for angular kinematics in these planes. Thus, kinematics in the sagittal plane were more easily detected by the two movement analysis systems than frontal and transverse kinematics.

In summary, IMUs have demonstrated excellent validity for measuring lower limb joint angles in the sagittal plane but their validity was lower in the frontal and transverse planes.

2.5.1.2 Reliability of the IMU-based movement analysis method

With respect to the reliability of IMUs, a small number of studies have been conducted on healthy populations to assess reliability while utilising an IMU movement analysis system to measure the angular kinematics of lower limb joints during functional activities (Cloete and Scheffer 2010; Nüesch et al. 2017; Teufl et al. 2018; Al-Amri et al. 2018; van der Straaten et al. 2019). Van der Straaten et al. (2019) evaluated reliability while employing IMU sensors between sessions and raters to assess lower limb kinematics in all planes, while performing SLS and sit to stand (STS) activities. In the sagittal plane for both tasks, the results showed that all reliability findings (within-session, between-session, and between-raters) ranged from fair-to-excellent (ICC range 0.52 to 0.96) (van der Straaten et al. 2019).

During the STS task, reliability findings were found to be fair-to-excellent in the transverse plane (ICC range 0.51 to 0.97), while the SLS task's reliability was poor to excellent (ICC range 0.20 to 0.84) (van der Straaten et al. 2019). All reliability findings for the frontal plane indicated fair-to-excellent reliability across all lower limb joints during both tasks (ICC range 0.53 to 0.87), apart from the ankle joint during SLS which demonstrated poor-to-fair reliability (ICC range 0.37 to 0.41) and the hip kinematics during the STS task which demonstrated poor reliability (ICC range 0.00 to 0.14). One of the strengths of this study is that the participants received detailed instructions regarding how to perform the various functional activities which helped to ensure that the trials were performed consistently. Standardising performance between trials and sessions can improve the comparability of results. This study might be constrained by the use of a small sample of 20 healthy participants and the failure to justify the number of participants.

According to a study by Al-Amri et al. (2018), the reliability of the IMU system was also evaluated and the results reported excellent between-session (inter-rater) reliability for the sagittal plane and at all lower extremity joints during three functional tasks: gait, squat and jump (ICC > 0.75). However, their results demonstrated fair-to-excellent between-session (intra-rater) reliability across the frontal and transverse plane of movements (ICC = 0.40 – 1.00) (Al-Amri et al. 2018). Additionally, the within-session reliability was fair-to-excellent for lower limb kinematics in all planes while walking and squatting (ICC > 0.60), yet the transverse plane indicated reduced within-session reliability which ranged from poor-to-excellent (Al-Amri et al. 2018). Despite the benefits of testing within- and between-session reliability during three distinct functional activities and the well-justified sample size, the participants were not provided with any instructions regarding how to complete the activity tasks. However, this could be a strength that could promote the normal performance of activities.

Four other studies assessed the between-session reliability for lower limb kinematics collected during an overground walking task using the IMU-based movement analysis method (Cloete and Scheffer 2010; Nüesch et al. 2017; Al-Amri et al. 2018; Teufl et al. 2018; van der Straaten et al. 2019). Consistent with Al-Amri et al.'s (2018) findings, they demonstrated excellent agreement for the sagittal plane lower extremity kinematics (Cloete and Scheffer 2010; Nüesch et al. 2017; Teufl et al. 2018) but fair-to-excellent agreement in the frontal and transverse planes (Cloete and Scheffer 2010; Teufl et al. 2018).

Although the movement analysis offered by IMU sensors has good validity and reliability, these studies revealed an issue which could potentially affect the transferability and generalisability of the findings. To clarify, all of the validity and reliability tests to date have been conducted in controlled laboratory environments. It is possible that research results obtained in these circumstances will not necessarily translate to clinical situations found in the real world.

In conclusion, IMU-based movement analysis systems may provide the necessary validity and reliability for measuring lower limb joint kinematics in various planes of motion during the performance of various functional activities. However further work is needed to test their validity and reliability in other non-laboratory settings.

2.5.1.3 Application of IMUs for clinical practice

IMUs provide the advantage of collecting data in real-time, allowing for immediate movement feedback and interventions during clinical assessments or rehabilitation sessions which are crucial components for the aim of the current study. The application of IMUs has been reviewed to provide a better understanding of the appropriateness of this tool for the current study.

Several studies have utilised IMUs to analyse changes in movement patterns for those experiencing knee pain during various functional tasks (Ismailidis et al. 2020; Ismailidis et al. 2021; Tadano et al. 2016; Rahman et al. 2015; McCarthy et al. 2013; van der Straaten et al. 2020; Bolink et al. 2012; Nakagawa et al. 2012; Nakagawa et al. 2015; Severin et al. 2017; McKenzie et al. 2010). A detailed explanation of these studies' findings is provided in Section 2.7. An example of this is the utilisation of different inertial sensor technologies for gait analysis. Van der Straaten et al. (2020) conducted a systematic review and found 14 different inertial sensor systems in 24 studies. Of these, three studies (McCarthy et al. 2013; Tadano et al. 2016; Rahman et al. 2015) examined the use of inertial sensors using a sample of patients with knee OA in comparison to a healthy population to identify differences in kinematic and other spatiotemporal parameters.

McCarthy et al. (2013) claimed that they were able to use the GaitWalk (an IMU-based system) to measure variations in stride duration and knee flexion ROM in swing and stance. Using the H-Gait IMUs system, Tadano et al. (2016) assessed kinematic variations at the hip, knee and ankle in the sagittal plane. Using the GaitSmart IMUs technology, Rahman et al. (2015) assessed the knee's sagittal kinematics, thigh and shank sagittal and frontal, and temporal gait parameters.

Another application of IMU for movement analysis was reported by Alanen et al. (2021) who conducted a systematic review of studies using IMUs to analyse sports direction changes of movement. They searched six databases and the grey literature and applied the PRISMA guidelines to ensure that they achieved comprehensive search results. The authors found that IMUs can be utilised to detect change of direction (COD) movements and COD heading angles with acceptable validity (Alanen et al. 2021). Most of the studies included in their review were inconsistent regarding the metrics used and the placement of sensors which might affect the reliability of their findings. The utilisation of small samples that were not justified in any of the studies is another factor that could have adversely affected the results of this review. Based on the available studies in the review, it appears that the information offered by IMUs is not particularly useful from a coach's perspective because current COD tests rely on time- or speed-related measurements. IMU-derived measures could offer additional information regarding individual differences and variability in acceleration on multiple axes and angular velocities during COD movement which could be very helpful for coaches and players (Alanen et al. 2021).

Some of the published literature has used IMUs to investigate the most studied joints and biomechanical parameters that are essential for movement analysis. A scoping review was conducted to summarise the literature that has employed IMUs for movement analysis (specifically gait) in lower limb OA (Kobsar et al. 2020). In the 72 articles reviewed, the most common use of IMUs was for patients with knee OA which was the joint of greatest interest (n = 46), followed by the hip (n = 22) and then the ankle (n = 7). The two locations where IMU sensors were most frequently placed on were on the back (n=41) and the shank (n=40). In terms of the most investigated parameters, spatiotemporal parameters (n = 45), segment or joint angles (n = 33), and linear acceleration magnitudes (n = 22) were the three biomechanical outcomes that were most frequently observed (Kobsar et al. 2020). Although the review offered valuable insights into the most studied biomechanical parameters and joints, there were significant variations among the studies in terms of patient populations, study designs, and sensor protocols. In addition, an evaluation of study quality that was conducted using a modified version of the Critical Appraisal of Study Design for

Psychometric Articles found no high-quality research; rather, most of the studies were of low (n = 43) or moderate-quality (n = 24).

Another application of IMUs in the literature has been to establish if the type of exercise performed can be detected and if this can be achieved using fewer sensors (O’Reilly et al. 2015; Crema et al. 2017; O’Reilly et al. 2018a; O’Reilly et al. 2017; Giggins et al. 2014). Giggins et al. (2014) conducted a cross-sectional analytical study to establish whether IMUs can classify exercise performance of the lower limbs with a high degree of accuracy and to test the application of single sensors in providing sufficient and accurate information relating to exercise performance. The findings revealed that exercise performance of the lower limbs could be detected with an acceptable degree of accuracy (81%) via IMUs. It was also confirmed that reducing the number of sensors did not adversely affect their accuracy and in some cases, a single sensor was found to be even more accurate when evaluating exercise performance (83% accuracy) and, therefore, can be used for exercise biofeedback purposes. Although the study yielded favourable results, there were some notable drawbacks. The study was conducted in an organised and controlled environment and the participants performed the exercises while wearing exercise clothing. These conditions may vary from what occurs in the home or in non-controlled settings. Besides, the heterogeneity of the study population may affect the generalisability of the findings to a specific population but it increases its external validity. Therefore, the results of the study are more likely to be generalisable to a wider range of people.

IMUs were used in some studies to enable better visualisation of patients' movement analysis data as a means of a visual feedback tool to improve their treatment outcomes (Argent et al. 2019; O'Reilly et al. 2018b; Bell et al. 2019; Oagaz et al. 2018; Loudon et al. 2012). O'Reilly et al. (2018b) evaluated the Formulift system which is a mobile health (mHealth) app where a single IMU is worn on the left thigh and connected to Formulift. Users' movements were recorded by the IMU as they worked out and the app analysed the information to identify their workout style and to count repetitions in real-time.

The app provides users with feedback and pointers to help them exercise safely and efficiently (O'Reilly et al. 2018b). In this study, there were three groups of users with five healthy participants in each group: those new to working out in the gym; experienced athletes; and strength and conditioning trainers. Four different categories were investigated in the study: usability, functionality, perceived impact, and subjective quality. To develop customised exercise classifiers for each participant, IMU data were first gathered from each of them. They subsequently used the programme to accomplish several tasks unrelated to exercise. The technique was then used to complete an exercise that included single-leg squats, deadlifts, lunges and squats.

After completing the System Usability Scale (SUS) and the user version of the Mobile Application Rating Scale (uMARS), the participants were questioned about their user experiences. According to qualitative and quantitative studies, the system's SUS score was 79.2, thereby indicating ‘good’ to ‘outstanding’ usability. Many users expressed satisfaction with the system’s functionality regarding its repeat counting, method classification and feedback features. The app's overall subjective quality was deemed to be good with a median star rating of 4 out of 5. The participants said that the approach would also improve their skills, motivate them, reassure them and prevent injuries (O'Reilly et al. 2018b).

It should be noted that O'Reilly et al.’s (2018b) findings are based on participants' initial system usage which is suitable for identifying usability and functionality issues. However, perceptions of the system's impact and quality may change over time. The results regarding the system's perceived impact are solely based on users' perceptions and additional research is needed to determine whether the method enhances aspects such as motivation, exercise adherence and exercise technique. To accomplish this, it was deemed that a RCT would be necessary. Additionally, the study was conducted in a biomechanics laboratory simulating a gym setting. The suggested system re-evaluation might be completed with participants working out in their ‘regular’ settings such as their gym.

A study by Loudon et al. (2012) included two focus groups (stroke survivors N=7, and therapists N=5) to explore stakeholder responses regarding a prototype of a visualisation of their movement and to facilitate therapists' explanation to patients regarding what they have achieved in their rehabilitation. The software (envisage) was created using various motion capture systems including Vicon and Kistler force platforms, wired electromagnetic sensors (Optitrack) and wireless IMUs to enable the investigation of the different visualisation techniques of biomechanical data that are important for the rehabilitation process for patients and therapists (Loudon et al. 2012). The findings from this study suggested that this kind of feedback would be very beneficial to elicit the patient's progress during their rehabilitation because it made patients' biomechanical data more comprehensible and facilitated patient-therapist communication. However, the time therapists needed to spend with the patient explaining the numerical data that was generated by the technology was questionable (Loudon et al. 2012). Loudon et al. (2012) acknowledged that different motion capture systems were used to address certain practical limitations such as the size of the room, system setup, and the use of a non-technical system operator. Indeed, for visualisation purposes, this could have affected the results of the study because the accuracy of the motion capture systems differs from one system to another (van der Kruk and Reijne 2018). Consequently, this may have affected the visualisation figure presented for patients in different settings (e.g., clinic, home or community centre).

In summary, IMUs have been successfully used for movement analysis in various contexts, including analysing altered movement patterns in individuals with knee pain, detecting changes in movement direction in sports, identifying types of exercise and providing visual feedback for patients and physiotherapists. These applications highlight the importance of IMU sensors as a practical for studying movement patterns in individuals with CKP.

In the next section, the search strategy conducted to identify relevant literature pertaining to the analysis of altered movement patterns during the performance of different functional tasks, in addition to the literature regarding the reporting of movement analysis and alteration, is introduced.

2.6 Search strategy

To identify appropriate published studies to include in the literature review, a comprehensive search strategy was designed and carried out for literature concerning the analysis of altered movement patterns during the performance of functional tasks as well as literature regarding the reporting of movement analysis and alteration because these aspects provide the knowledge base for the current research.

For this literature review, an initial electronic search was conducted between December 2018 and March 2019. The online search of the medical literature was carried out using the following electronic databases: the National Library of Medicine Database (MEDLINE), the Cumulative Index to Nursing and Allied Health Literature (CINAHL), and the Physiotherapy Evidence Database (PEDro). For literature concerning movement patterns, the search was restricted to the years from 2010 to the present. This criterion was applied because advances emerged in the literature regarding the field of movement analysis using 3D motion capture systems for the knee pain population and this period allows for the identification of appropriate studies for the current review that align with the contemporary understanding and advancements in the field (Cimolin and Galli 2014; Wren et al. 2020). Additionally, older studies might have utilised outdated or less sophisticated techniques which could potentially introduce inconsistencies in the comparison and synthesis of the findings. For the literature concerning reporting movement analysis and alteration, the search was expanded from 2000 to the present.

A PRISMA flowchart was used to depict the search and refinement process applied to the studies discovered. The PRISMA flowchart used to refine the studies concerning gait kinematic alterations is presented in Figure 3.

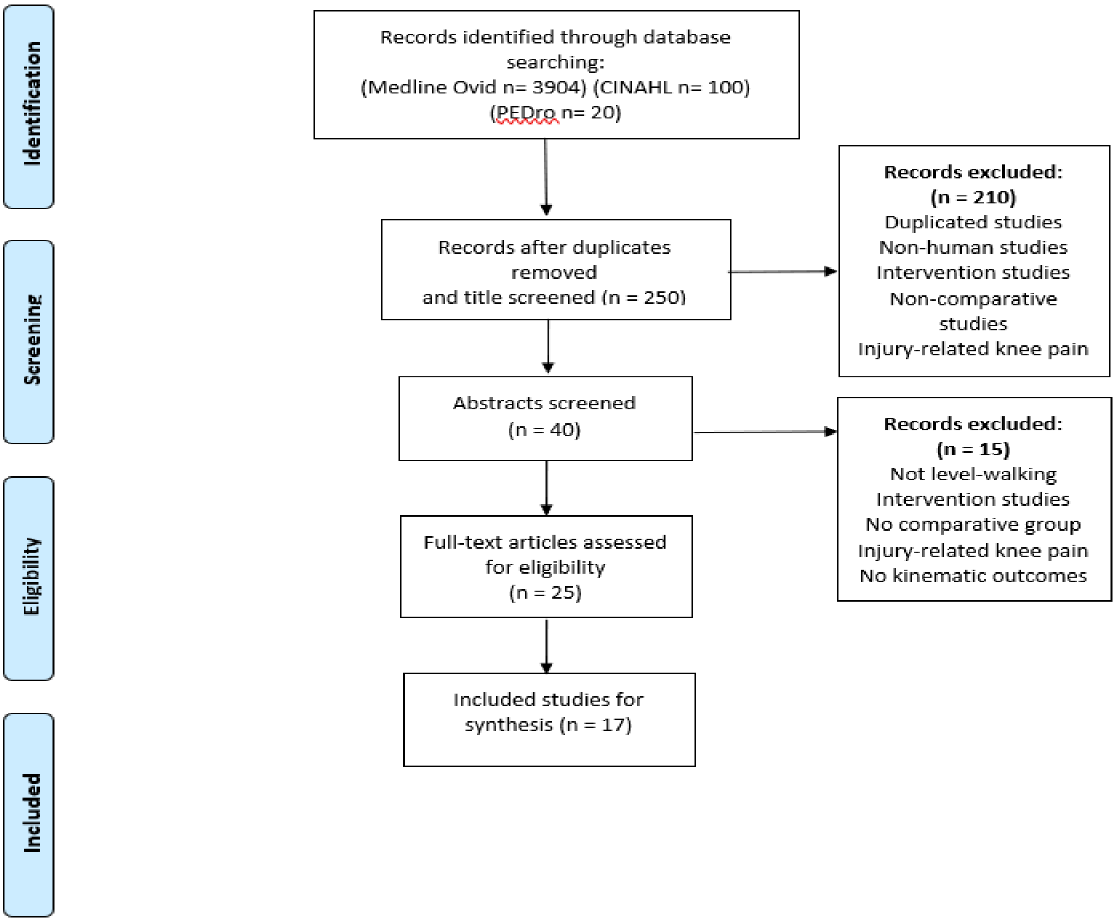


Figure 3: PRISMA flowchart for gait kinematic alterations

The search was repeated in between November 2022 and January 2023 using the same databases employed previously to check for any newly published studies that could be included in the thesis. Table 1 presents the word categories and how they were combined in the text. Meanwhile, Table 2 presents the inclusion and exclusion criteria for both topics.

Table 1: Search terms used in Medline for gait kinematic alterations

	Movement kinematic alteration for people with CKP
Keywords	(Osteoarthritis OR knee pain OR knee joint OR chronic knee pain OR patellofemoral pain syndrome OR jumper’s knee) **AND** (Gait analysis OR gait OR walk OR walking OR squat OR jump OR stair ascent OR stair descent) **AND** (Kinematics OR movement OR joint angles OR ROM OR biomechanics) **AND** (Movement analysis OR motion capture OR three-dimensional)

CKP= Chronic knee pain

Table 2: Inclusion and exclusion criteria for literature review studies

Inclusion criteria	Exclusion criteria
Individuals with CKP conditions (i.e., OA, PFPS, ITB syndrome, jumper's knee etc.).	Knee pain related to trauma or injuries, rheumatoid arthritis or surgery.
Kinematic outcome measures during gait, squat, jump, and/or stair ascent and descent.	Functional activities unrelated to the current study such as hopping or jogging.
Adult population aged 18+ years.	Animal studies.
Only English language.	Young individuals (under 18 years of age).
Full-text studies.	Non-English papers.
Comparative studies (knee pain vs. healthy or a different CKP population. For example: between differing KOA subgroups such as disease severity; the involved compartment; sex; etc.).	Abstracts and conference proceedings.

OA=Osteoarthritis, PFPS= Patellofemoral pain syndrome, ITB= Iliotibial band syndrome, CKP= Chronic knee pain, KOA= Knee osteoarthritis

2.7 Analysis of altered movement patterns during the performance of functional tasks

Altered biomechanics plays an important role in the progression of knee pain due to the altered movement patterns patients use, which may limit the effectiveness of the prescribed exercises (Bolink et al. 2012). Therefore, a better understanding of these altered movements is crucial to enable targeted rehabilitation. Given the limited literature on sensor-based movement analysis, studies using any motion capture technology were included in this review to provide a comprehensive understanding of altered kinematic movement patterns. Kinematic analysis is more accessible, practical and relevant to daily activities, thereby making it feasible for research and clinical settings. It also serves as a foundation for exploring the relationships between kinematics, pain and functional limitations, potentially guiding future studies and interventions.

Patients with CKP experience difficulties with activities of daily living (ADL) and, therefore, it is recommended that performance tests of multiple activities are used for routine clinical settings. It is preferable in knee rehabilitation and lower extremity injuries to use functional exercises due to their similarities to daily activities and sport (Button et al. 2014). According to the Osteoarthritis Research Society International (OARSI), a series of performance-based physical function tests that represent testing of typical activities relevant to persons diagnosed with knee pain conditions such as knee OA was recommended (Dobson et al. 2013). These tests are recommended as prospective outcome measures in future OA research and to aid therapeutic decision-making as a complement to patient-reported measurements. Their recommendations for future research were to focus on expanding the evidence of the proposed tests' measuring properties (Dobson et al. 2013).

Additionally, they recommended the inclusion of five functional tests when evaluating this population and among the suggested activities were walking, chair-stand (which is similar to rise from squatting) and stair negotiation. Accordingly, the following activities which were found to pose distinct challenges for the knees of individuals with CKP considering the different age-groups that could be affected by the condition were chosen for the current study: gait, DLS, SLS, VJ, SA and SD. Moreover, these activities were shown to be valid and reliable when assessed using various motion capture systems, especially when using IMUs (as discussed in Sections 2.6.1.1 and 2.6.1.2).

Although vertical jumping is not an activity that is performed daily by individuals with CKP, jumping involves more dynamic movements with faster execution speed and is important for those who like to participate in sport (Cleather et al. 2013). As such, it is an important activity to consider when assessing movement alterations.

Regarding the planes of movement, the literature concerning the sagittal, frontal and transverse planes of movement was reviewed. It should be acknowledged that transverse plane motion is important and relevant data is available in the Xsens MVN but the studies featured in the current PhD thesis only included sagittal and frontal planes of movement in all of the selected activities (Schurr et al. 2017) because the validity and reliability of IMUs for lower limbs were better for motions in the sagittal and frontal planes than for the transverse plane (Poitras et al. 2019). Sagittal plane lower limb joint kinematics affects the risk of knee pathologies (Blackburn and Padua 2008). Also, subjects who employed less sagittal plane joint movement were more reliant on frontal plane knee moments to slow down their centre of mass which contributes to frontal plane movement alterations (Dingenen et al. 2014). It has been recommended that frontal plane movements are important when screening people with knee pathologies (Felemban et al. 2020).

In the following section, the literature concerning altered movement patterns using 3D motion capture systems is reviewed in people with CKP, while executing the selected functional activities.

2.7.1 Gait kinematic alterations

Seventeen studies evaluated gait patterns for people with CKP using various 3D motion analysis systems (see Table 3). While some studies investigated all lower limb kinematics (hip, knee and ankle) (Ismailidis et al. 2021; Ismailidis et al. 2020;

van der Straaten et al. 2020; Ro et al. 2019; Sparkes et al. 2019; Crossley et al. 2018; Duffell et al. 2017; Tadano et al. 2016; Barton et al. 2011), others focused exclusively on the knee joint (Farrokhi et al. 2015; McCarthy et al. 2013; Nagano et al. 2012; Hunt et al. 2010), or the hip and knee joints (Duffell et al. 2014), or ankle joint alterations. The methodologies, findings and limitations of these studies are summarised in Table 3 and are now discussed with regards to kinematic variables (e.g., joint angles and ROM).

Two recent studies (Ismailidis et al. 2020 and van der Straaten et al. 2020) evaluated movement alterations in people with OA and healthy controls using the Statistical Parametric Mapping (SPM) approach which helps researchers to examine differences between comparable kinematic waveforms across the whole movement cycle (Nüesch et al. 2017). At the knee joint, both studies indicated that compared to the controls, those with knee OA had significantly less knee flexion ROM throughout the mid-stance and early swing phases. Reduced sagittal plane knee flexion ROM found in the two previous studies were in accordance with the findings of other studies that explored discrete joint angle kinematics rather than the entire gait cycle (Ismailidis et al. 2021; Ro et al. 2019; Rahman et al. 2015; Farrokhi et al. 2015; McCarthy et al. 2013; Nagano et al. 2012).

Reducing knee flexion during the initial stance phase of walking, also known as the knee stiffening strategy (Fok et al. 2013; Farrokhi et al. 2015), may be a movement alteration adopted by knee OA patients to unload the knee or minimise pain by enhancing the co-activation of the thigh and leg muscles (Childs et al. 2004). However, the combined changes in kinematics and muscle activity may result in knee stiffening which could increase the compressive load and reduce the femoral contact area where force is administered (Childs et al. 2004). These motor adaptation methods are employed to alleviate discomfort and stabilise the joint.

It is important to note that the OA patients in both studies (Ismailidis et al. 2020 and van der Straaten et al. 2020) were similar in terms of their disease severity (all had severe OA) but they differed in terms of the compartment affected. The OA sample in van der Straaten et al. (2020) was of a mixed compartment but Ismailidis et al.'s study (2020) lacked clarity regarding which compartment in the OA cohort was impacted. It has been shown that the involvement of the OA lateral compartment correlates with valgus alignment, whereas the medial OA compartment correlates with varus alignment (Sharma et al. 2001). Therefore, changes in alignment could affect the forces and loads imparted to the knee joint, thereby contributing to a variety of altered movement patterns.

Three other studies (Sparkes et al. 2019; Tadano et al. 2016; Duffell et al. 2014) found no significant difference in knee flexion ROM between both groups (OA and healthy people). The OA participants included in Sparkes et al.'s (2019) study had moderate knee OA matched for age, gender and BMI. However, in Tadano et al.'s (2016) study, the participants were of mixed OA severity (severe and mild) and were not matched for age, height, weight or BMI. As for Duffell et al.'s (2014) study, there were 18 participants with mild medial OA who were also not perfectly matched (the OA group was significantly heavier). Matching can help to reduce bias, increase power and improve the precision of studies (De Graaf et al. 2011). However, in instances where the two groups are not perfectly matched, it is possible for differences to arise between the groups with regards to other variables which could influence the study outcomes.

Despite the fact that knee joint loading becomes greater as the severity of the disease increases (Mündermann et al. 2005; Thorp et al. 2006) and may be associated with changes in kinematics (Chang et al. 2007), the absence of sagittal plane differences could be attributed to the small sample size presented in two of these studies (10 OA participants vs. 8 controls in both studies) (Sparkes et al. 2019; Tadano et al. 2016) which were not based on power calculations, leading to limited power and an increased risk of type II errors. As for the frontal plane knee angles, Duffell et al. (2017) and Nagano et al. (2012) presented similar findings of increased knee adduction angle of the OA limb and/or group at 50% of the stance phase, which is the point where the peak ground reaction force occurs (GRF) (Jiang et al. 2020).

Altered movement patterns were also found in the hip joint sagittal, frontal and transverse planes of motion among people with CKP conditions (mainly OA). Four studies demonstrated consistent findings of reduced hip extension ROM during the stance phase of the gait (Ismailidis et al. 2021; Ismalidis et al. 2020; Ro et al. 2019;

Crossley et al. 2018). Ro et al. (2019) also found that a reduced coronal motion arc for the hip, which was defined as the difference in angles between the maximum adduction angle and the minimum adduction angle of the stance phase, was significantly smaller in the OA group than in the control group ($p<0.001$). There was also a correlation between the coronal arcs of the knee joint with that of the hip joint in the OA group compared to the controls ($r2 = 0.36$, $p<0.001$).

The results of the study by Ro et al. (2019), however, may have been affected by certain factors. For instance, there was a large difference between the number of OA participants (89) and the control subjects (42) who were only matched for sex and age, without giving an account for the effect of height, weight or BMI, which were all significantly different between groups. The study also only included females and this may have affected the generalisability of the results because MicKenzie at al. (2010) found that males and females demonstrate different kinematic strategies to reduce their knee symptoms.

Crossley et al. (2018), Duffel et al. (2017) and Hunt et al. (2010) showed that people with OA had a significant reduction in the hip adduction angle during the stance phase of the gait cycle. However, Barton et al. (2011) found that people with PFPS had reduced peak hip internal rotation compared to the controls. Other studies found no significant difference in the hip joint angle in any plane of movement when comparing the OA groups and healthy controls (van der Straaten et al. 2020; Sparkes et al. 2019; Duffell et al. 2014). These studies had limitations in relation to heterogeneity in the OA population, the affected compartment and the sample size.

Seven studies included the ankle joint in their analysis of movement alterations during gait in patients with CKP (Ismailidies et al. 2021; Ismailidis et al. 2020; Ro et al. 2019; Sparkes et al. 2019; Crossley et al. 2018; Duffell et al. 2017; Tadano et al. 2016; Barton et al. 2011). Ismailidies et al. (2021) and Ismailidis et al. (2020) found a significant difference in ankle dorsiflexion between the OA group and healthy controls which was increased during the stance phase. They also found reduced ankle plantar flexion at initial swing (push-off). Tadano et al. (2016) reported a significant reduction in ankle abduction between mild and severe OA groups compared to controls at the stance phase. Barton et al. (2011) investigated the ankle joint (forefoot and rearfoot peak angles and ROM) in people with PFPS and demonstrated that people with PFPS attain earlier peak rearfoot eversion and increased rearfoot dorsiflexion ROM.

The finding of increased ankle dorsiflexion at heel-strike was hypothesised to reduce the knee flexion angle at the initial contact and decrease the mechanical load on the knee while increasing the extensibility of the gastro-soleus muscle complex (Aali et al. 2021). Adhering to this ankle position results in the knee being unlocked, which compromises motor control and interferes with the hip joint's natural movement patterns. The observed activation of the hip extensor muscles appears to suggest that the hamstring and gluteal muscles exert a synergistic dominance. Hence, it is evident that an extension in the duration of heel contact may cause a modification in the posture of knee flexion during the stance phase, resulting in suboptimal motor control of the lower extremities (Aali et al. 2021).

The remaining studies (van der Straaten et al. 2020; Ro et al. 2019; Sparkes et al. 2019; Crossley et al. 2018; Duffell et al. 2017) found no significant difference at the ankle joint between the knee OA group and the controls. These studies had a variety of shoes/unshod walking protocols, which could have affected the data. Indeed, footwear and its effect on walking kinematics have been explored in the literature and found to have a significant impact on an individual’s movement patterns. People who walk barefoot experience decreased ankle dorsiflexion compared to those wearing shoes (Moisan et al. 2020; Hannigan and Pollard 2021; Zhang et al. 2013b) and this could account for the difference found at the ankle between both studies.

Several limitations were identified in the literature when attempting to recognise the different altered movement patterns between studies. For example, most studies examined kinematic alterations during the phase-specific gait cycle and only investigated alterations in the stance phase of gait. This phase-specific analysis could have limited the investigation of some important alterations that could have occurred during the rest of the cycle, such as the swing phase. There were some differences in the compartment, chronicity and severity of pain of the recruited participants; for example, some had experienced severe knee pain for a long time, whereas others had experienced mild or moderate pain for shorter periods (Ismailidis et al. 2020; van der Straaten et al. 2020). Some of the studies had small sample sizes that were not based on power calculations (Sparkes et al. 2019; Tadano et al. 2016). Consequently, this might have affected the power of these studies and increased the likelihood of type II errors.

There were also different ways of normalising the data. For instance, not all studies normalised the gait speed to body weight or leg length and this should have affected the consistency of the results among the studies. Additionally, in most of studies, healthy participants were enrolled on the condition that they did not have a diagnosis of knee OA or trauma. However, prior research has demonstrated that the gait kinematics and kinetics of individuals with early OA are similar to those of healthy participants (Duffell et al. 2014). Although most studies were observational, there was heterogeneity in the methods used. To clarify, there were some differences in the distance of the walkway used for gait analysis and this could have affected some of the results due to the relatively short walkway used in some studies (approximately 6 metres (m)) (Duffell et al. 2017), causing some healthy participants to potentially walk at a slower pace than usual.

Another important factor to consider is the way in which the motion capture systems were calibrated. Almost all of the studies used static calibration techniques to define the biomechanical model and calculate joint angles. Static calibration could provide less accurate results in some knee pain populations, especially those with severe OA pain who were found to suffer from joint contractures and cannot stand in a neutral position without some bending of the knee, which could influence the kinematic data (Favre et al. 2014; Nagano et al. 2012).

In summary, studies using different motion capture technologies to investigate movement patterns during gait have identified several kinematic alterations to the lower limb joints in individuals with CKP conditions, especially those with knee OA. In the sagittal plane, reduced knee flexion ROM during early stance (stiff knee), reduced hip extension ROM during stance, increased ankle dorsiflexion during stance, and decreased ankle plantarflexion at early swing were the most common alterations. In the frontal plane, increased knee adduction angle during stance, decreased hip adduction angle during stance, and reduced ankle abduction during stance were observed. Regarding the transverse plane, reduced hip internal rotation was mostly presented.

Table 3: Summary of studies evaluating gait kinematic alterations for people with CKP and healthy controls

Authors/ date	Design	Subjects	Type of motion analysis and plane of motion	Method	Kinematic outcome variables	Key findings	Limitations
Ismailidis et al. (2021)	Within and between subjects.	23 unilateral severe KOA. 46 age-matched controls.	Sensor system (7 sensors) (RehaGait). Sagittal plane only.	Walking for 20 metres at self-selected speed. An average of 8 steps per side were included for analysis.	Hip, knee and ankle joint angles and ROM in stance and swing phase **(differences between discrete kinematics).**	**Knee OA vs. control groups:** - Reduced maximum hip extension during stance (variation: -1.8°) - Reduced maximum knee flexion during stance and swing phase (maximum difference: -5.2°) and -8.8°) **-** 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 (greatest difference: - 7.9°) - Increased maximum dorsiflexion (maximum difference: 5.6°) and dorsiflexion ROM (maximum difference: 4.7°) during stance - Reduced maximal plantar flexion (maximum difference: -4.6; *p* = 0.009**) during push off.	Age in the inclusion criteria for severe OA not representable (>30 years). Only severe OA. No details of what participants wear on their feet.

						Knee OA affected vs. unaffected sides: -Reduced maximal knee flexion during the stance and swing phases (-4.8; $p = 0.002$**; -6.1◦; $p = 0.009$**) in the affected compared to non-affected. - Reduced knee flexion at HS in the affected compared to the non-affected side (-2.2°).	
Ismailidis et al. (2020)	Between subject design.	23 unilateral severe KOA. 28 age-matched controls.	Sensor system (7 sensors) (RehaGait). Sagittal plane only.	Walking for 20 metres at self-selected speed (wearing their **own shoes**).	Hip, knee and ankle joint kinematics **(within the whole movement cycle).**	Reduced knee flexion angles from the loading response to mid-stance phase (4–24% of the gait cycle; maximum difference: -6.8°, $p < 0.001$**) and at the end of the terminal stance to mid-swing phase (60–77% of the gait cycle; maximum difference: -11.0°, $p = 0.001$**). Increased ankle dorsiflexion and reduced ankle plantarflexion, from mid-stance to the initial swing phase (8–68% of the gait cycle; maximum difference: 12.5°; $p < 0.001$**).	Age in the inclusion criteria for severe OA not representable (>30 years). Only severe OA. -No adjustment for multiple comparisons (increase the chance of finding significant differences).

						Reduced hip extension during the terminal stance (38–54% of the gait cycle; maximum difference: 4.2°; $p = 0.004$*).	
van der Straaten et al. (2020)	Part of a large longitudinal study.	19 severe unilateral KOA. 12 healthy controls.	Sensors (15 sensors, MVN BIOMECH Awinda). Optoelectronic (65 markers and 10 camera VIKON system). Frontal, transverse and sagittal planes.	Walking **barefoot** for 10 metres at a self-selected speed.	Hip, knee and ankle kinematics **(within the whole movement cycle).**	Reduced knee flexion ROM during stance phase (0 - 33%; $p = 0.001$**) and swing phase (49 - 92%; $p = 0.001$**).	OA participants were significantly older. Small sample size. No distinction for the compartment of KOA (medial or lateral). Only severe OA.
Ro et al. (2019)	Cross-sectional observational study.	89 Severe KOA. 42 age- and sex-matched controls.	3D optical motion capture with 12 cameras. Sagittal and frontal.	Walking for 9 metres at a self-selected speed (an average of 3 strides included in the analysis).	ROM for hip, knee and ankle. Coronal motion arc for hip and knee.	Reduced knee ROM in OA group ($p < 0.001$**). Reduced hip and ankle ROM ($p < 0.001$**). A correlation found between reduced knee ROM and reduced hip and ankle ROM (r2 = 0.71–0.42; $p < 0.001$**).	Groups were significantly different in weight and BMI. Cross-sectional study; no definitive

						Reduced coronal motion arc for hip and knee in the OA group (*p* < 0.001**). A correlation found between reduced knee coronal motion arc and hip (r2 = 0.36, *p* < 0.001**).	conclusions on causality. Only female participants included. No details of what participants wore on their feet.
Sparkes et al. (2019)	Case-control study.	10 moderate OA. 8 matched controls.	3D optical motion capture with 9 cameras and full-body markers and 4 force plates. Frontal, sagittal and transverse.	Walking six times across a level laboratory floor.	ROM for hip, knee and ankle.	No significant differences were found at any joints between OA affected and unaffected limbs and corresponding control limbs.	More females than males in both groups (80% OA and 75% controls). Only moderate OA. Small sample size, limited power and precision.

							No power calculation for sample size. Population not representative. No adjustment for multiple comparisons and no blinding.
Crossley et al. (2018)	Cross-sectional analysis.	69 participants with lateral PFOA. 18 age-matched controls.	VICON Motion Systems 3D trajectories of reflective markers and 9 cameras. Frontal, sagittal and transverse.	Walking for 10 metres at a self-selected speed wearing **standardised shoes;** 3 gait trials performed.	Hip, knee and ankle kinematics for **stance phase only.**	PFOA had 3.9° greater hip adduction (*p* = 0.003*). 8° reduced hip extension. No difference in knee and ankle kinematics.	PFOA had greater weight and BMI ($p < 0.05$). Random selection of extremities in the control group (dominancy). Small sample size for controls. No mention of disease severity for PFOA. Only lateral PFOA included.

							Static calibration.
Duffell et al. (2017)	Cross-sectional study	25 unilateral medial KOA. 84 controls.	3D VICON Motion System, two force plates, 20 markers and 10 cameras. Frontal and sagittal planes.	Participants were asked to walk at a comfortable speed along the 6-metre walkway until three clean foot strikes were recorded by each force plate.	Hip, knee and ankle joint angles at HS and toe-off.	Frontal plane hip and knee angles were affected by OA presence ($p < 0.001$**, $p < 0.05$* respectively). Reduced hip adduction angle in OA affected side (at peak GRF). Increased hip adduction angle in OA unaffected side (at HS). OA group had increased knee adduction angles (at HS and peak GRF; $p = 0.04$*). Increased knee adduction at peak GRF in the affected OA side compared to unaffected of 60+ age group.	Significant difference in the weight between OA and healthy ($P < 0.001$). Walking protocol lacked some details (barefoot or wearing shoes?).
Leibbrandt and Louw. (2017)	Systematic review.	19 studies reviewed; 3 studies on gait biomechanics for people with PFPS.	2D or 3D motion capture systems.	NA.	Hip, knee, ankle and foot kinematics during gait.	**For the hip:** - 2 studies showed significant reduction in hip internal rotation during gait. - 2 studies showed significant delay in peak rear foot eversion in PFPS compared to controls. - 1 study showed earlier peak hip internal rotation and increased peak hip adduction at peak knee extensor moment during self-selected walking in people with AKP.	All of the included studies were cross-sectional which prevented cause-effect conclusions. Most studies included only female participants with PFPS (gender bias).

						For the knee: - 1 study showed increased peak knee extension, another showed reduced knee flexion at HS and one showed reduced flexion in early stance. **For foot and ankle:** - 1 study showed increased rear foot eversion at HS, another presented increased overall ankle ROM and increased ankle dorsiflexion when walking.	Only English language studies were included (language bias). No consistency in the measured outcomes. No standard procedures for gait.
Tadano et al. (2016)	Cross-sectional study.	10 bilateral KOA (mixed severity – more affected ‘severe’ and less affect ‘mild’). 8 healthy controls.	7 wearable sensors (H-Gait system). Frontal, sagittal and horizontal planes.		Hip, knee and ankle joint angles.	Reduced ankle abduction between mild and severe OA during the stance phase (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.	No matching between groups in terms of age, height, weight or BMI. Small sample size.

Rahman et al. (2015)	Cross-sectional study.	29 KOA (pre-operative). 29 healthy controls.	2 sensors: one on the thigh and one on the shank (GaitWALK system). Sagittal and frontal planes.	Walking for 20 metres in non-laboratory settings.	Knee sagittal ROM, thigh and shank sagittal and frontal ROM **(differences between discrete kinematics).**	Reduced stance knee flexion ROM (difference: 13.8˚) and swing knee flexion ROM (difference: 20.1°). Reduced thigh and shank sagittal ROM (difference: 7.2° and 15°, respectively). Reduced shank frontal ROM (difference: 4.8°).	No details regarding what participants wore on their feet. BMI for OA participants was significantly higher.
Farrokhi et al. (2015)	Experimental laboratory study.	24 no PFOA. 38 mild PFOA. 44 severe PFOA.	Vicon motion analysis with 8 cameras. Sagittal plane only.	walked along a 8.5 metre walkway at a self-selected pace. Five gait trials were collected.	Knee sagittal plane kinematics for **stance phase only.**	Reduces peak loading response knee flexion in the severe PFOA relative to the mild PFOA (*p* = 0.045).	Severe PFOA had significantly higher BMI. Cross-sectional design make it unclear if pain in PFOA was associated with altered knee biomechanics or the specific impairments. No frontal or transverse investigation. No hip, foot or ankle joint analysis. No details of what participants

							wore on their feet.
Favre et al. (2014)	Cross-sectional study.	29 young asymptomatic (29 ± 4 years). 81 old participants (59 ± 9 years) including 27 asymptomatic, 28 moderate, and 26 with severe medial knee OA.	An optoelectronic 3D motion capture system and a force-plate embedded in the middle of the walkway. Sagittal plane only.	Walking for 10 metres at their preferred walking speed wearing their **own shoes.**	Discrete knee flexion-extension angles **for the whole cycle.** Anterior-posterior displacement of the femur relative to the tibia. Backward-forward inclination of the thigh and shank.	The knee was less extended at HS in all 3 older groups compared to the younger asymptomatic group (*p* <0.001**). The knee was less extended in the 3 older severe group compared to the older asymptomatic and moderate OA (*p* <0.001**). Both OA groups presented the femur less posterior relative to the tibia (*p* <0.001**). The shank was less inclined in the 3 older groups than in the asymptomatic group (*p* <0.001**).	Only medial knee compartment. Participants wore their own shoes. -High inter-participant variability. No radiographs available for asymptomatic subjects. More females in the older severe KOA group than in the other groups.
Duffell et al. (2014)	Case-control study	18 people with early medial KOA. 18 age- and gender-	Vicon motion capture system with 10 cameras, two portable force plates and 20	walking at a comfortable speed along a 6-metre walkway 5 times (three clean	**Differences between discrete kinematics:** - Knee sagittal angle at HS - Knee sagittal angle at PKF - Knee sagittal ROM	No significant differences in kinematics reported in people with early knee OA.	Groups were not perfectly matched (OA were significantly heavier).

		matched controls.	reflective markers. Sagittal and frontal planes.	foot strikes recorded by each force plate).	- Hip frontal angle at HS.		No details for the walking protocol (wearing shoes or not).
McCarthy et al. (2013)	Case-control study.	23 patients with medial compartment KOA (14 females, 9 males), mean ± SD age of 65.1 ± 7.7 years and a mean BMI 28.7 ± 3.7. 21 matched controls.	4 IMUs (GaitWALK) placed onto the lower limbs (thighs and shanks). Sagittal plane only.	Walking at their normal, self-selected speed on a 20-metre level surface. 7 strides (approximately 8 metres) when the participant was walking steadily were chosen for analysis.	Knee flexion ROM during stance. Knee flexion ROM during swing.	Significant differences found between groups in both swing and stance phases. Reduced knee flexion ROM between OA knees (10.3° ± 4.0°) and controls (18.0° ± 4.0°) in the stance phase (*p* <0.001**). Reduced knee flexion ROM between OA knees (54.8° ± 5.5°) and controls (61.2° ± 6.1) in the swing phase (*p* <0.003**).	No mention of the sample size calculation or any justification. Exclusion criteria only focused on knee and LL deficits, with no mention of back pain if present. Static calibration. Significant difference in age between females and males in the OA group (males younger than females). No radiographs allowed for the OA group.

							Recruitment at 2 different sites and countries.
Nagano et al. (2012)	Cross-sectional study.	14 early KOA. 17 moderate KOA. 14 severe KOA. 13 healthy.	3D high-speed motion analysis (Hawk) with 8 cameras, 3 force plates and 25 markers. Sagittal, frontal and horizontal planes.	Walking on a 10-metre walkway at a self-selected speed. Five successful trials analysed.	Knee flexion/extension. Knee abduction/adduction. External/internal tibial rotation. **Measurements at HS and 50% of stance phase only.**	-Reduced knee flexion angle in the severe OA group at HS relative to the healthy and early OA participants (*p* <0.01**, 0.05*, respectively). Reduced knee flexion angle in the moderate OA group relative to the healthy group (*p* <0.05*). Reduced knee flexion angle in the severe and moderate OA group at 50% stance phase relative to the healthy and early OA subjects (*p* <0.01*). Reduced knee abduction angle in the moderate and severe OA at HS relative to the healthy subjects (*p* <0.01**. 0.05*, respectively). Reduced knee abduction angle in the severe OA group at 50% stance phase relative to the healthy subjects and those with early and moderate OA (*p* <0.05*, 0.01**, 0.01**, respectively). The entire OA group had smaller external tibial rotation at HS than	Exclusion criteria only focused on knee and LL deficits, with no mention of back pain if present. Static calibration. Healthy people were significantly younger and taller. The participants with severe OA were heavier than those in all of the other groups. Cross-sectional design.

						the healthy subjects (p <0.05, 0.01, 0.05, respectively).	
Barton et al. (2011)	Cross-sectional study.	26 patients with PFPS. 20 controls.	3D Vicon motion capture system with10 cameras, 2 force plates and 36 reflective markers. Frontal, sagittal and transverse.	Walking for 12 metres at a self-selected speed (5 successful trials collected).	**Peak angles and ROM during stance phase:** - Forefoot dorsiflexion/abduction /supination - Rearfoot dorsiflexion/internal rotation/eversion - knee flexion/abduction/internal rotation - Hip adduction/internal rotation.	Reduced peak hip internal rotation in the PFPS group compared to the controls (p <0.024). Earlier peak rearfoot eversion (relative to laboratory) in the PFPS (p = 0.010). Earlier peak rearfoot eversion (relative to the tibia) in the PFPS (p = 0.030). Increased sagittal plane rearfoot ROM (relative to the laboratory) in the PFPS (p = 0.007).	No justification for sample size or power analysis. No details of what the participants wore on their feet. Static calibration.
Hunt et al. (2010)	Cross-sectional study.	20 asymptomatic controls (15 women, 5 men). 75 individuals (38 women, 37 men) with	Vicon motion analysis with 8 cameras and 2 force platforms (no details for markers). Frontal plane hip angles.	Walking for 10 metres **barefoot** at a self-selected speed (5 successful trials collected).	**Discrete kinematics in stance phase only:** - Peak hip adduction and abduction angles.	Reduced maximum hip adduction angle in the severe OA group (5.0°) relative to all 3 of the other groups (p <0.01).	Exclusion criteria only focused on knee and LL deficits. Static calibration. No radiographs allowed for asymptomatic controls. Asymptomatic controls not

		medial compartment KOA.					perfectly matched (only matched for age). Cross-sectional design, so no relationship or conclusions could be drawn.

Abbreviations: * = Statistical significance <0.05; ** = Statistical significance <0.01; 3D = Three-dimensional; cm = centimetres; m = metres; HS = heel-strike; ROM = Range of motion; KOA = Knee osteoarthritis; PFPS = patellofemoral pain syndrome; PTOA = Patellofemoral osteoarthritis; OA = osteoarthritis.

2.7.2 Single leg squat kinematic alterations

Following the literature search, 12 studies were included in this literature review that applied different motion capture systems for analysing the movement patterns of people with CKP when performing SLS (see Table 4).

Nine of the included studies fully evaluated SLS regarding hip and knee joints using 3D motion capture systems (Carvalho et al. 2022; van der Straaten et al. 2020; Glaviano et al. 2019; Schmidt et al. 2019; Severin et al. 2017; Leibbrandt and Louw 2017; Nakagawa et al. 2015; Graci and Salsich 2015; Nakagawa et al. 2012) (see Table 4 for details). Nakagawa et al. (2015), Nakagawa et al. (2012) and Schmidt et al. (2019) presented increased hip adduction and knee abduction in the PFPS group compared to the controls. Graci and Salsich (2015) reported similar findings but only with regards to increasing hip adduction during SLS.

The strength of the studies by Nakagawa et al. (2015) and Nakagawa et al. (2012) is that the methods were standardised in terms of squat depth (more than 60°) and speed using a metronome. However, these studies were constrained by the fact that prior to the kinematic evaluation during squat, the subjects had performed gluteal muscular strengthening tests (maximal voluntary isometric contraction) using a hand-held dynameter. These tests may have resulted in muscular fatigue and a greater number of kinematic alterations during a squat examination, especially because it is unknown whether the individuals were given appropriate recovery time.

Glaviano et al. (2019) investigated the sagittal and frontal plane movements and found no significant findings in the hip or knee joints for both planes. Severin et al. (2017) investigated hip and knee angles in the sagittal and frontal planes and found reduced peak hip flexion and knee abduction in the affected limb compared to the non-affected limb and controls. These conflicting findings could be a result of the inclusion criteria applied by Severin et al. (2017) which included participants with PFPS who had reported unilateral knee pain for a minimum of 3 months, otherwise they were considered healthy. To the author's knowledge, these inclusion criteria do not reflect people with PFPS who should demonstrate retro-patellar or anterior knee pain that lasts for more than six weeks and is aggravated by at least two of the following: stairs, squatting, prolonged sitting, and/or ascending or descending stairs

(Liebbrandt and Louw 2017). Consequently, it is possible that some knee pain participants were categorised as healthy despite having their pain triggered by these activities but misdiagnosed by the inclusion criteria, thereby giving different results.

In addition, there was no standardisation of the depth of the squat in their method and the participants were instructed to squat to any depth, unlike Nakagawa et al. (2012) and Nakagawa et al. (2015) who stated that a squat angle of > 60° was required. Arguably, movement alterations in the hip and knee joints associated with knee pain conditions are more likely to present when the angle of the squat increases (Zawadka et al. 2020; Chan et al. 2022). Therefore, methodological limitations may produce different results. In addition, the participants were instructed to outstretch their arms, unlike in other studies which asked the participants to cross their arms over the chest. Glave et al. (2012) evaluated the effect of different arm positions on the trunk and lower limb kinematic movements when squatting and presented that holding the arms at shoulder level resulted in increased knee flexion ROM ($P<0.01$), unlike the other position where the arms are kept stretched by the sides of the participants (Glave et al. 2012). Therefore, the findings from this study could explain the different results presented by Severin et al. (2017).

Carvalho et al. (2022) found no significant difference in knee abduction yet they found increased hip adduction during SLS in the OA group compared to the controls. Van der Straaten et al. (2020) reported no significant findings in either the frontal or transverse plane but found reduced knee flexion ROM in the severe knee OA group compared to the controls. The main limitation of Carvalho et al.'s (2022) study is their small sample size of 10 participants which increases the risk of type II errors and could have affected the findings. The findings presented by van der Straaten et al. (2020) could be due to the heterogeneity found in the study population because the OA group was significantly older than the controls. They were also included with no distinction in the included knee compartment, a factor that was previously prescribed in the gait alteration section (Sharma et al. 2001).

Leibbrandt and Louw (2017) conducted a systematic review evaluating evidence concerned with the analysis of functional tasks such as SLS. The authors found some similar findings in the SLS task that people with PFPS experienced a significant increase in hip adduction and knee abduction, which is consistent with the findings of most of the reviewed studies. Willy et al. (2012) evaluated the hip and knee joints and showed that people with PFPS demonstrated increased hip adduction and knee abduction but males with PFPS presented with less hip adduction and knee abduction compared to their female counterparts.

Two studies conducted by Cabral et al. (2021) and Herrington (2014) evaluated the knee joint solely. Cabral et al. (2021) investigated the sagittal plane knee angular kinematics for people with knee OA and found reduced knee angles in the knee OA group compared to the controls. Although their results were consistent with other studies that have evaluated knee joint angles, the study still had some limitations worthy of consideration, such as the inclusion of participants with only mild and moderate knee OA which were affected by one or more compartments. The knee OA group was also significantly heavier, with greater BMI than the controls. In addition, the velocity of the squat was not controlled but the squat depth was limited to a standardised 45˚ of knee ROM while keeping the arms extended. This standardisation of the depth of the squat could have affected the findings. Two recent studies evaluated the effect of squat depth on lower limb kinematics and found that deeper squats have a greater influence on hip and knee kinematics with the knee joint being the prime contributor (Chan et al. 2022; Zawadka et al. 2020).

Salsich et al. (2012) evaluated the hip and knee joints only at peak knee flexion of the SLS task in a group of people with PFPS who were categorised into 3 conditions: usual condition, exaggerated dynamic knee valgus condition, and corrected condition. Their results revealed that those with an exaggerated condition presented increased hip internal rotation and increased dynamic knee valgus compared to those with the usual condition. However, the study only included female participants who were found in another study by Nakagawa et al. (2012) to have greater hip internal rotation and knee abduction than males with PFPS. The female participants in Salsich et al.'s (2012) study were also instructed to keep their trunk upright while performing the task, which could have affected their normal pattern of movement.

To conclude, altered movement patterns were primarily identified in the frontal and transverse plane during the execution of the SLS task in those people with CKP, such as increased hip adduction/internal rotation and knee abduction/external rotation. As for the sagittal plane, reduced knee flexion ROM was also identified.

Each of the studies examined has its flaws which should be considered to provide the best treatment evidence for knee pathology. First, SLS performance and instructions varied across the studies (see Table 3). Some of the research studies required the participants to squat as deeply as possible, whereas others required a minimum angle of 60°. Some studies controlled the velocity of the squats, whereas others did not. Some researchers gave their participants running shoes but others let them perform barefooted. Meanwhile, some researchers required the participants to stretch their arms, put them on the iliac crest or cross them over their chest. Most of the research studies were cross-sectional, thereby preventing cause-effect conclusions being made. The validity and generalisability of the outcomes may also be affected by the study participants. Most of the knee pain sufferers were female and they tended to be heavier and/or taller than the controls.

Table 4: Summary of studies evaluating double leg squat and single leg squat kinematic alterations for people with CKP and healthy controls using different motion capture systems

Authors/ date	**Design**	**Subjects**	**Type of motion analysis and plane of motion**	**Method**	**Kinematic outcome variables**	**Key findings**	**Limitations**
Carvalho et al. (2022)	Cross-sectional study.	10 PFOA. 10 controls.	3D VICON Motion System, 28 markers and 10 cameras. Frontal plane.	To squat greater than 60° knee flexion in 2s period and return to start position in 2s without losing balance. Five successful repetitions analysed.	Hip and knee abduction/adduction at 30°, 45° and 60° of knee flexion in the ascending and descending phase of **SLS.**	Increased hip adduction angle during SLS at 45° *(p* = 0.045*) and 60° (*p* = 0.01**) of knee flexion in the ascending and descending phase PFOA group. No significant differences found in knee abduction at 30°, 45° and 60° of knee flexion in the ascending and descending phase of SLS.	Small sample size could have led to the lack of difference in other joints (type II error). Study design restricts cause-and-effect relationship. Only frontal plane.
Cabral et al. (2021)	Between-subjects design	30 participants with KOA. 30 controls.	Electro goniometer used for kinematic analysis. Sagittal plane.	To stand on one leg on a force plate platform **barefooted and** squat at self-selected speed to a **standardised** 45° while keeping their **arms extended** along their body. 3 trials analysed.	Knee angular displacement during **SLS.**	Reduced knee angular displacement in the OA group (32.28±7.47) relative to the controls (42.90±6.8), (*p* =0.000**).	Trunk movement was not controlled. Velocity of squat was not controlled. OA group included only those with mild and moderate OA and one or

							more affected compartments. KOA were significantly heavier with greater BMI. Only knee sagittal plane (frontal plane is important for SLS and pelvis stabilisation).
van der Straaten et al. (2020)	Part of a large longitudinal study.	19 severe unilateral KOA. 12 healthy controls.	Sensors (15 sensors, MVN BIOMECH Awinda). 3D optoelectronic (65 markers and 10 camera VIKON system). Frontal, Transverse and sagittal planes.	To stand on one leg **barefooted** and squat as deep as possible while maintaining balance until maximum flexion is reached and then extend the leg.	Hip, knee ankle kinematics **(within the whole movement cycle)** (for **SLS**).	Reduced knee flexion (12-72% of movement cycle).	OA participants were significantly older. Small sample size. No distinction between the compartment of KOA (medial or lateral). Only severe OA.
Glaviano et al. (2019)	Case-control study.	16 PFPS divided into 2 groups: 7	3D Vicon Motion Analysis with 12 cameras.	Participants stood on their painful limb on the force plate while	Hip and knee kinematics during **SLS.**	Decreased knee abduction in the L-FAB group compared to E-FAB and controls (*p* =0.01**).	Small sample size with subgrouping.

		with elevated fear avoidance (E-FAB) and 9 low fear avoidance (L-FAB). 9 controls.	Sagittal and frontal planes.	flexing the contralateral limb to 90° and crossed their arms across their chest. They were instructed to squat as deep as possible and return to the starting position while maintaining balance within 4 seconds (2s descent and 2s ascent). Five successful repetitions analysed.		No significant difference identified in sagittal plane hip or knee kinematics.	Significant difference between groups regarding the duration of the symptoms. No Standardisation pf the depth of the squat.
Schmidt et al. (2019)	Cross-sectional study.	20 women with PFPS. 20 controls.	3D Vicon Motion Analysis with 8-cameras. Frontal and transverse planes.	To shift their bodyweight to their tested limb and flex the uninvolved limb. Then, while standing on the tested leg **wearing running shoes,** they were asked to squat as deep as possible while maintaining their balance until maximum flexion was	Hip abduction/internal rotation and knee abduction/internal rotation at **PKF during SLS.**	Decreased knee internal rotation (increased external rotation) in the PFP group relative to the control (moderate effect size ≥0.40). Increased hip adduction (effect size= 0.74). Increased hip internal rotation in the PF group relative to the control (moderate effect size= 0.46).	No standardisation of the time or depth of squat. Different laboratories and different days for data collection between PF and controls. PF group wore shoes but the controls did not.

				reached and then extend the leg. At least 60° should be reached which was estimated visually. 3 trials were analysed.			
Severin et al. (2017)	Cross-sectional study.	20 PFPS (10 males and 10 females). 20 healthy controls (10 males and 10 females).	4 inertial sensors (Nanotrak, Catapult sports, Docklands, VIC). Sagittal and frontal planes.	**For SLS**, the participants were asked to flex the uninvolved limb 70°-90° and positioned behind the body with arms outstretched in front, then to squat with the painful limb (no instructions for the squat width or depth). Speed standardised at approximately 12 squats per minute. **For DLS:** Squat using both limbs with arms outstretched	**For DLS**: Peak knee and hip flexion/abduction angles (affected vs. non-affected). **For SLS:** Peak knee and hip flexion/abduction angles (affected vs. non-affected).	No significant differences were found in **DLS** in any of the peak kinematic variables at the hip or knee joints in the sagittal and frontal planes. **For SLS:** - Reduced peak hip flexion (moderate-large effect size: Cohen's d= -0.75). - Reduced peak knee abduction (large effect size: Cohen's d= -0.89). - Increased peak shank medial rotation (large effect size: Cohen's d= 1.35).	Inclusion criteria only included participants with anterior knee pain who reported lateral pain for at least 3 months, otherwise they were considered healthy (this criterion is not representative of those with PFPS). Static calibration. No standardisation of depth and width of squat. No details of footwear.

				across the body. Speed standardised at approximately 12 squats per minute.			
Leibbrandt and Louw (2017)	Systematic review.	19 studies reviewed, 4 studies on SLS for people with PFPS.	2D or 3D motion capture systems.	NA.	Hip, knee, ankle and foot kinematics during **SLS.**	Three studies showed significant increase in peak knee valgus (adduction) in people with PFPS compared to controls (MD = 4.93; CI 2.06, 7.80). 2 studies showed significantly increased hip adduction in people with PFPS compared to controls (MD = 4.51; CI: 1.98, 7.04).	All included studies were cross-sectional which prevented cause-effect conclusions being made. Most studies included only female participants with PFPS (gender bias). Only English studies were included (language bias). No consistency in the measured outcomes. No standard procedures for SLS.
Nakagawa et al. (2015)	Cross-sectional study.	30 participants with PFPS **(mixed males and females).**	3D electromagnetic sensor tracking system **(Folk of Birds).**	Participants were instructed to squat greater than 60° knee flexion at an average of 15 squats/minute. One minute of rest	Peak hip adduction and peak knee abduction during **SLS.**	Increased peak hip adduction in the PFPS group relative to the controls (*p* = 0.04*).	Each painful limb in the PFPS group was compared with the corresponding limb in the controls.

		30 controls.	Frontal plane.	was allowed between trials. 3 trials were analysed.		Increased peak knee abduction in the PFPS group relative to the controls ($p = 0.03^*$). No significant correlation was found between hip and knee kinematics in the PFPS group but there was significant correlation between hip and knee kinematics in the controls.	No mention of the validity or reliability of the electromagnetic tracking system. Static calibration. No clear description of the method (Did the participants wear shoes? What was the position of the arms and the other leg?). Did the participants reach the 60° squat depth (unclear). Mixed gender.

Graci and Salsich (2015)	Cross-sectional study.	20 females with DKV and PFPS.	3D Vicon motion capture with 8 cameras. Frontal and transverse planes.	**Condition 1**: Participants were instructed to flex their non-weight-bearing leg behind their body and to squat with their painful limb with their arms by their sides and to complete a squat from start of knee flexion to full extension in 4 seconds. **Condition 2 (correction of DKV):** Subjects were instructed to squat while keeping their knees over the middle of their foot during the descent phase. 10-15 seconds rest allowed between trials. 3 trials were analysed.	Femur and tibia joint angles **at PKF** during **SLS.**	Increased femoral adduction in the non-corrected condition (*p* = 0.001) and internal rotation (*p* = 0.01**).	No standardisation of the depth of the squat. No clear description of the calibration process. Small sample size may have led to the lack of a significant difference in some variables and small effect size. A significant difference found in the usual condition that was above the standard error of measurements (SEM) (used for within-session reliability).

Nakagawa et al. (2012)	Cross-sectional study.	20 females with PFPS. 20 female controls. 20 males with PFPS. 20 male controls.	3D kinematics measured using a **Flock of Birds** tracking device with 5 electromagnetic sensors. Frontal and transverse planes.	Participants were asked to stand on the evaluated limb and elevate the contralateral limb to 90° knee flexion with arms crossed over their chest, then to squat greater than 60° knee flexion within a 2s period, then to return to the starting position within 2s (overall 4s) without losing their balance. 3 trials were analysed.	Hip abduction/internal rotation and knee abduction during **SLS.**	Greater hip adduction in females than males (*p*< 0.0001**). Those with PFPS experience greater hip adduction than the controls (*p* < 0.0001**). Females with PFPS demonstrated greater hip internal rotation than males with PFPS and both control groups (all *p* <0.05*). Females with PFPS demonstrated greater knee abduction than the males (*p* < 0.0001**). Those with PFPS experienced greater increased knee abduction than the controls (*p* < 0.0001**).	Each painful limb in the PF group was compared with the corresponding limb in the controls. No mention of the validity and reliability of the electromagnetic tracking system. Static calibration. Males were significantly heavier than the females. No details of the footwear in the method.
Salsich et al. (2012)	Controlled laboratory study (within-subject design).	20 females with PFPS under 3 conditions (usual, exaggerated DKV condition, and	3D Vicon motion capture system with 8 cameras. Frontal and transverse.	Subjects were instructed to **wear a running shoe** and keep their trunk upright and their arms by their sides as they bend their knees to a minimum of 60° knee flexion	Hip and knee angles at **PKF** during **SLS.**	Increased hip internal rotation at PKF in the exaggerated condition compared to the usual condition (*p* < 0.001**). Increased knee external (lateral) rotation at PKF in the exaggerated	Static calibration. Use of skin markers is subject to errors and inaccuracies from skin artifact.

		corrected condition).		(usually confirmed) in a 4s period. For exaggerated condition: The participants were asked to let their knee fall medially during the descent phase. For the corrected condition: The participants were asked to not let their knee fall in the descent phase. 3 trials were analysed for each condition.		condition compared to the usual condition ($p < 0.001$**). Increased pain in the exaggerated condition compared to the usual condition ($p < 0.007$**). Decreased hip adduction ($p = 0.001$**) and knee external rotation ($p = 0.06$) in the corrected condition compared to the usual. Increased pain in the usual and the exaggerated condition was associated with increased knee external rotation (usual: $p = 0.04$*; exaggerated: $p = 0.03$*). Increased pain in the corrected condition was associated with increased hip medial rotation ($p = 0.05$*) and knee adduction ($p = 0.02$*).	Instructions given to participants to keep their trunk upright could have affected their normal pattern of task performance. Small sample size that included only female participants (affects the generalisability of the results to all PFP).
Willy et al. (2012)	Cross-sectional study.	18 males with PFPS.	3D Vicon motion capture system with 8 cameras and 30	To squat to 60° knee flexion while maintaining arms at approximately 90° of shoulder abduction	Peak hip adduction.	Increased knee adduction in males with PFP than matched male controls ($p = 0.021$*).	Static calibration. Males with PFP were significantly heavier than

		18 matched male controls. 18 females with PFPS.	retroreflective markers.	(speed was standardised to a 1-Hz count) while wearing a **standardised running shoe.** Five trials were analysed.	Peak hip internal rotation. Peak knee adduction. All of the above at peak knee flexion **PKF during SLS.**	Increased knee adduction in males with PFP relative to females with PFP (p = 0.000**) who squatted with increased abduction, Decreased hip adduction in males with PFP relative to females with PFP (p = 0.007**). Increased femoral adduction in females with PFP compared to males with PFP (p < 0.000**).	females with PFP and matched male controls. Cross-sectional design makes it difficult to draw causal links among the altered kinematics.

Abbreviations: * = Statistical significance <0.05; ** = Statistical significance <0.01; 3D = Three-dimensional; cm = Centimetres; m = metres; ROM = Range of motion; KOA = Knee osteoarthritis; PFPS = Patellofemoral pain syndrome; DKV = Dynamic knee valgus; DLS = Double leg squat; SLS = Single leg squat; PKF = Peak knee flexion.

2.7.3 Double leg squat kinematic alterations

For DLS, only one study was found in the literature search that evaluated DLS altered movement patterns for people with CKP compared to controls using 3D motion capture systems (Severin et al. 2017) (see Table 4). The study presented no significant differences between groups in the sagittal or frontal plane hip and knee peak angles yet the same study evaluated SLS movement (as discussed in the above section) which is a more challenging task for people with CKP and revealed some significant findings.

However, many studies have been conducted to analyse the normal squat movement patterns and biomechanics of healthy individuals. It has been stated that a deep squat can be used as a screening test to evaluate the bilateral symmetry of lower limb joints (hips, knees and ankles) (Kritz et al. 2009; Cook et al. 2014). Other studies have been conducted to identify the factors related to altered movement patterns (Lee et al. 2015; Zawadka et al. 2018). For instance, previous studies have shown that there is a relationship between the ROM of the lower limbs and the depth or kinematics of the squat (Drinkwater et al. 2012; Kim et al. 2015; Zawadka et al. 2020). Zawadka et al. (2020) evaluated the relationship for the sagittal plane ROM of the lower limbs during bodyweight squats to the depth of the squat. The knee ROM contributed most significantly to the squat depth out of all the lower limb joints in both females and males ($r = 0.92$, $p < 0.001$). Therefore, the knee flexion ROM is highly recommended as a parameter for describing squat depth. The squat depth was related to lumbar, hip and knee motion in females and additionally to the pelvis and ankle in males (Zawadka et al. 2020). It is important to consider the difference between males and females in the kinematic analysis and training of deep squats.

A systematic review by Lorenzetti et al. (2018) and a study by Lima et al. (2018) evaluated the effect of ankle dorsiflexion ROM on knee movement during the performance of DLS by healthy individuals. Their results revealed that limited dorsiflexion ROM was associated with increased knee valgus and medial knee displacement. These findings were most prevalent in people with CKP conditions such as PFPS (Salsich et al. 2012; Leibbrandt and Louw. 2017). The studies suggested that if an individual has restricted ankle dorsiflexion ROM that is usually associated with knee pain, they may be at a greater risk of injury to the knees, hips or low-back during DLS (Bell et al. 2013; Powers 2003). In other words, each joint must exhibit appropriate ROM for the efficient transference of forces through the body to produce ideal movement (Powers 2003).

Bell et al. (2013) reported that limited ankle dorsiflexion during a squat may reduce the ability of an individual to control knee valgus and foot pronation due to the weakness of the surrounding musculature. This forces the individual to achieve additional ROM by altering their foot mechanics. This limited ankle ROM usually contributes to altered movement patterns in the form of excessive medial knee displacement and dynamic valgus which is often a cause of PFPS or/and ACL injury (Bell et al. 2013; Dill et al. 2014; Macrum et al. 2012). Furthermore, the knees are incapable of tracking over the toes in the sagittal plane due to reduced ankle mobility; therefore, motion is borrowed from another plane via external rotation of the feet, pronation at the foot/ankle complex, or elevating the heels off the floor (Hemmerich et al. 2006; Toutoungi et al. 2000). Therefore, the clinical evaluation of ankle ROM must be considered because it could affect the movement patterns of the lower extremities.

In conclusion, lower limb kinematics and ROM are related to squat depth and should be considered in movement alteration studies of DLS. Squat asymmetry, medial knee displacement, and reduced ankle dorsiflexion should also be examined.

Most DLS research has examined the descending portion of the squat, from beginning to maximum knee flexion (Donohue et al. 2015). Numerous research studies have examined the kinematics and other confounding aspects of the squat, including the squat depth, stance width, speed of movement and loading conditions in the lower extremities during different squat forms. Most of these studies were conducted on healthy, recreationally active volunteers who have fewer movement alterations than patients, thereby raising issues regarding their applicability to the knee pain population. Due to the diverse execution of the squat exercise and the wide variances between studies in terms of the modifying factors (e.g., load intensity, technique, foot placement and speed of movement), these studies are difficult to evaluate. These factors may affect squat performance and the movement alteration by increasing or decreasing these alterations. Thus, future research should seek to investigate altered movement patterns among the knee pain population.

2.7.4 Stair ascent kinematic alterations

Nine studies were found in the literature that evaluated SA (Sparkes et al. 2019; Fok et al. 2013; Hicks-Little et al. 2011; McKenzie et al. 2010; van der Straaten et al. 2020; Iijima et al. 2018; Ferrari et al. 2018; de Oliveira Silva et al. 2016; de Oliveira Silva et al. 2015) (see Table 5).

Some of these studies presented consistent findings regarding reduced peak knee flexion angle in the knee pain group compared to the healthy controls (Ferrari et al. 2018; de Oliveira Silva et al. 2016; de Oliveira Silva et al. 2015; Hicks-Little et al. 2011) and increased hip adduction and rearfoot eversion during a SA (Ferrari et al. 2018; de Oliveira Silva et al. 2016; de Oliveira Silva et al. 2015).

Hicks-Little et al. (2011) was the only study that evaluated stair negotiation in the sagittal and frontal planes for the hip, knee and ankle joints during the whole movement cycle in addition to the timing of the peak angles during the movement cycle. The results regarding SA revealed increased hip abduction at foot strike and late peak hip abduction and flexion angles during support in the OA group compared to the healthy controls. They found no difference in the average hip flexion angle at foot strike between groups (Hicks-Little et al. 2011). A reduced peak knee flexion angle was identified during support and swing, late peak flexion during support and reduced average knee flexion angle at foot strike. In the ankle, no significant differences were found in terms of the average and peak joint angles but the OA group demonstrated delayed peak ankle dorsiflexion and adduction angles during support. Although this study was the only one that provided a detailed movement analysis of the stair movement cycle for the hip, knee and ankle joints, the study only included OA participants who were of mild and moderate severity, which would not be representative of those with severe OA.

van der Straaten et al. (2020) evaluated SA during the whole cycle of the hip, knee and ankle joints and found decreased knee flexion ROM in the OA group compared to the controls during 15-41% of the movement cycle. However, no difference was found in the sagittal or the frontal planes for the hip or ankle joints. Similarly, neither Hicks-Little et al. (2011) nor van der Straaten et al. (2020) found any significant differences in knee frontal plane kinematics. Sparkes et al. (2019), however, evaluated the hip, knee and ankle joints and found no difference in the sagittal plane knee movement but reported an increase in knee abduction ROM in the OA unaffected limb compared to the healthy controls (*P*=0.049). Contrary to the findings of van der Straaten et al. (2020), they presented significant differences at the ankle joint with reduced ankle dorsiflexion ROM in the OA-affected limb compared to the controls.

Decreased ankle dorsiflexion ROM reported by Sparkes et al. (2019) was only presented in the affected limb of the OA group and not among the controls. Although this was the only study to evaluate both OA limbs (the affected and unaffected) and provided a significant finding that some movement alterations may be presented in the unaffected limb as a strategy to unload the affected limb, there were several limitations associated with the study. Only 4 steps were used when evaluating the stairs and there was only a small number of participants (10 OA and 8 controls). In addition, no details were provided regarding the height and depth of the stairs used and these factors are known to affect joint kinematics during stair ascent and descent (Trinler et al. 2016).

Fok et al. (2013) investigated sagittal and frontal plane kinematics during the stance phase for 17 participants with isolated patellofemoral osteoarthritis (PFOA), 13 with combined PFOA/ tibiofemoral osteoarthritis (TFOA) and 21 matched controls for the hip, knee and ankle. They found no significant differences in sagittal plane movements for the knee and ankle joints but some movement alterations only presented in the hip joint, such as increased hip flexion in both OA groups compared to the controls. While this study was the only one that included OA participants of mixed compartments, they used a staircase that consisted of only 3 steps of 16.5 cm in height, with no details provided regarding the tread depth. According to Livingston et al. (1991), the knee's flexion/extension is adjusted for different stair dimensions (height and tread depth) to a greater extent than for the hip or ankle joints (Livingston et al. 1991). It is important to note that Fok et al.'s (2013) study was the only one to use stairs with a height of 16.5 cm, which was the lowest among all of the other included studies. Therefore, this may have been responsible for the lack of significant findings for the knee joint.

The results of the previous research were consistent with a comprehensive systematic review and meta-analysis which examined eleven studies utilising various movement analysis techniques to reveal the altered biomechanical variables performed by OA people when negotiating stairs (Iijima et al. 2018). The results of the meta-analyses showed that, in comparison to healthy controls, people with knee OA climb stairs with greater trunk and hip flexion (SMD = 0.38 and 0.34, respectively), as well as decreased knee flexion and ankle dorsiflexion (SMD = -0.28 and -0.32, respectively) (Iijima et al. 2018). However, there were no significant variations in the frontal kinematics in the lower limb joints between those people with OA and the healthy controls (SMD range = -0.10 to 0.14) (Iijima et al. 2018). This systematic review was constrained by the fact that the data extraction and study inclusion processes were carried out by a single author, which may have reduced the internal validity and produced greater errors than Higgins et al. (2019) who advocated using two or more researchers. The authors also noted that the quality of the evidence for these findings was very low according to the GRADE approach (Balshem et al. 2011).

The altered movement patterns revealed in the previous research (increased hip flexion and decreased knee flexion kinematics) show that people with knee OA have potentially developed a compensating strategy. This altered movement pattern may be the result of quadriceps muscular weakening (Ling et al. 2007; Rudolph et al. 2007) and painful step loading during functional activity. Although trunk kinematics were not investigated in this LR, people with OA strive to limit the loading time for a single leg. This was found to be achieved through higher trunk flexion which generates greater force for vertical displacement with larger maximum acceleration (Bolink et al. 2012). In addition, the correlation between increased peak trunk flexion and decreased external knee flexion moment (KFM) during stair ascent in knee OA patients may indicate the presence of a compensation mechanism (Asay et al.

2009). In addition, increasing KFM in conjunction with an increased knee adduction moment (KAM) is a strong predictor of increased knee contact force (R2 = 0.73) (Richards et al. 2018). Therefore, decreasing KFM by enhancing sagittal trunk kinematics could reduce knee joint loading.

In summary, the previous studies that have evaluated SA for people with knee pain using 3D motion capture systems demonstrated some consistent findings. Reduced peak knee flexion, increased hip flexion and adduction, and rearfoot eversion during SA were mainly reported in the literature.

2.7.5 Stair descent kinematic alterations

Eight studies evaluated SD (Sparkes et al. 2019, Fok et al. 2013; Hicks-Little et al. 2011; McKenzie et al. 2010; van der Straaten et al. 2020; Schwane et al. 2015; Igawa and Katsuhira 2014; Lessi et al. 2012) (see Table 5). Reduced knee flexion ROM was evident among those with CKP compared to healthy controls in some of the included studies (van der Straaten et al. 2020; Igawa and Katsuhira 2014; Fok et al. 2013; Hicks-Little et al. 2011). van der Straaten et al. (2020) and Hicks-Little et al. (2011) also provided consistent findings for the hip and ankle joints with no significant findings observed in all of these joints. However, Igawa and Katsuhira (2014) indicated decreased hip flexion and overall hip ROM in the OA group compared to the healthy controls. Meanwhile, Fok et al. (2013) and Igawa and Katsuhira (2014) presented no significant difference at the ankle joint.

In Igawa and Katsuhira’s (2014) study, only a very small number of participants were included (4 OA and 8 controls) and the OA participants all exhibited mild severity, with no clarification of the affected compartment. The authors also used many markers in their movement analyses (34 markers) which could be affected by skin artifacts and, consequently, affect the analysis and results. Igawa and Katsuhira (2014) and Lessi et al.’s (2012) studies were the only two that relied exclusively on the sagittal plane for their analysis. Therefore, other movement alterations which could be presented in the frontal or transverse planes were dismissed.

Sparkes et al. (2019) did not find a significant difference in knee sagittal plane motion but there was an increased knee abduction ROM in the OA-affected side compared to the controls and decreased knee transverse ROM in the unaffected side of the OA group compared to the controls. Similar to van der Straaten et al. (2020) and Hicks-Little et al. (2011), Sparkes et al. (2019) did not find any significant differences in the hip or ankle joints.

Schwane et al. (2015) included female participants with PFPS in their study and presented increased knee internal rotation angular displacement in the PFPS group compared to the controls of approximately 4 degrees but there were no differences at the hip or trunk. While the study included only 20 participants in each group, that figure was determined by a power calculation. They included only young female participants who were under 35 years of age and, thus, the generalisability of their findings is restricted. Additionally, speed in their SD protocol was limited to 96 beats/minutes and the participants were asked to wear their own athletic shoes and, therefore, these factors could have affected their normal pattern of walking and led to the absence of certain findings which are usually reported in people with PFPS, such as increased hip adduction and knee abduction (Leibbrandt and Louw 2017).

McKenzie et al. (2010) also evaluated female participants with PFPS and presented no significant findings at the knee joint during SD. However, their results demonstrated increased hip adduction and internal rotation ROM during the whole stance phase, and increased hip adduction and internal rotation at initial contact. It is important to note that their study was limited to the hip and knee joints and they demonstrated a different stair ascent and descent protocol because the participants were asked to ascend/descend the stairs continuously for three minutes using stairs with a depth of 22 cm. This step depth is lower than the building standard code but was determined based on a previous study which allowed for a step height of 20 cm between steps and a tread depth of 30.5 cm (Schwane et al. 2015). Asking the participants to ascend/descend continuously for minutes may have led to fatigue.

In conclusion, decreased knee flexion ROM, in addition to increased hip internal rotation were the most observed alterations. Some other alterations were reported less frequently such as reduced hip flexion and increased hip adduction. Among both

SA and SD, stair negotiation demanded greater sagittal plane ROM among all of the lower limb joints. Meanwhile, more alterations were observed in SA because it is believed that this is a more challenging and demanding activity.

Table 5: Summary of studies evaluating stairs ascent and stairs descent kinematic alterations for people with CKP and healthy controls using different motion capture systems

Authors/ date	Design	Subjects	Type of motion analysis and plane of motion	Method	Kinematic outcome variables	Key findings	Limitations
van der Straaten et al. (2020)	Part of a large longitudinal study	19 severe unilateral KOA. 12 healthy controls.	Sensors (15 sensors, MVN BIOMECH Awinda). Optoelectronic (65 markers and 10 camera VIKON system). Frontal, transverse and sagittal planes.	**For SA:** To ascend the stairs **barefooted** and wait at the top of the staircase until given the instruction to turn around. **For SD:** To descend the stairs as instructed and wait at the bottom until instructed to turn around. 5 trials collected.	Hip, knee and ankle kinematics **(during the whole movement cycle).**	**For SA:** - Decreased knee flexion ROM in the OA group compared to controls (15-41% of movement cycle). **For SD:** - Decreased knee flexion ROM in the OA group compared to controls (12-72% of movement cycle).	OA participants were significantly older. Small sample size. No distinction for the compartment of KOA (medial or lateral). Only severe OA. Many markers (some data were lost due to some invisible markers which led to technical errors). Static calibration with severe OA patients (may not be able to fully extend their knees).

							No details provided for the depth or height of the stairs.
Sparkes et al. (2019)	Case-control study	10 moderate OA. 8 matched controls.	3D optical motion capture with 9 cameras and full-body markers and 4 force plates. Frontal, sagittal and transverse.	To ascend and descend a 4-step staircase 6 times. 3 trials leading with each leg.	ROM for hip, knee and ankle.	**For SA:** - Increased knee abduction ROM in the OA unaffected limb compared to controls (*p* = 0.049*). - Decreased ankle dorsiflexion ROM in the OA-affected limb compared to the controls (*p* = 0.049*). - No significant differences found in the hip joint. **For SD:** - Increased knee abduction ROM in the OA-affected limb compared to the controls (*p* = 0.025*). - Decreased knee transverse ROM in the OA-unaffected limb compared to the controls (*p* = 0.036*). - No significant differences found in the hip or ankle.	More females than males in both groups (80% OA and 75% controls). Only moderate OA. Small sample size, limited power and precision. No power calculation for the sample size. Not representative of the population. No details provided for the depth or height of the stairs. No details for the speed of ascent/descent.
Ferrari et al. (2018)	Cross-sectional	25 females with PFPS.	3D Vicon motion capture.	To ascend a **7-step** staircase (height: 18 cm, depth: 28 cm) at a self-selected	Peak hip adduction, knee flexion and rearfoot eversion	**For SA:**	Static calibration. Only female participants.

		25 matched controls.	system with 4 cameras. Sagittal and frontal planes.	speed with a 2 m walkway in front and behind the stairs. 5 trials collected and the 4th step analysed.	angles during **stair ascent.**	- Increased peak hip adduction in the PF group compared to the controls. - Increased peak rearfoot eversion in the PF group compared to the controls. - Reduced peak knee flexion angle in the PF group compared to the controls.	Cross-sectional design.
Iijima et al. (2018)	Systematic review	12 studies included and reviewed for individuals with knee OA.	3D motion Capture systems or IMUs. Sagittal plane.	Differed according to the included studies.	Lower limb joint kinematics during **stair ascent.**	**For SA:** - Increased hip flexion angles - Reduced knee flexion Angle - Reduced ankle dorsiflexion angle.	Most of the included studies were observational cross-sectional studies, which are more susceptible to bias and numerous confounding factors compared to randomised controlled trials. A singular reviewer conducted the review procedures, including study selection and data extraction, which increased the likelihood of error.
de Oliveira Silva et al. (2016)	Between-subject design	29 females with PFPS.	3D Vicon motion capture system with 4 cameras.	To ascend a **7-step** staircase (height: 18 cm, depth: 28 cm) at a self-selected speed with a 2 m	Peak hip adduction, knee flexion and rearfoot eversion angles during **stair ascent.**	**For SA:** - Increased peak hip adduction in the PF group compared to the controls (*p* = 0.009**, small effect size= 0.38).	Static calibration. Only female participants.

		25 matched controls.	Sagittal and frontal planes.	walkway in front and behind the stairs. 5 trials collected and the 4th step analysed.		- Increased peak rearfoot eversion in the PF group compared to the controls (p = 0.000**, moderate effect size= 0.55). - Reduced peak knee flexion angle in the PF group compared to the controls (p = 0.001**, small effect size= 0.33).	Some participants were not experiencing pain at data collection.
de Oliveira Silva et al. (2015)	Cross-sectional	29 females with PFPS. 25 matched controls.	3D Vicon motion capture system with 4 cameras Sagittal plane only.	To ascend a **7-step** staircase (height: 18 cm, depth: 28 cm) at a self-selected speed with a 2 m walkway in front and behind the stairs. 5 trials collected and the 4th step analysed.	Peak knee flexion during **stair ascent.**	**For SA:** - Significant reduction in peak knee flexion angle (2.51°, p = 0.020*) in the PFPS group compared to the controls.	Static calibration. Only female participants. Participants with unilateral and bilateral PFPS were included (confounding factor). Cross-sectional design.
Schwane et al. (2015)	Cross-sectional	20 females with PFPS. 20 matched controls.	3D Vicon motion capture system with 7 cameras, 2 force plates and 46 reflective markers.	To descend **4 steps** (height: 20 cm, depth: 30.5 cm) in a step-over-step way led by the unaffected leg while wearing (the participants' own) **athletic shoes** at a	Hip, and knee joint displacement during the **stance phase** of **stair descent.**	**For SD:** - No significant difference found in terms of hip joint displacement. - Increased knee internal rotation angular displacement by about 4° in the PF group relative to the controls (p = 0.004**).	Static calibration. Only female participants included. Speed was controlled. Only 4 steps without eliciting participants' pain.

			Sagittal, frontal and transverse planes.	**controlled speed** (96 beats/minutes). 5 trials for each participant and 3 trials analysed.			Many markers used (one participant's data was affected by marker occlusion).
Igawa and Katsuhira (2014)	Between-subject design	4 participants with early KOA. 8 healthy participants.	3D Vicon motion capture system with 12 cameras, 6 force plates and 34 reflective markers. Sagittal plane.	The participants were instructed to descend a **5 step** staircase (height: 160 mm, depth: 300 mm) **barefooted** at a self-selected speed with no assistance. 3 trials analysed.	Mean peak joint angles and ROM for the hip, knee and ankle in the sagittal plane during the **early stance** phase of **stair descent.**	**Sagittal plane in SD only:** - Decreased knee flexion angle in the KOA group compared to the healthy controls ($p < 0.05$*) during 12-23% of the gait cycle. - Reduced hip flexion angle in the KOA group compared to the healthy controls ($p < 0.05$*) during 9-20% of the gait cycle. - Decreased hip and knee ROM in the OA group compared to the healthy controls ($p < 0.05$*). - No significant differences found at the ankle between both groups.	No clarification for the affected compartment and only mild OA. Many markers used (effect of skin artifact). Very small sample size that was not based on a power calculation. Only sagittal plane (no frontal or transverse planes).
Fok et al. (2013)	Cross-sectional	30 with PFOA (17 isolated PFOA, 13 combined PF and TFOA).	3D Vicon motion capture system with 9 cameras and 2 force plates.	The participants were asked to ascend and descend a flight of **3 steps** (height = 16.5 cm) with no aids at a self-selected	Hip, knee and ankle sagittal joint angles during only **the stance** phase of **SA** and **SD** at the time of	**For SA:** - Increased hip flexion (mean difference 4.6°; $p = 0.023$*) in the isolated PFOA relative to the controls. - Increased hip flexion (mean difference 7.1°; $p = 0.002$**) in the	Static calibration. No mention of the radiographic procedure for the controls (who were

		21 age-matched controls.	Frontal and sagittal planes.	speed wearing **standardised footwear.**	**contralateral toe-off** (peak knee extension moment).	combined OA relative to the controls. - No significant difference found between the OA groups in terms of knee flexion or ankle dorsiflexion. **For SD:** - Decreased knee flexion in the isolated PFOA group compared to the controls (mean difference 7.7°; *p* = 0.001**) but not in combined OA. - No significant difference found between OA groups for knee flexion or ankle dorsiflexion.	approximately 56 years of age). Controls leg was chosen at random. Stair depth was not mentioned.
Lessi et al. (2012)	Between-subject design	17 males with early KOA (grades 1 and 11). 14 healthy controls.	2 digital video cameras (NV-Panasonic) placed in the frontal and sagittal plane perpendicular to each other. Sagittal plane.	Instructed to descend a **3 step** staircase (height: 20.5 cm, depth: 27.5 cm) **barefooted** at a self-selected speed leading with the evaluated limb, **while positioning their hands on their waist.** 5 trials analysed.	Task time, total knee ROM, peak knee flexion angle, knee flexion at HS, knee flexion at loading response, time from HS to peak loading response (all during **stair descent**).	**For SD:** - No significant kinematic differences found between OA and the healthy groups.	Any compartment included (one subject with medial TF compartment, one subject with lateral TF, 8 with PF and 7 with combined compartment). Only 3 steps in the staircase. Only sagittal plane. Only mild OA.

Hicks-Little et al. (2011)	Case-control	18 with KOA. 18 matched controls.	3D motion capture system with 8 cameras and 28 reflective markers. Frontal and sagittal planes.	To walk up and down a customised staircase consisting of **4 steps** (height = 18 cm, tread length = 28.5cm) **barefooted** and unaided at a self-selected speed, ensuring that only one foot hits each step. 5 trials for SA and SD analysed.	Average angle at HS/peak angle during support/time (% of gait cycle) of peak angle during support/peak angle during swing/and average angle at toe off. In the sagittal and frontal plane for the hip, knee and ankle **during the whole cycle (stance and swing).**	**For SA:** **Hip:** - Increased hip abduction at HS in the OA group compared to the controls ($p = 0.03$*). - Late peak abduction angle during support in the OA group compared to the controls ($p < 0.05$*). - Late peak hip flexion in the OA group compared to the controls ($p < 0.05$*). - No differences in the average hip flexion angle at HS between both groups. **Knee:** - Reduced peak knee flexion during swing in the OA group compared to the controls ($p = 0.001$**). - Late peak knee flexion during support in the OA group compared to the controls ($p = 0.001$**). - Decreased average knee flexion angle at HS in the OA group ($p < 0.05$*). - Decreased peak knee flexion angle during support in the OA group ($p < 0.05$*).	Static calibration. Only mild and moderate knee OA included.

						Ankle: - No significant difference in average ankle abduction at HS between the OA group and the controls. - No significant difference in peak ankle dorsiflexion during support between the OA group and the controls. - OA group demonstrated late peak ankle dorsiflexion during support phase relative to the controls ($p < 0.05$*). - No significant difference in peak ankle dorsiflexion during swing between the OA group and the controls. - Late peak adduction angle during support in the OA group compared with the controls ($p < 0.05$*). **For SD:** **Hip:** - No differences in the average hip flexion angle at HS between both groups. **Knee:**	

						- Reduced peak knee flexion during swing in the OA group compared to the controls ($p = 0.001$**). - Late peak knee flexion during support in the OA group compared to the controls ($p = 0.001$**). - Increased knee abduction angle during the swing phase in the OA group compared to the controls ($p < 0.05$*). **Ankle:** - No significant difference in average ankle abduction at HS between the OA group and the controls. - No significant difference in peak ankle dorsiflexion during support between the OA group and the controls. - No significant difference in peak ankle dorsiflexion during the swing between the OA group and the controls.	
McKenzie et al. (2010)	Cross-sectional Case-control	10 females with PFPS.	Magnetic-based sensors (Polhemus Systems, Skills	**For SA:** To ascend a 5-step staircase at a self-selected speed	Knee flexion/extension, hip flexion/extension,	**For SA:** - No significant differences observed at the hip joint overall ROM.	Static calibration. Only female participants included.

		10 matched controls.	Technology, Colchester, VT). Sagittal, frontal and transverse planes.	(height: 20 cm, depth 22 cm) with no assistance for 3 minutes continuously, initiated by the evaluated limb. **For SD:** Upon reaching the top, the participants were instructed to turn around and walk back down the stairs to the floor.	adduction/abduction/ and internal/external rotation during the **stance** phase (at **HS**).	- Increased knee flexion angle at HS in the PF group compared to the controls during self-selected speed but to a lesser extent at fast speed. - No significant difference for hip flexion, adduction and internal rotation angles upon HS. **For SD:** - Increased hip adduction/internal rotation overall ROM in the PFPS group relative to the controls. -Increased hip adduction angle at HS (difference: 7.5°). - Increased hip internal rotation angle upon HS (difference: 5.9°). - No significant difference for hip and knee flexion angles upon HS. - Increased knee flexion angle at HS in the PF group compared to controls during self-selected speed but to a lesser extent at fast speed.	Step depth was less than building standard code (greater slope and task demand). All of the included participants were athletic females (could be different with men or sedentary individuals). Small sample size (no difference in SA). Repetition of the task for 3 minutes could have led to fatigue.

Abbreviations: * = Statistical significance <0.05; ** = Statistical significance <0.01; 3D = Three-dimentional; cm = Centimetres; m = metres; IC = Initial contact; ROM = Range of motion; KOA = Knee osteoarthritis; PFPS = patellofemoral pain syndrome; DKV = Dynamic knee valgus; SA = Stair ascent; SD = Stair descent; PKF = Peak knee flexion.

2.7.6 Vertical jump kinematic alterations

The number of studies that evaluated VJ performance for people with CKP using 3D motion capture systems was very limited. This could be due to the dynamic nature of the VJ task which is utilised more frequently for evaluating the kinematics of certain sports-related injuries such as ACL rupture (van der Straaten et al. 2020). Some studies evaluated different types of jump activity using 3D motion capture technologies for individuals with PFPS. For example, Nunes et al. (2019), Baellow et al. (2020) and Souza and Powers (2009) evaluated the drop vertical jump (DVJ), Harris et al. (2020) evaluated VJ, Willson and Davis (2009) evaluated single jump landing (SLJ) and Souza and Powers (2009), dos Reis et al. (2015) and Alvim et al. (2019) evaluated single leg hopping (SLH). However, none of these jumping strategies were included and nor were they within the scope of the current review because they are primarily used for athletic performance assessment, with the exception of VJ.

Harris et al. (2020) conducted a systematic review in which the studies analysed VJ-landing mechanics in 3D for athletes with patellar tendinopathy (PT) or asymptomatic athletes with a history of PT or patellar tendon anomaly (PTA) on imaging. PT is a clinical condition of the patellar tendon which is characterised by localised pain in the anterior knee that is not caused by injury (Crossley et al. 2007) but by repetitive VJ-landing tasks (Khan 1998). Their results from 13 studies revealed that among the 37 variables identified to be statistically significant and associated with PT, there were only two variables that were consistently replicated between the studies: knee flexion angle at initial contact and an altered hip flexion/extension strategy during a horizontal land phase of a VJ (Harris et al. 2020).

It was also found that for evaluating those with PT, sagittal plane hip and knee kinematics during the landing phase of VJ were the most important factors to analyse. The authors of the review recommended that analysing the landing phase or take-off phase in isolation is inadequate to identify different jump-landing variables and clinicians need to evaluate the whole jump-landing task. However, there were a number of limitations associated with this research. There was heterogeneity between the included studies and it was unclear if this lack of consistency among the research means that a particular characteristic is irrelevant in all situations or that it is reliant on the experimental settings such as the experimental task, cohort, sport, age or skill level. Some of the studies may have misdiagnosed PT with other anterior knee pain conditions such as PFPS (Harris et al. 2020).

Pedley et al. (2020) conducted a systematic review on healthy subjects to identify kinetic, kinematic and performance measures of jumping and landing and their association with the risk of experiencing lower extremity injuries for studies using different motion capture systems. Consistent with Harris et al.'s (2020) findings, their results revealed that the landing phase of VJ appears to be better at identifying people who are more likely to sustain an injury. This could be attributed to the similarity between landing and the mechanism of injuries but they recommended evaluating knee frontal plane motion (knee valgus, valgus displacement, normalised knee separation distance) in addition to the sagittal plane (knee flexion at initial contact and peak knee angular displacement) kinematic variables for assessment of this activity (Pedley et al. 2020).

In conclusion, a very limited number of studies have evaluated lower limb kinematics for people with CKP during the VJ task using different motion capture systems. Different investigations have shown varying kinematics at the lower limb joint in various planes. During VJ exercises, reduced knee flexion exhibited by people with CKP (notably PT) has been observed. The variety of jumping activities, variables, measuring techniques and populations that have been examined have led to disagreement and inconsistency, making it difficult for researchers to synthesise the results.

2.7.7 Section summary

This review has identified a large number of studies that have investigated lower limb kinematics during gait, DLS, SLS, VJ, SA and SD for people with CKP conditions. The range of functional tasks is important because they present different challenges for people with CKP. When performing these functional activities, kinematic alterations were evident in the three planes of motion. A reduction in knee flexion, an increase in knee abduction and hip adduction, and reduced ankle dorsiflexion are among them.

Human movement analysis is a complex process that requires the examination of three planes of motion (sagittal, frontal, and transverse) across numerous joints. The level of difficulty is dependent upon the functional requirements of the individual. This presents a challenge in clinical practice, where physiotherapists have traditionally depended on observational analysis to evaluate human movement. The utilisation of conventional observational methods would impede a physiotherapist's ability to precisely monitor numerous joints and planes concurrently throughout a range of functional activities. Therefore, different motion capture systems were utilised to analyse these functional tasks. This enables PT treatment to be customised considering the discovered altered movement patterns. However, the gold-standard motion capture system is limited to being used in a laboratory and cannot be utilised in everyday clinical settings. Technological developments have led to the creation of portable, wearable IMUs to quantify human movement in clinical settings.

However, motion capture systems simultaneously generate large volumes of kinematic data for multiple planes of motion and joints. These data need to be reported in a user-friendly manner to help physiotherapists interpret the kinematic results. Few studies to date have utilised kinematic data. Therefore, the following section elaborates on the literature concerned with reporting movement analysis and the interpretation of kinematic data.

2.8 Reporting movement analysis and alterations

Current practice in the clinic involves ‘eyeballing’ of the movement of the limb, joint angles and execution of functional tasks to try and ascertain whether the movement is ‘normal’ or ‘abnormal.’ It is up to the individual physiotherapist in the clinic to determine if an observed difference in movement pattern is clinically relevant. There are no published guidelines for the knee that define what is and is not an important or clinically relevant alteration in movement. Movement analysis is a key PT skill but because it is subjective, it lacks accuracy and standardisation and, therefore, is less reliable (Skaggs et al. 2000). Factors such as subjectivity in observations, the lack of standardisation for protocols and the criteria for movement analysis, variability in data collection, and the complexity of human movement with regards to multiple joints, muscles and coordination patterns contribute to these challenges. To improve accuracy and reliability, physiotherapists are exploring technology-driven approaches such as 3D motion capture technologies which provide more objective measurements (Jones et al. 2014). Embracing these advances in clinical settings can enhance movement analysis and lead to more effective and evidence-based PT practices. By being able to address movement alterations, it is believed that patients with CKP will experience less pain and improved function (Roper et al. 2016).

Summary statistics can be created from IMUs-based movement analysis systems to provide a quantitative description of motion but visual analysis of movement cycle waveforms offers further insight into a person's performance throughout a task that can guide the decision-making process with regards to treatment (Button et al. 2022). Individuals' movement data should be presented in a clear, understandable and user-friendly format (Button et al. 2022). This requires a movement analysis report featuring a graphical representation of the patient's kinematics and/or kinetics for bilateral sides of individuals in multiple planes of motion, in addition to normative values for the asymptomatic population (Button et al. 2022).

When bilateral data (e.g., for the ankle, knee and hip) are included, it is common for a clinical movement analysis report to comprise upwards of 50-line graphs analysing a performed movement. Even the most skilled PT may find it difficult to synthesise and analyse such a vast amount of data. There is a gap in the literature regarding how physiotherapists report and interpret movement patterns of functional tasks. The literature search strategy identified seven studies that provided information for the reporting and interpretation of movement analysis. Detailed study characteristics and methods are presented in Table 6. Four studies were conducted to investigate within- and between-rater agreement on identifying a presence or absence of altered movement patterns between limbs within kinematic waveform graphs in one or more planes of motion for certain functional tasks (Nieuwenhuys et al. 2017; Wang et al. 2019; Button et al. 2022; Brunnekreef et al. 2005). Other studies established how clinicians describe or interpret the identified alteration in movements (Button et al. 2022; Fellin et al. 2010; Crenshaw and Richards 2006; Manal and Stanhope 2004).

Nieuwenhuys et al. (2017) evaluated the between and within rater agreement for 2 different group of raters (experienced and inexperienced) for the interpretation of kinematic and kinetic data attained from the 3D optoelectronics motion capture system for 82 children with spastic cerebral palsy (CP). In their study, 28 raters completed two rounds of classification for the 3D gait analysis reports of 27 or 28 CP patients. All movement patterns at the pelvic, hip, knee and ankle joints showed a substantial-to-almost perfect agreement according to the agreement findings (within-rater Kappa = 0.64–0.91; between-rater Kappa = 0.63–0.86, except for the knee patterns during stance K=0.49, ‘moderate agreement’) (Nieuwenhuys et al. 2017).

Similarly, Wang et al. (2019) conducted a study to evaluate the interobserver consistency of interpreting 3D gait analysis reports for children with gait abnormalities within a single institution. Seven experienced raters interpreted 15 patients’ reports and a variety of issues and suggested treatments were presented to the interpreters, where they were asked to choose ‘yes,’ ‘no’ or ‘indeterminate.’ The interpretation of the 3D gait analysis data (kinematics, kinetics, EMG and video) identified potential altered gait movement patterns in 15 children with gait abnormalities with moderate agreement (averaged Kappa = 0.55).

Wang et al.’s (2019) study demonstrated some limitations because they did not assess the intra-observer variability analysis and all of the included raters were experienced orthopaedic surgeons. Thus, it is uncertain whether conducting the same investigation with inexperienced participants would provide similar results. In addition, they analysed data for only 15 patients and this limited number of participants may not be representative of all alterations. Although Nieuwenhuys et al. (2017) included a larger number of patients and a group of raters with differing levels of experience in their study, there were 4.7% unclassified patterns in their analysis which was mostly presented at the hip joint across three planes of motion. In both of the studies by Nieuwenhuys et al. (2017) and Wang et al. (2019), raters were directed to detect the presence of multiple gait deviations by presenting 3D movement analysis data and only responding ‘yes’ or ‘no’ to a list of gait issues

(Wang et al. 2019) and an outline of movement alterations that occurred during various gait phases (Nieuwenhuys et al. 2017). However, no attempt was made to describe these movement changes and gait problems (Nieuwenhuys et al. 2017; Wang et al. 2019).

Brunnekreef et al. (2005) investigated the inter-rater and intra-rater agreement between experienced and inexperienced raters by employing a standardised gait analysis template to analyse the recorded footage of individuals with orthopaedic disabilities for gait movement patterns. Thirty patients who were sent to a physical therapist for gait therapy had their gait videotaped. Ten raters (four experienced, four novice and two experts) each assessed the patients' filmed gait patterns twice using a standardised gait analysis form that included 12 items and reflected the movement of the trunk, arm, pelvis, hip, knee and ankle within the gait cycle. The results of their study reported moderate between- and within-rater agreement (between experienced raters, ICC = 0.42; between novice raters, ICC = 0.40; within experienced raters, ICC = 0.63; within novice raters, ICC = 0.57).

Brunnekreef et al. (2005) evaluated kinematic data from video footage. Visual observation of video footage is inadequate and unreliable when assessing most gait cycle events due to the difficulty of distinguishing movements from multiple planes. For instance, compared to a simpler set of movement alterations at the knee in the sagittal plane, Brunnekreef et al. (2005) reported less agreement between raters on items that were thought to be challenging to identify, such as movement alterations at the pelvis in the transverse plane (ICC ranges = 0.19 - 0.33 vs 0.58 - 0.60, respectively). Additionally, Kawamura et al. (2007) found that only pelvic obliquity and knee flexion at first contact can accurately be assessed solely based on visual cues. Therefore, it is preferable to include quantitative evaluation alongside observational analysis when assessing most gait cycle events. This data also supports the use of waveform graphs rather than films in movement analysis reports that are to be used in clinical settings.

Manal and Stanhope (2004) proposed an alternative method to show altered movement patterns in gait analysis. Current methods of plotting kinematic and kinetic data against mean and standard deviation values are time-consuming and complicated. This is because when using standard approaches, six-line graphs of the patient's data plotted against normative values would be examined to obtain the same conclusion. The proposed method uses colour-coded magnitude and direction of the alteration to create a compact and visually appealing overview of all of the changing magnitudes on one page. The colour-coding methodology was explained and the gait data from an affected patient was compared to 15 healthy persons. This approach simplifies the displaying of alterations and simultaneously interprets numerous variables. However, reporting data as modifications may result in some information being lost, hence it should be utilised alongside other methods. The sign protocol for anatomical motion should also be considered when evaluating colour-coded alterations. The proposed method is limited to gait analysis but can be used for other movement analysis.

This technique has some drawbacks, such as the loss of joint angles when data are displayed as an alteration. For example, the magnitude of the ankle angle (marked red in the report) at a certain time during stance may be relevant. This information is not available in colour-coded variants. It is not recommended that this method replace the alternative methods of presenting data but rather it should serve as a useful supplement. Another consideration is the joint's anatomical motion sign format. In Manal and Stanhope’s (2004) study, knee flexion was a negative value and, therefore, excessive flexion was marked in red. In most studies, flexion is a positive score and excessive flexion is highlighted in blue. The lack of a standard sign format for time history data should be examined in future studies. Finally, the study limited the reported variations to ±3. The authors justified this range because movement patterns beyond these extremes are abnormal and, from a clinical standpoint, it is useless to distinguish between excessive alterations (Manal and Stanhope 2004). This reasoning should be reconsidered because for people with CKP or who have any other pathology that alters their movement (e.g., CP), large deviations from the norm are clinically important to assist with patient-therapist decision-making and treatment planning.

Crenshaw and Richards (2006) analysed gait pattern symmetry and normality using a novel approach called eigenvectors to compare the entire waveforms. To determine symmetry, the right and left limbs of a single person’s sagittal plane movement were compared to a normative file based on the average of healthy controls. Four measurements were provided by the analytical procedure: phase shift, trend symmetry/normality, the range amplitude ratio, and range offset. When the curves were an identical shape, trend symmetry would equal zero. This can be used to contrast symmetry between joints. For instance, if the trend symmetry at the knee is 3.2 and the trend symmetry at the hip is 1.5, it can be concluded that the hips are more symmetrical than the knees. A comparison of each limb's ROM is undertaken using the range amplitude ratio, with a value of one indicating that each curve has a similar ROM, whilst a score of more than one indicates increased ROM and a score of less than 1 signalling decreased ROM. The range offset compares the operating ranges of each limb and according to their analysis, a range offset value of zero indicates that both sides operate within the same ROM, whereas a positive value indicates flexion and a negative value indicates extension (Crenshaw and Richards 2006). Although using the eigenvector method to assess joint and waveform symmetry and normality can help quantify and monitor alteration in joint motion and present better visualisation of the data, the method is only suitable for waveform data. As such, it cannot be used to assess symmetry for discrete time points.

Fellin et al. (2010) compared 3D lower limb kinematics during overground (OG) and treadmill (TM) running. Quantitative kinematic curve analysis was used to examine the 3D kinematics of the hip, knee and rearfoot during OG and TM running. Subsequently, the trend symmetry method introduced by Crenshaw and Richards (2006) was utilised. An additional goal of the study was to contrast the findings of each analysis approach.

Twenty runners were observed running at 3.35 m/s 5% on a treadmill and in open space while right lower extremity kinematics were captured. Utilising intraclass correlation coefficients, the kinematics of the hip, knee and rearfoot during foot strike and peak were compared (Fellin et al. 2010). The study’s results demonstrated an average high trend symmetry between running modes of 0.94 (perfect symmetry is 1.0). A lower similarity value was recorded between the knee frontal plane and transverse plane (0.86-0.90). All variations were less than 1.5˚, except for a 4.5˚ decrease in rearfoot dorsiflexion at foot strike during treadmill running. There were 8/18 discrete variables with high correlations (>0.8) and 17/18 discrete variables with moderate correlations (>0.6). When averaged across the subjects, the kinematic curves for treadmill and overground running were similar (Fellin et al. 2010). Although trend symmetry compares two waveforms using a range of variables to ensure a thorough analysis, there are several limitations associated with the technique. For instance, the method does not specifically deal with the waveforms' variability. Accordingly, for data that are extremely changeable, this approach can return results that are not truly indicative of the raw data.

A study by Button et al. (2022) developed a template for reporting and interpreting altered movement patterns. Firstly, the authors investigated the identification of altered movement patterns in the sagittal and frontal planes during various functional activities and, secondly, described these alterations. In Button et al.'s (2022) study, within and between user agreements for the evaluation of 14 IMU movement analysis reports for 14 individuals with ACL reconstruction containing 225 kinematic waveform graphs for three functional activities (gait, DLS and SA) were created. A total of six people (five physiotherapists with differing levels of experience and one clinical movement scientist) independently examined each report and three users again examined the reports a week later. Users were told to note whether they believed a movement alteration was present for each parameter by writing down either 'yes' or 'no.' They were instructed to text-describe any altered pattern they believed to exist. Then, quantitative content analysis was utilised to categorise the written text on the movement alteration and describe it (Button et al. 2022). Their results indicated good agreement, with between-user agreement ranging from 0.6-0.9 for the sagittal plane and from 0.75-1.0 for the frontal plane for the presence of a movement alteration. The within-user agreement was 0.57-1.00 for the sagittal plane and 0.71-1.00 for the frontal plane.

As for describing the identified alteration and results of the content analysis, there was variation in terms of how movement alterations were described. However, three main themes and seven categories were identified from the waveform interpretations: the amount (qualitative and quantitative description), timing (phase, discrete-time point, cycle) and nature (peak, ROM, timing) of the alteration. Based on their results, a standardised reporting template for the interpretation of movement analysis reports was developed (Button et al. 2022).

It is important to note that there were several limitations with this study. For instance, most rater disagreements regarding the detection of altered movement patterns were observed for kinematic waveform graphs in the sagittal plane, as opposed to the frontal plane. This was because the kinematic data for several planes were displayed using various scales and, therefore, frontal plane waveforms appeared to be more obvious for raters than those used for the sagittal plane. While the results from this study are distinctive because users had to identify kinematic waveforms with and without movement alterations and describe how they interpreted the data, which had not been examined in previous studies, the users were not provided with any instructions regarding how to interpret the data to decide if small deviations in the waveforms should be considered as alterations.

In summary, movement analysis has become a critical component of the rehabilitation process for those people with CKP. Therefore, future studies should focus on how to improve the reporting of data, interpretation and standardisation. These interpreted reports can be observed and referred to multidisciplinary teams such as physiotherapists and doctors in order to provide the best possible treatment options for patients. For this reason, it is crucial that the movement analysis reports are precise and provide complete answers to the clinical queries. However, it can be concluded from the literature that there is no standardised method for reporting kinematic data.

2.8.1 Section summary

Rapid technological advances have enabled the development of precise and reliable equipment as well as new methods for objectively assessing numerous functional movement characteristics, thereby offering physiotherapists a plethora of knowledge about an individual's movement. Graphics make data easier to interpret and many of these systems also create databases and allow users to access data files. These elements can be used to generate a movement analysis report that can be evaluated and analysed to discover altered movement patterns, aid physiotherapist decision-making and individualise treatment strategies. However, the literature is lacking in terms of how physiotherapists evaluate altered movement patterns. There is no standard means of interpreting movement. In the literature, some research studies concentrated on identifying movement alterations, whilst others focused on describing them. However, for both of these, there is no consensus regarding what constitutes the optimal method. Future research in this area should seek to standardise the reporting of waveform data in movement analysis and identify interactive user-friendly reporting tools.

Table 6: Summary of studies reporting movement analysis and alterations

Authors/ date	Aim	Design	Subjects	Method	Key findings	Limitations
Button et al. (2022)	To create a standardised template that will help physiotherapists to report data from lower limb kinematic waveforms.	Inter-rater and intra-rater agreement for identification of movement compensation strategies (reliability). Quantitative content analysis to describe alteration.	14 patients with ACLR. 6 raters with different levels of experience.	Wearing body-worn sensors, 14 people with anterior cruciate ligament reconstruction undertook stair climbing, double-leg squats and overground walking. 252 kinematic waveforms of hip, knee and ankle joint angles in the sagittal and frontal planes were inspected by six users.	The observed inter-user agreement for the presence of a movement compensation ranged from 0.60 to 0.90 in the sagittal plane and from 0.75 to 1.00 in the frontal position. Within-user agreement for the sagittal plane was 0.57-1.00 and for the frontal plane, 0.71-1.00. The waveform interpretations revealed three themes and seven categories: amount (qualitative and quantitative description), timing (phase, discrete time point, cycle) and nature (peak, ROM, timing). An interactive report and a standardised template for interpreting kinematic waveforms were developed.	No instructions were provided to users regarding how to determine the presence of an alteration. As a result of variations in the scales employed to represent the data in the sagittal and frontal planes, disparities in the waveforms of comparable magnitude in the frontal plane seemed more obvious to the user and were thus more likely to have been considered as an altered strategy.

Wang et al. (2019)	To evaluate the interobserver reliability of (3DGA) interpretation for children with gait abnormalities within a single institution.	Inter-rater agreement/ reliability.	15 patients (14 with CP, 1 with myelodysplasia). 7 experienced raters.	7 skilled interpreters reviewed the 3DGA data of a single patient every 3 months. The data of 15 patients were interpreted and the interpreters were asked to choose 'yes,' 'no' or 'indeterminate.' Calculations of kappa and percentage of agreement were used to assess consistency.	The average kappa for the ten most common problems and suggested solutions were 0.69 and 0.59, respectively. Hip and knee anomalies had the most consistency in the sagittal plane.	No intra-observer variability analysis was performed. Only 15 patients' data were analysed.
Nieuwenhuys et al. (2017)	To measure physician inter-rater/intra-rater agreement on joint movement patterns in children with spastic cerebral palsy (CP).	Inter-rater and intra-rater agreement/ reliability.	82 patients with CP (57 males, 25 females). 16 'experienced' and 16 'inexperienced' rater groups based on their experience with 3DGA.	2 classifications of 3DGA results from 27 or 28 patients were requested from each rater. Using the percentage of agreement and kappa statistics, inter- and intra-rater agreement on 49 joint motion patterns was assessed.	For all joints, intra-rater agreement ranged from "substantial" to "almost perfect" (K= 0.64 - 0.91). The results of the inter-rater agreement were similar (K= 0.63 - 0.86), except for the knee patterns during stance (K= 0.49, "moderate agreement").	4.7% of all ratings for all patterns were determined to be unclassifiable, with hip patterns in all three anatomical planes accounting for the majority of these scores. The learning phase of the study was uncontrolled and purposely brief. This lack of standardisation could have resulted in decreased interrater agreement for criterion classification. The joint movement patterns tested in this investigation were the outcome of a Delphi

						consensus study which relied on the knowledgeable but subjective judgement of specialists.
Fellin et al. (2010)	To evaluate the hip, knee and rearfoot 3D kinematics of overground and treadmill runners using both kinematic curve and discrete variable comparisons. Compare kinematic curves during stance phase using the trend symmetry method within each subject.	Exploratory and correlation.	20 healthy runners.	20 runners were observed running at 3.35 m/s 5% on a treadmill and overground while right lower extremity kinematics were captured using 3D. Utilising intraclass correlation coefficients, the kinematics of the hip, knee and rearfoot during foot strike and peak were compared.	Most of the kinematic curves between OG and TM running appeared to be similar. The trend symmetry analysis supported the visual evaluation by demonstrating that all kinematic curves had a mean trend symmetry value of 0.94. Lower similarity was observed between the knee frontal plane and transverse plane (0.86–0.90). All variations were less than 1.5˚, except for a 4.5˚ decrease in rearfoot dorsiflexion at foot strike during treadmill running. There were 8/18 discrete variables with high correlations (>0.8) and 17/18 discrete variables with moderate correlations (>0.6).	The method does not specifically deal with the waveforms' variability. For data that are extremely changeable, this approach can return results that are not indicative of the actual data.

Crenshaw and Richards (2006)	To analyse symmetry and normalcy of gait patterns using eigenvectors to compare the entire selected waveform.	Exploratory study.	1 subject. A group of healthy participants for comparison.	To determine symmetry, the right and left limbs of a single person were compared. A single subject's limb was compared to a normative file made from the average of the healthy control participants to determine normalcy. The 4 metrics of symmetry and normality provided by the analytical approach are trend phase, trend symmetry/normalcy, range amplitude ratio, and range offset.	The same ROM is used by both sides when the range offset value is 0 (positive values indicate increased flexion, negative values indicate increased extension). For range amplitude, a value of 1 indicates that each curve has the same ROM (>1 indicates increased ROM; <1 indicates decreased ROM). For trend symmetry, if the curves were the same shape, the score would be zero (the larger the trend symmetry, the greater the difference in the shape of the curves).	Sagittal plane only. No details for the number of healthy participants used for comparison. The method described for determining joint symmetry and normality is only suitable for waveform data; it cannot be used to determine symmetry for discrete data points.
Brunnekreef et al. (2005)	To assess the reliability of visual gait analysis in patients with orthopaedic problems.	Inter-rater and intra-rater reliability.	30 patients with orthopaedic impairment. 10 raters: 4 experienced, 4 novice and 2 experts.	Patients had their gait videotaped. Using a standardised gait analysis form, ten raters analysed the videotaped gait patterns of the patients twice. Reliability was measured using the intraclass correlation coefficient (ICC),	Moderate between- and within-rater agreement. Between experienced raters, ICC = 0.42. Between novice raters, ICC = 0.40.	Different study population (multiple orthopaedic conditions). Videos were condensed into a one-minute film-clip for analysis; a short period that may have led to items being difficult to observe.

				calculated using a two-way random design and based on absolute agreement.	Within experienced raters, ICC = 0.63. Within novice raters, ICC = 0.57.	Objective standard to assess the validity of raters' visual observations was not accomplished. Visual observation using video footage.
Manal and Stanhope (2004)	To present a different approach to reporting movement pattern alterations in comparison to normative data by colour-coding the size and direction of the difference to improve visualisation.	Exploratory study.	1 patient. 15 healthy subjects to compare.	To illustrate the use of colour coding, gait data from one patient with impaired gait were compared to normative data for 15 healthy people. During the stance phase of walking, the sagittal plane ankle, knee and hip angles and moments were calculated using Visual3D. The variables of 101 data points representing 0% to 100% of the stance phase were interpolated.	The deviations shown were successfully converted from a vertical spatial dimension to a colour-based range using the colour-coding technique. This significantly minimises the amount of space needed to show how far the patient's data deviates from the norm in both size and direction. Shades of red represent significant negative deviations in the patient's ankle angle during first stance, whereas shades of yellow and green represent an increasing normal pattern.	Alterations were only presented as colours ranging from red (increased alteration) to blue (normal) without the ability to establish the joint angle at the point of alteration. The sign convention association with the anatomical motion of the joint was different for some joints than in the majority of the reported literature (e.g., knee flexion was a negative value and shaded red). The range of the reported alteration was limited to ±3.

Abbreviations: ICC = Interclass correlation coefficient; CP = Cerebral palsy; 3D = Three dimensional; ACLR = anterior cruciate ligament reconstruction; DGA = Dynamic gait assessment; OG = overground; TM = treadmill.

2.9 Literature review summary

Chronic knee pain is one of the leading causes of disability and activity limitation. It represents a substantial burden for individuals, society and the healthcare system. Multiple aetiologies can induce or exacerbate CKP. Some individuals with CKP do not respond favourably to conservative PT management. It has been suggested that the reduced success of typical therapy treatments in terms of their ability to alleviate pain and improve function may be attributable to the presence of certain movement alterations (Kobsar et al. 2015; Watari et al. 2016). Thus, the pain might result in a range of motor alterations, from small adjustments in muscle activity to movement avoidance (Hodges and Tucker 2011).

Kinematic analysis provides valuable information about joint motion and movement patterns during various functional tasks which are directly relevant to the daily activities and challenges faced by individuals with CKP. Understanding kinematic alterations can help to identify specific movement deficits and guide interventions to improve functional performance. The associations between pain and the movement system are complex and often fluctuate. The hypotheses posit that pain can incite diverse motor alterations such as increased or reduced muscular activity (Roland 1986; Henriksen et al. 2011), altered movement patterns and restricted motion (Hodges and Tucker 2011). These alterations are affected by both peripheral and central mechanisms and can provide short-term protective benefits yet they may engender prolonged functional constraints and amplified pain. By understanding movement alterations, physiotherapists can develop targeted interventions that address specific impairments, restore optimal movement patterns and alleviate pain, thereby ultimately improving functional outcomes for patients. Thus, taking a more individualised approach to exercise prescription could prove more beneficial for the CKP population by targeting these alterations.

Accordingly, movement alterations were investigated in three planes of motion during various functional activities which present different challenges for the knee and are necessary for everyday life. Several movement alterations were identified in the literature which necessitate the need for individualised treatment plans. Movement analysis aims to comprehend the reason for altered movement patterns, thereby aiding in the prevention, detection and rehabilitation of a broad spectrum of diseases, disabilities and injuries. However, movement analysis is complex because it produces considerable volumes of kinematic data in three planes of motion (sagittal, frontal and transverse) across numerous joints and the complexity of tasks varies according to the individual's functional needs. Physiotherapists can use movement analysis reports generated by motion capture systems to identify abnormal movement patterns, make decisions and develop individualised therapy regimens. Therefore, the motion capture systems required for movement analysis were scrutinised. Optoelectronic motion capture systems provide 3D measurements and they are regarded as the gold standard (Munro et al. 2012). Whilst they offer significant advantages, these systems are costly, their application is highly complex and their configuration is time-consuming (Schurr et al. 2017). Therefore, it may be challenging to install these systems in clinics. Moreover, optoelectronic systems are limited to laboratory surroundings and may be unable to accurately simulate outdoor activities. The commonly available camera-based 2D movement analysis method may be utilised as an alternative to the gold standard motion capture devices to generate movement data in clinical settings (Alahmari et al. 2020). However, because of the inconsistent validation findings, the merits of 2D movement analysis have proven to be debatable (Neal et al. 2020).

IMUs are an alternative technology. It has been determined that IMU-based movement analysis is accurate and consistent when assessing kinematics for all planes during various functional tasks (Al-Amri et al. 2018). In clinical contexts, the IMU-based movement analysis method is therefore the most suitable alternative to the gold standard motion capture systems. However, IMU-based movement analysis generates a large amount of kinematic data in the three anatomical planes, thereby making it very challenging for physiotherapists to interpret them. In clinical practice, it is the responsibility of the individual reporter to decide if an ‘observed difference’ is sufficiently large to be clinically significant. There are no published criteria for the knee to state what is or is not an important alteration in movement. To improve the uniformity of kinematic data interpretation among users, there is a need to standardise the method for reporting altered movement patterns in kinematic waveform graphs. Reporting movement alterations through statistical summaries can be constructed to provide a quantitative description of motion, but visually examining the waveforms of movement cycles that is individualised for each person provides extra information on how an individual performs throughout a task, which is more applicable for clinical settings and can be used to guide tailored therapy choices. Previous research presented in the literature has emphasised the need to develop online reporting tools that are user-friendly to help physiotherapists facilitate the individual assessment and management of those experiencing CKP conditions. Accordingly, the current thesis sets out to address the following aims:

2.10 Thesis aim

The overall aim of the thesis is **to explore the utility of individualised IMU-based clinical movement analysis for those with CKP.**

2.10.1 Part 1 aim

To explore the between- and within-subject kinematic differences of those with CKP and healthy people during various functional tasks including gait, DLS, SLS, VJ, SA and SD in the sagittal and frontal planes for the hip, knee and ankle joints using clinically available IMUs.

2.10.2 Part 2 aim

To test the usability of a digital version of an IMU-based movement analysis and reporting tool for physiotherapists treating individuals with CKP.

It is important to note that the word '**utility**' in the current study's topic and aim refers to the two parts in this thesis. In part one, altered movement patterns were explored and movement was analysed during the performance of functional tasks **utilising** IMU kinematic reports and a standardised reporting template to inform PT practice. In part two, the usability (another meaning for the word **utility)** of converting IMU kinematic reports to an interactive electronic version and making them available online for physiotherapists to use was also explored.

Chapter 3, Part 1: Movement alterations in individuals with chronic knee pain and in healthy people using inertial measurement units and a standardised reporting template

3.1 Introduction

This study is linked to previous works carried out by our research team on the development of the sensor-based movement analysis and reporting toolkit, as well as the standardised reporting template. Therefore, providing a summary of previous works conducted for the development of the toolkit and the template is crucial to providing a comprehensive view of what has been done and informing the next stages.

Multiple studies were conducted by members of our research team, including PhD students (M.F.) and (K.N.), to develop a movement analysis toolkit that is provided by the portable inertial sensors. As a result, an ergonomic, rapid, and accessible movement analysis kinematic report was created in accordance with the instructions presented by Baker (2013). This was meant to promote the use of sensor-based 3D systems among users and provide access to kinematic testing for those with CKP. The kinematic report was developed employing custom-written code on MATLAB software (version 9.6.0.1150989 (R2019a) Update 4) (Nicholas et al., 2018; Davies et al., 2021). The report represents kinematic data (temporo-spatial and joint angle waveforms) acquired from inertial sensors for joints in the lower limbs (e.g., hip, knee, and ankle) as well as in the sagittal and frontal planes during a variety of functional tasks (Gait, DLS, SLS, VJ, SA and SD). These functional tasks included were rationalised by the previous validation study (Al-Amri et al., 2018) in addition to other literature reviewed concerning the validity and reliability of the sensor-based movement analysis. The kinematic data reported in our report can be interpreted by physiotherapists and patients to guide therapeutic decision making, inform treatment planning, and monitor progress.

As a result of this, a first version of the movement analysis toolkit comprising inertial sensors and a kinematic report was developed. Following this, the PhD candidate (K.N.) conducted two exploratory qualitative studies to assess the initial version of a toolkit's acceptability among physiotherapists and individuals with CKP. The first study involved interviews with physiotherapists to explore their perspectives on the toolkit's suitability within the clinical setting for ACL patients, aiming to refine its design. The second study comprised qualitative interviews with patients before and after utilising the toolkit during their rehabilitation, aiming to understand their experiences and opinions regarding its usage. Findings from the studies revealed disparities in physiotherapists' interpretation of kinematic data and the terminology employed to describe observed altered movement patterns. This uncertainty suggests the necessity for further investigation into the ability of physiotherapists to accurately and consistently interpret supplied kinematic data, thereby highlighting the need for additional research.

To address this, an exploratory study was conducted by another PhD candidate (M.F.) (Button et al., 2022). This study evaluated within and between-rater agreement in identifying the presence of movement alterations within kinematic waveform graphs for lower limb joints (e.g., hip, knee, and ankle) in the sagittal and frontal planes during three functional tasks (Gait, DLS, and SA). Also, raters qualitative description of the identified movement alterations was investigated. The findings exhibited that raters were consistent when identifying movement alterations; however, the way of how they qualitatively describe these alteration was varied. Therefore, a standardised reporting template was created. Using this template can enhance users’ reporting and interpretation of kinematic waveform data in accurate and consistent manner. This template included a series of standardised terminologies arranged into four boxes according to the 3 themes identified in the study by Button et al. (2022) (“Amount”, “Nature”, and “Timing”) and their categories. 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 movement alteration identified. This was followed by integrating and writing the chosen terms in the required space according to the joint and plane of movement analysed.

Users’ agreement of using the developed template to interpret kinematic waveform graphs was then evaluated. This was conducted by members of our research team

(Zhou et al., 2021). The findings revealed a moderate agreement among raters with limited experience in movement analysis, which suggested consistent users' reporting of the movement alterations identified in waveform graphs.

These preceding works had led to a modified version of the sensor-based movement analysis toolkit containing inertial sensors and a movement analysis kinematic report, which was used alongside the standardised reporting template. **In Part 1 of the thesis, this modified version of the toolkit was used alongside the standardised reporting template to identify altered movement patterns in individuals with CKP.** This was achieved by achieving the following aim and objectives:

3.1.1 Aim and objectives for Part 1

Aim

- To **explore the between-group and within-subject kinematic differences of people with CKP and healthy people during various functional tasks including gait, DLS, SLS, VJ, SA and SD in the sagittal and frontal planes for the hip, knee and ankle joints using clinically available inertial measurement units (IMUs).** This was achieved by achieving the following objectives:

Objectives

- Performing a **structured clinical interpretation (SCI) of kinematic data** by kinematic analysis of waveform data for people with CKP and healthy people in the sagittal and frontal planes using previously developed IMU kinematic reports (Davies et al. 2021) and a standardised reporting template (Button et al. 2022) for gait, DLS, SLS, VJ, SA and SD.

It is important to note that the SCI of kinematic data involved a descriptive analysis of the entire waveform graphs. This method utilised a standardised (structured) reporting template tailored for each individual participant. Utilising descriptive waveform analysis can uncover subtle individual differences which might otherwise remain undetected if the data were averaged at discrete time points, thereby enabling rapid evaluation and improved clinical decision-making for PT.

- To conduct **standard quantitative analysis (SQA) of kinematic data** to evaluate differences in kinematics within and between subjects with CKP and healthy people for gait, DLS, SLS, VJ, SA and SD in the sagittal and frontal planes for hip, knee and ankle.

It is important to note the SQA of kinematic data focused on the examination of specific datapoints within the movement cycle. Utilising conventional statistical tests such as t-tests, this analysis method allows for the comparison of discrete time points to evaluate differences or similarities in the kinematic parameters.

To explore these objectives, the study was conducted outside of the movement laboratory in a non-controlled environment. First, the method and protocol of the study will be reported. Then, the data analysis will be explained. Finally, ethical considerations are introduced.

3.2 Materials and methods

3.2.1 Research design

A between-groups and within-subjects study design was applied in a non-controlled environment to identify differences in lower limb joint kinematics during the gait, DLS, SLS, VJ, SA and SD used by patients with CKP compared to healthy individuals undertaking the same functional tasks. This design was selected because of its ability to identify movement characteristics (Portney and Watkins 2015).

The between-group design implies that differences in conditions occur across groups of subjects rather than within a single subject across conditions. The goal of a between-group design is usually to test if the groups differ significantly from one another (Oeldorf-Hirsch 2017). In the current study, the movement patterns of people with CKP were compared to those of individuals who do not experience knee pain.

The benefits of this design include the following: the results are more generalisable to the population due to the use of a variety of participant groups and it eliminates the possibility of order effect which occurs when the order of conditions influences the outcomes (Bordens and Abbott 2002).

The within-subject study design requires data collection from the same group of participants under different conditions. In the current study, the movement patterns of individuals with and without CKP were investigated on their injured/dominant and uninjured/nondominant legs. This design offers various benefits. For instance, employing the same participants in multiple situations while performing different tasks allows for better control of individual variables such as age, gender and the level of physical activity (Portney and Watkins 2015). Moreover, the lack of variability between the participants increases the statistical power as well as the capacity to identify changes. Because the same participants are utilised, a smaller sample size is required to achieve statistical significance. Finally, by employing the same participants in multiple situations, confounding variables which could influence the results (e.g., environmental factors) are eliminated (Charness et al. 2012; Portney and Watkins 2015).

3.2.2 Ethical approval

The current study was conducted as part of Biomechanics and Bioengineering Research Centre Versus Arthritis (BBRCVersusArthritis) initiative at Cardiff University and received ethical approval from the Wales Research Ethics Committee 3 (10/MRE09/28). All of the participants provided written informed consent.

3.2.3 Setting

The current study was conducted at the School of Healthcare Sciences in Ty Dewi Sant (TDS), Cardiff University, United Kingdom. Regular classrooms were booked and organised for research purposes. This setting was selected because IMUs is a motion capture technology which does not require markers and is a wearable device that does not require extensive and/or controlled laboratory preparations. Therefore, it can be used as an alternative to the expensive marker-dependent 3D motion capture technologies that cannot be performed outside of laboratory settings (Kim et al. 2021).

3.2.4 Sample size

A power calculation was determined for the current study using G*power version 3.1.9.2 (Faul et al. 2009) where (α)= 0.05, the effect size = 0.9 and the power of 1 - ß is 95%. This resulted in 28 participants in each group. The alpha level (0.05) was selected because it is the most common number used in the majority of the previous academic research (Toutenburg 1974). The power of the study was chosen based on the fact that the ideal study is one with higher power, which means that the possibility of detecting the existing differences between groups is high (Suresh and Chandrashekara 2012). Also, a power of 80% or more is considered to be the perfect power for any study (Hintze 2008; Suresh and Chandrashekara 2012).

3.2.5 Recruitment procedures

3.2.5.1 Recruitment strategies for people with chronic knee pain

People with CKP were recruited using various strategies, as follows:

1. Members of staff and students from Cardiff University were recruited via an invitation letter which described the study. This letter was distributed via the Yammer online networking service which is an enterprise social networking service included in the Microsoft 365 product bundle. It is primarily used for private communications within organisations but also for inter-organisational networks. Anyone interested in participating was able to contact the researcher via email and express their interest. The researcher then contacted them to provide them with a participant information sheet and to provisionally book an appointment for them.

2. CKP participants were also recruited from a patient and public involvement (PPI) event organised by the Biomechanics and Bioengineering Research Centre Versus Arthritis. Invitation letters were distributed to the attendees and those who expressed an interest were asked to complete a permission to contact form during the event. The researcher then contacted them via email to provide them with the relevant information sheet and to book an appointment for them.

3.2.5.2 Recruitment strategies for healthy individuals

Healthy participants were recruited from the general population in addition to volunteers who were hospital staff, university staff and students. They were recruited using the following procedure:

1. Adverts were placed on Yammer providing a brief description of the study, the procedures and contact information. Individuals who were interested in taking part contacted the lead researcher. They were then sent a participant information sheet as well as a permission to contact form and they were contacted to book an appointment.

2. Study posters were also displayed around Cardiff University (see Appendix B). These included an invitation and a brief description of the study with accompanying pictures and contact details. Interested participants then contacted the lead researcher via email. A participant information sheet (see Appendix C) and permission to contact form (see Appendix D) were then sent to them and they were contacted to book an appointment.

3.2.6 Study inclusion and exclusion criteria for people with CKP

The CKP population in this study was defined in detail in Section 2.3.1. Most of the inclusion criteria for the CKP group were determined according to the recommendations made by Bennell et al. (2012b), which were as follows:

Inclusion criteria

- Adults aged 18+ years. The current study sought to investigate participants with CKP and was not limited to the OA population.
- Males and females experiencing CKP not related to injury or surgery for more than 3 months and on most days during the previous month.
- Experiencing activity-related joint pain.
- Able to understand written English or Welsh language.
- Able to provide consent.

Exclusion criteria

- Patients with pathologies that impair walking.
- Lower limb neurologic deficits, injuries, or surgeries.
- Spinal pain (individuals will be excluded from the study if their primary complaint is back pain and not knee pain). The reason for this exclusion criterion is that in many knee conditions, individuals may experience back pain as a comorbidity (Suri et al. 2010), thereby meaning that back pain can coexist with knee pain. This could potentially confound the results. Consequently, altered lower limb kinematics observed in these participants may be attributed to their back pain rather than their knee pain (Rahbar et al. 2015).
- Refusal to sign the consent.
- Allergy to adhesives.

3.2.7 Study inclusion and exclusion criteria for the healthy individuals

Inclusion criteria

- Adults aged 18+ years.
- No history of chronic or acute lower limb or spinal pain in the previous 6 months.
- No previous history of knee injury for in the previous 6 months or surgery in the previous 12 months.

- Participants who have no activity restricting conditions such as neurological compromise, knee ligament instability, evidence of rheumatoid or any other type of arthritis, prolonged knee pain that required medication or knee surgery (Kianifar et al. 2017; Gök et al. 2002).
- No allergy to adhesives.
- Able to understand written English or Welsh language.
- Able to provide consent.

Exclusion criteria

- Subjects currently experiencing spinal pain or who have undergone lower limb surgery in the previous 6 months.
- History of hip and/or knee joint replacement.
- Any joint condition affecting lower extremity function.
- Inability to walk without an assistive device.
- Pregnant subjects.

3.2.8 Instrumentation and equipment

The movement analysis tool involved 3D IMU sensor-based movement analysis using the Xsens MVN Awinda system (version 2019.0, Xsens Technologies, Enschede, The Netherlands). The kinematic data were collected at a frequency frame rate of 60 Hz, using the Xsens MVN Analyze software package.

The MVN Awinda system comprises the following (see Figure 4):

- 17 (+1 spare) wireless motion trackers (MTw).
- 1 Awinda station.
- 1 Awinda dongle.
- 2 Awinda chargers.
- MTw full-body Velcro straps including 3 shirts, a headband, footpads, 2 pairs of gloves.

- 1 Segmometer.
- Quick setup sheet.

The MTw provides 3D acceleration, 3D angular velocity, atmospheric pressure, and 3D earth magnetic field data. These are crucial to ensure accurate movement analysis. The Awinda Station and USB dongle receive synchronised data from the MTw units. MVN Studio (controlled by MVN Analyze) is the software displaying real-time and recorded 3D movement data. All of these components are essential to ensure comprehensive movement analysis results.

A digital weighing scale (model 862, SECA Ltd., Medical Scales, Birmingham, UK) was used to measure the participants’ weight in kilograms (Kg) and a stadiometer was employed to measure their height (Marsden HM-250P Leicester Portable Height Measure, UK) in centimetres (cm). Furthermore, a laptop (HP Envy x360, HP Inc., Palo Alto, California, USA) was used for the data collection and system setup. A privacy screen was provided for the subjects to change their clothing.

xsens

2.5 MVN Awinda backpack/suitcase with contents

The MVN Awinda arrives in durable backpack with protective frame, which contains:

- 18 Wireless Motion Trackers (MTw)
- 1 Awinda Station
- 1 Awinda Dongle
- 2 Awinda Chargers
- MTw full body Velcro straps, including 3 shirts, headband, footpads, 2 pairs of gloves
- 1 Segmometer
- Quick Setup sheet

Suitcase containing the MVN Awinda System

2.6 Motion Tracker (MTw)

Like the MTx, the MTw is a miniature inertial measurement unit containing 3D linear accelerometers, 3D rate gyroscopes, 3D magnetometers, and a barometer. Additionally each MTw contains an internal battery. The trackers are placed at strategic locations on the body (secured by the straps), to measure motion of each body segment. For more details about the MTw, see Section 5.7.1.

Motion Tracker (MTw)

nda Station

Awinda Station

: Awinda USB Dongle

Document MV0319P.N

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MVN User Manual

Figure 4: MVN Awinda suitcase and contents (MTw, Awinda station, USB dongle) adapted from Xsens Technologies B.V. (2021).

3.2.9 Outcome variables

Kinematic outcome measures in addition to the self-reported outcome measures of pain and function which were investigated in the current study are explained in the next section.

3.2.9.1 Kinematic variables

Range of motion (ROM) during the whole movement cycle and the joint angle at peak knee flexion (PKF) were collected and compared for each of the predetermined activities (gait, DLS, SLS, VJ, SA and SD), each joint (hip, knee and ankle), each plane of movement (sagittal and frontal) and each side of the body (right and left). For gait, SA and SD trials, the joint angle at heel strike (HS) was also identified.

3.2.9.2 Self-reported measures

The Knee Injury and Osteoarthritis Outcome Score (KOOS) questionnaire was administered to determine the individuals' self-rated assessment of their knee health and problems. The Numeric Pain Rating Scale (NPRS) was used to explore the pain severity of the CKP population.

3.2.9.2.1 Knee Injury and Osteoarthritis Outcome Score

The KOOS (see Appendix E) is a valid and reliable knee-specific tool which was developed to determine patients' opinions of their knees and related issues (Roos and Lohmander 2003). It was developed for use with knee injuries or knee OA in a young and active group of patients. KOOS can be used with individuals aged between 13-79 years and it is suitable for both short- and long-term follow-up assessments of various knee pain conditions, including OA (Roos and Lohmander 2003). This allows for a more holistic assessment of a patient's knee-related health status, regardless of the specific knee condition they are experiencing (Roos and Lohmander 2003).

The questionnaire claims to capture a wider range of patient-relevant functional capabilities using subscales include leisure and daily living activities. The KOOS assesses both the short- and long-term consequences of knee injury. It contains 42 elements in five separately graded subscales: pain (nine items), other symptoms (seven items), daily living function (ADL) (17 items), sport and recreation function (five items), and knee-related quality of life (QOL) (four items) (Peer and Lane 2013).

The KOOS scoring system uses a five-point Likert scale, ranging from zero (no problems) to four (extreme problems), and each of the five scores shall be measured as the total of the included items. The ratings are converted to a scale of 0-100, with zero representing extreme knee problems and 100 representing no knee issues. The KOOS does not compute an aggregate ranking and it is instead necessary to interpret each sub-scale separately (Collins et al. 2016; Peer and Lane 2013; Roos and Lohmander 2003).

3.2.9.2.2 Numeric Pain Rating Scale

The validity and reliability of the NPRS (see Appendix F) as a measure of pain have been extensively documented in the literature (Williamson and Hoggart 2005; Boonstra et al 2008; Hjermstad et al 2011). The NPRS, as described by Hawker et al. (2011), is an eleven-point ordinal scale in which zero denotes "no pain" and ten signifies "extreme, unbearable pain." Mild pain is classified as scores one to three, moderate pain as scores four to six, and severe pain as scores seven to ten (Goulet et al. 2015).

Individuals with CKP were requested to rate the severity of their knee pain during periods of rest over the preceding week by placing a mark on a pre-designed scale (Hjermstad et al. 2011) to answer the following questions:

- On a scale of zero to ten, with zero being no pain at all and ten being the worst pain imaginable, how would you rate your pain RIGHT NOW?
- On the same scale, how would you rate your USUAL level of pain during the last week?
- On the same scale, how would you rate your BEST level of pain during the last week?
- On the same scale, how would you rate your WORST level of pain during the last week?

3.2.10 Study protocol

3.2.10.1 Venue preparation

Before the subjects arrived, the classroom was prepared to ensure that there was sufficient space to perform and record the trials and to set up all of the equipment listed in Section (3.2.8). The following activities were selected: gait, DLS, SLS, VJ, SA and SD. Justification for the chosen activities was provided in Section 2.7. All of the tasks were performed in the classroom except for the gait, SA and SD. Gait was performed in a long corridor close to the classroom where sufficient space was available. The participants performed SA and SD on the building's staircase located just beside the corridor. The area was blocked off to non-participants for the duration of the trials.

The researcher took precautions to ensure the accuracy of the data by checking the room for any magnetic fields which could interfere with the motion tracker's orientation estimates and affect the quality of the data (Seel and Ruppin 2017). This check was performed once during the piloting phase before starting the actual data collection. Magnetic disturbances are common in indoor and outdoor environments and can particularly affect the inclination of the motion tracker's orientation estimates (Jambrosic et al. 2020). However, it was found that there were no magnetic disturbances in the area selected for this study.

3.2.10.2 MVN system software setup

To identify differences in lower limb joint kinematics, 17 IMUs were attached to the participants' bodies by one researcher (RA), in accordance with the Xsens guidelines (Xsens Technologies B.V. 2021). IMUs were secured in place using elastic Velcro straps which consist of a non-latex composite material. The IMUs were positioned as follows (see Figure 5): one on the head; one over the sternum in the middle of the chest; two at the back on the superior border of each scapula (shoulder blades); two on both upper arms on the lateral side above the elbow; two on both forearms just above the wrist; two on both hands flat on the dorsal side. For the lower limbs, two were placed in the centre of both upper thighs between the greater trochanter and lateral epicondyle of the knee; two on both lower legs flat on the shin bone proximal and medial to the surface of the tibia; and two on the middle of the dorsum of the feet. One sensor was placed centrally on the sacrum (L5, S1), with the upper border of the sensor in line and centred between the right and left posterior superior iliac spine. The sensor on the sacrum was stabilised using 3M™ Tegaderm™

Transparent Film Roll dressing double-sided adhesive tape to secure the sensor in place because this is gentle on the skin and a comfortable dressing that stretches with the movement of the skin (3M 2019).

The software setup stage consists of three parts: the body dimensions of the subject; the fusion of data (the process of combining information from multiple sensors to achieve a more accurate and complete understanding of the subject's movements or orientation); and sensor-to-segment calibration. To quantify the body segments, the body measurements of the subjects must be given as inputs for the complete body configuration model in the MVN program (Roetenberg et al. 2007a). When attaching the sensors, the initial pose between the body segments and sensors is unknown. Hence, it is difficult to assess the distances between the body segments by numerical integration. Accordingly, a calibration procedure must be performed to determine the sensor-to-body dimensions and body alignment (Roetenberg et al. 2007a).

Figure 5: MVN straps adapted from Xsens Technologies B.V. (2021)

3.2.10.3 System calibration

System calibration is required to align the IMU sensors with the subject segments to ensure accurate and high-quality data collection (Xsens Technologies B.V. 2021). Using the IMUs, a dynamic calibration procedure was performed in accordance with the manufacturer's instructions to improve the accuracy of the sensor data during use (Xsens Technologies B.V. 2021) and this is described below:

Calibration procedure step 1: The subjects stood in a neutral position (N-pose) with the body upright and head looking forwards, feet parallel and pointing forwards with the arms close to the body. They held this position for approximately 20 seconds (see Figure 6). Step 2: The subject was asked to walk at their normal pace for a distance automatically determined by the system on the screen. They were then asked to turn around and walk back, before finally returning to the starting position of the static N-pose until the calibration process was complete. Step 3: The quality of the calibration (good, acceptable, poor or fail) was checked in the system which automatically started processing the recording to obtain the calibration results. Following the application of the calibration, the participants were instructed to walk around slowly and freely for approximately 30 seconds to warm up the engine. After confirming that the calibration procedure had been successful by examining the resulting quality and comparing the actual participant's movement performance to that of the avatar (a 3D visual representation of the participants' movements) and providing real-time feedback during the data collection process, data collection could begin. While avatars themselves are not the direct outcome of the current study, they play a crucial role in facilitating accurate motion capture and data collection. Disruptions to the avatar's display could lead to misalignment between the participant's actual movements and the captured data which might compromise the reliability of the captured data. If calibration is unsuccessful, recalibration is required.

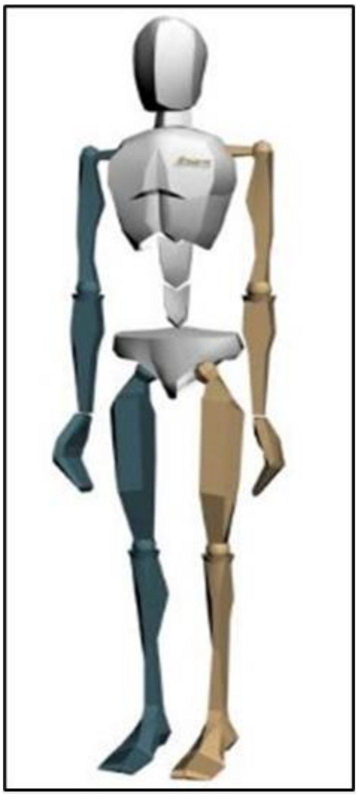


Figure 6: Static N-pose adapted from Xsens Technologies B.V. (2021)

3.2.10.4 Experimental procedure

All of the participants were invited to attend one movement analysis session. On the day of the session, the subjects were welcomed and a hard copy of the information sheet that had been sent to the participants via email was provided, followed by an explanation of the study procedures. The participants were able to ask any questions before and during the trials, if needed. The participants were provided with a written consent form to sign. The subjects were informed that they have the right to withdraw from the experiment at any time without needing to provide any explanation for their decision and that their data would not be used in any other studies without their permission.

The participants were asked to remove their shoes so that they could have their measurements taken and perform the tasks barefooted. Then, baseline sociodemographic data, namely, age, sex, body height (in centimetres (cm)), and weight (in kilograms (kg)) were collected by the researcher. The participants then changed their clothes and wore comfortable non-restricting clothing such as tight leggings or shorts. They were also provided with a t-shirt that comes with the sensor toolkit in three sizes with a zip-fastening. This was provided to the participants based on their size to ensure a tight fit. These t-shirts were washed in between each data collection session to prevent any possibility of cross infection. The t-shirt features Velcro patches to secure the shoulders and sternum in place (Robert-Lachaine et al. 2017). The participants were also provided with a headband and gloves to ensure reliable and easy placement of the head and hand sensors.

At the beginning of the session, the lead researcher (RA) took the anthropometric measurements including shoulder height and width, arm span, hip height and width, knee height, ankle height and foot length in the standing position using a Xsens measuring tape (Xsens Technologies, Enschede, The Netherlands). The measurements were then entered into the MVN software (see Table 7). This information was needed to develop a body configuration model in the MVN software which allowed the segment of the body to be quantified (Roetenberg et al. 2007b).

Table 7: Measurements needed for subject dimension input

Body measurements (cm)	**Description**
Body height	From the ground to top of the head when standing upright.
Foot size	From the back of the heel to the front of the toe.
Arm span	From the top of the right fingers to the top of the left fingers in T-pose.
Hip height	From the ground to the most lateral bony prominence of the greater trochanter.
Knee height	From the ground to the lateral epicondyle on the femoral bone.
Ankle height	From the ground to the distal tip of the lateral malleolus.
Hip width	From the right to the left anterior superior iliac spine.

Shoulder width	From the right to the left distal tip of acromion (acromial angle).
Shoulder height	From the ground to the tip of acromion.

Cm= Centimetres

After attaching the IMUs and conducting the calibration, the researcher gave a verbal explanation of the activities that needed to be undertaken: DLS, SLS, VJ, gait, SA and SD. The order of the tasks was standardised as follows: DLS, SLS, VJ, gait, SA and SD. Before each activity, they received instructions regarding how to perform the movement but no specific instructions in terms of how this should be achieved (for example, no details regarding how fast to walk, how deep to squat, etc.). For DLS, starting from the standing position, the participants were asked to perform eight squats (Kwong et al. 2020; Severin et al. 2019) by bending both knees to the extent they found comfortable. For SLS, the participants were asked to start the SLS with their right leg fixed on the floor and they were asked to go down by bending their right knee and lifting the other one whilst remaining in their comfort zone without specific instructions with regards the depth of the squat and whilst trying to maintain their balance as best they could. The same technique was performed for the left leg. Eight trials were performed for each leg (Kwong et al. 2020; Severin et al. 2019). For VJ, the participants started from the standing position and they were asked to perform eight VJs in their own way to the maximum height. For gait, the subjects performed two gait trials along a straight flat corridor at a speed of their choice. The distance for gait was pre-determined by the lead researcher (RA) using two traffic cones based on the available space, which was approximately 20 gait cycles for each trial (Tura et al. 2012), starting from the initial contact of one foot with the ground (heel strike) to the moment that same foot made contact again (toe-off) in the subsequent step (Caldas et al. 2017). For SA and SD, the subjects were asked to ascend and descend 12 stairs (each with a height of 17 cm and a depth of 27.5 cm) at their preferred speed without holding the rail, starting with their right limb in a single step pattern.

For each of the functional tasks, a trial was deemed to be a failure if the subject lost their balance, the trial was interrupted, the Xsens software was not configured to record, or the sensors moved. If the test was a failure, it was repeated. In the event that an individual was unable to perform a functional task due to knee pain, no data was gathered.

A data collection sheet was prepared to organise the reporting of the data collection trials and facilitate data analysis (see Appendix G). For every subject, each trial was reported and marked ‘S’ if successful or ‘F’ if failed. Once all of the tasks had been completed, the sensors were removed.

Finally, the individuals were instructed to rest before completing the NPRS and KOOS questionnaires. The scores from these two surveys were used to describe the pain and function levels of the CKP patients. The entire procedure took between 35 and 60 minutes to complete.

3.2.11 Pilot study

A pilot test on four healthy subjects was undertaken to ensure the feasibility of the research procedure, standardise it, check if any amendments were needed to the data collection procedures and to measure the amount of time required to collect the data.

The researcher practiced using the measuring tape to measure the dimensions of the body (as mentioned in Section 3.2.10.4). The researcher also practiced putting on the straps, applying the sensors to the participant’s body, giving the instructions, initiating the calibration, and letting the subject perform the predetermined activities to become familiar with the procedure and the system. It took approximately 10-15 minutes to apply the sensors to the subject’s body, provide an explanation and practice the task prior to recording.

Three issues arose during the piloting and recording of the data in the MVN studio. First, the avatar did not appear correctly on the full screen and was manifested with missing body parts or incorrect orientation. This was solved by ensuring that the MVN studio software was up to date because newer versions featured bug fixes and improved compatibility. Also, issues were encountered when performing a thorough calibration and ensuring that the sensors attached well on the participant's body and functioned appropriately to ensure accurate data capture. Second, difficulties were encountered with regards to saving and processing the data but with practice, this issue was overcome. Third, the walking distance (20 gait cycles) was sometimes found to affect the quality of the data and when the participants walked far away from the computer, the walking avatar was interrupted and the signal was affected, thereby resulting in unnatural jerky movements in the avatar’s movements, making it less representative of the participant's actual walking pattern. Therefore, the solution to this was to position the computer and the awinda station halfway along the walking distance and this proved successful.

3.2.12 Data processing

The data collected using the MVN Analyse software were exported as a *.mvnx file for both groups (healthy and CKP). Each subject in both groups had a specific file with the raw data of the eight saved trials. The MVN Analyse data was reprocessed using a high-definition (HD) mode. It was necessary to reprocess the data in order to collect and integrate the sensor data with the advanced biomechanical models in order to determine the position and direction of the human body segments (Schepers et al. 2018).

Joint angles and segment orientations and positions calculated by the MVN Analyse software were extracted from the *.mvnx file using MATLAB software (Matlab version 9.6.0.1150989 (R2019a) Update 4) (Nicholas et al. 2018; Davies et al. 2021) by uploading the exported (*. mvnx) files. Movement cycles were defined using a custom-written script and then checked manually. Positive joint angles indicate flexion/dorsiflexion in the sagittal plane and abduction in the frontal plane, whereas negative angles indicate extension/plantarflexion and adduction, respectively (Xsens Technologies B.V. 2021).

For gait, heel strike was determined via the anterior-posterior position of the foot relative to the pelvis, as described by Zeni et al. (2009). For DLS and SLS, the beginning and ending points of the movement cycle were defined as the start and end of knee flexion. For SA, the initiation of each movement cycle was indicated by the local minima in the vertical distance between the pelvis and the foot segments, specifically at the point where the foot was closest to the pelvis. Each movement cycle concluded with the beginning of its subsequent cycle. For SD, each movement cycle commenced at the local minima of the vertical distance between the pelvic and the opposing foot segments.

For the VJ task, two distinct jump strategies were observed and, therefore, it was important to analyse them separately. These strategies were referred to as the continuous and discrete strategies, respectively. For both strategies, the initiation of take-off was at PKF. During the continuous jump strategy, the participants flexed their knee on landing and then immediately extended into the next jump. The next PKF was used to indicate the completion of the landing phase. This also marked the start of the next take-off phase. During the discrete jump strategy, the participants flexed the knee on landing and then extended the knee to come to a standstill before flexing the knee to begin the next jump. The end of the landing phase was characterised as the first local maxima in knee angle that surpassed 5 degrees (i.e., an extension of at least 5 degrees). Following this period of knee extension, knee flexion marked the next take-off phase.

3.2.13 Data analysis of Part 1

In the current study, kinematic data for the CKP group and for the healthy group were collected once for gait, DLS, SLS, VJ, SA and SD but analysis of the data extracted from the IMUs was conducted in two different ways: the **SCI of kinematic data** and the **SQA of kinematic data**. In the SCI analysis, kinematic data for the whole waveform graphs were analysed using a standardised reporting template for each participant individually. In the SQA analysis, the data were analysed at discrete time points of the movement cycle using the standard statistical tests (t-tests in the current study).

3.2.13.1 Structured clinical interpretation of kinematic data

This part of the analysis sought to identify individualised movement alterations of the whole kinematic waveform of the movement cycle using a standardised reporting template developed for the clinical setting. Button et al. (2022) reported that using the template improved the robustness and consistency of the interpretation.

The kinematic waveforms of the hip, knee and ankle joints in the sagittal and frontal planes were analysed for gait, DLS, SLS, VJ, SA and SD. Using the template, each waveform graph was interpreted by comparing the knee pain painful limb (KPPL) to the non-painful limb (KPNPL) in the CKP group and by comparing the dominant limb (HDL) to the non-dominant limb (HNDL) in the healthy group.

Before analysing the data using the SCI, certain predetermined criteria were set to determine whether a movement pattern between limbs was an alteration or a normal variation. These criteria were determined based on the existing literature concerning movement analysis and are as follows:

1) Evidence supported the use of 5° as the cut-off point for the difference in joint angle ROM between limbs. This is the boundary for clinical relevance, so anything greater than 5° (see Figure 7) was reported as an alteration (Ismailidis et al. 2021; Ismailidis et al. 2020). However, this value should be interpreted with caution because ROM is dependent on the plane, joint and activity.

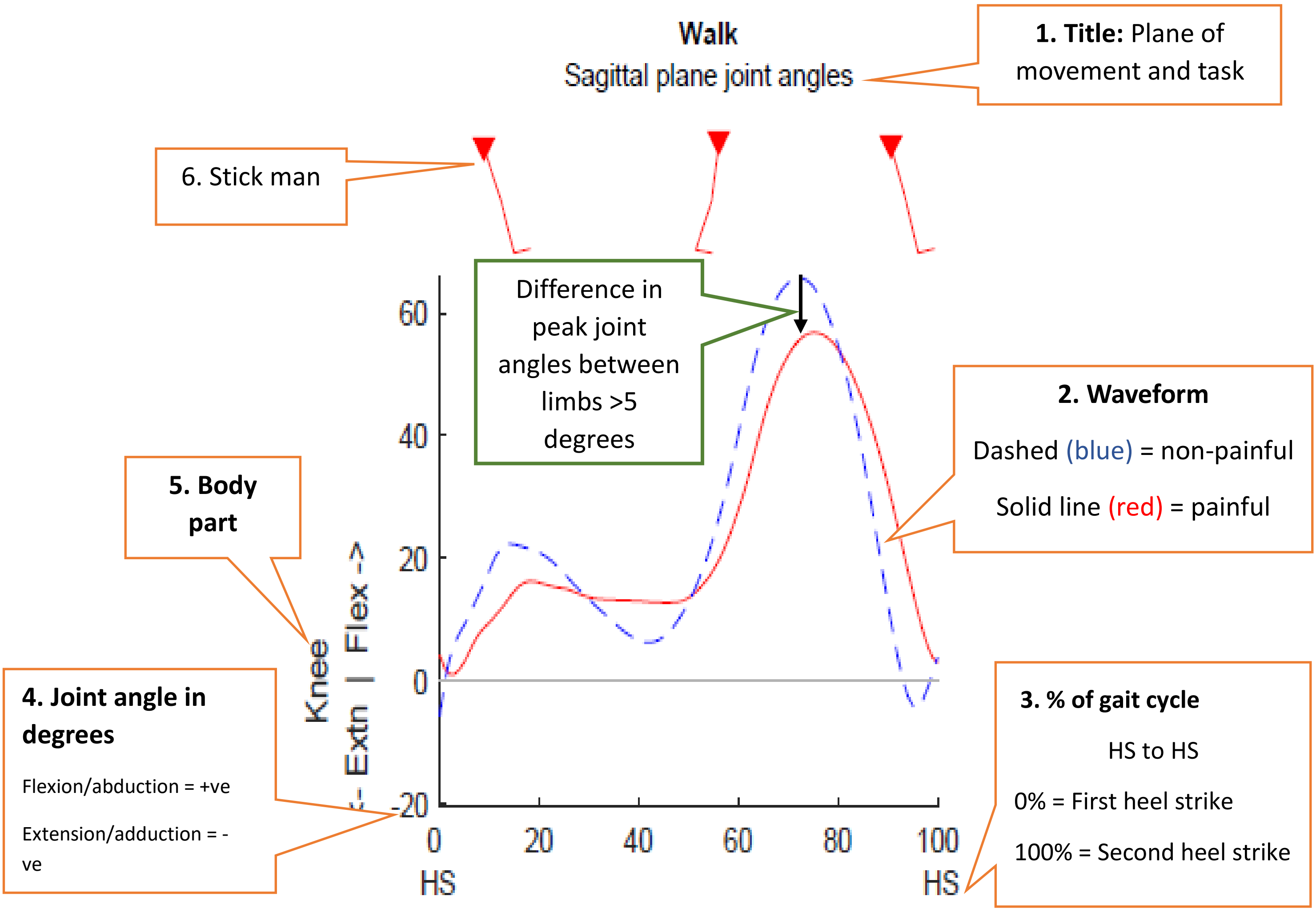
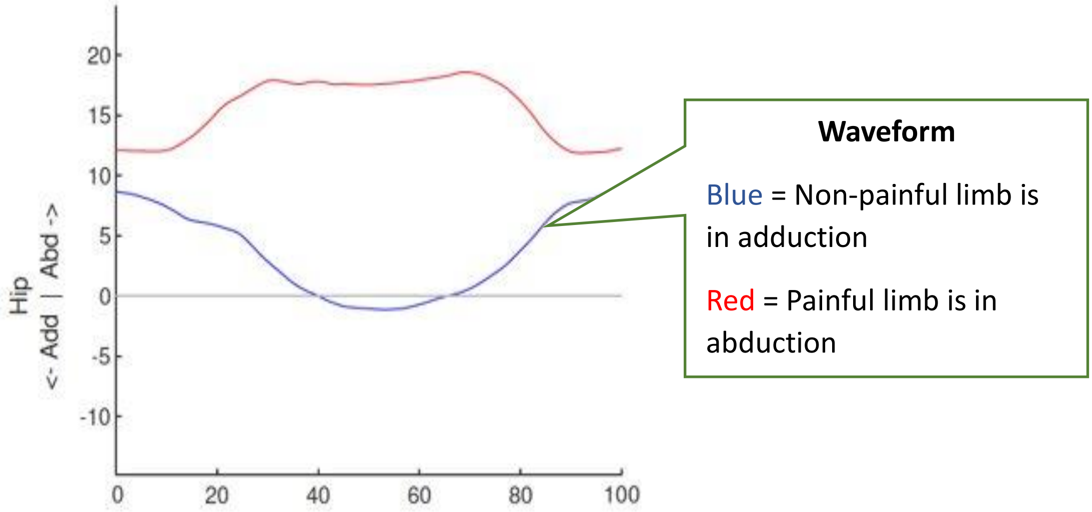


Figure 7: Example of the differences in the joint angles between two limbs

2) Waveforms going in an opposite direction for the KPPL compared to the KPNPL or for the HDL compared to the HNDL (see Figure 8); e.g., valgus direction compared to varus at the comparison joint indicating a movement alteration (Horan et al. 2014).



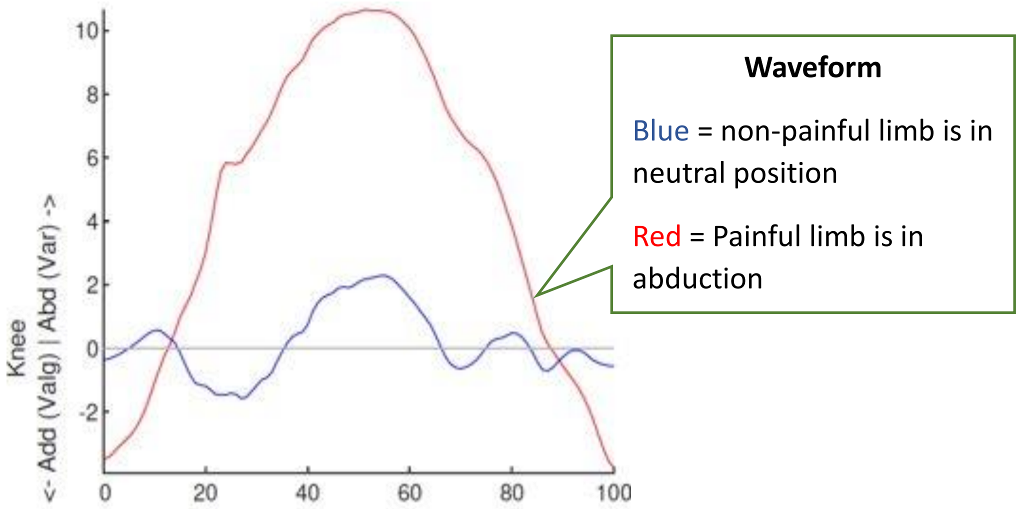
Waveform

Blue = Non-painful limb is in adduction

Red = Painful limb is in abduction

Figure 8: Example for the difference in the direction of the waveforms

3) Differences in the overall shape of the waveforms of the two limbs (see Figure 9). Waveform similarity is an important consideration in movement analysis when comparing kinematic patterns to reference results, particularly when comparing data from a group of patients to data from healthy people or data for a painful limb to that of a non-painful limb (Iosa et al. 2014). To clarify, Figure 9 presents waveform data for the frontal plane knee joint during the performance of DLS for a painful limb (red line) and a non-painful limb (blue line). The painful limb presents a waveform with increased knee varus but the non-painful limb is in a neutral position. This lack of similarity between the limbs in the waveform data is considered an alteration.



Waveform

Blue = non-painful limb is in neutral position

Red = Painful limb is in abduction

Figure 9: Example of the difference in the shape/similarity of the waveforms

There were five progressive stages to this SCI of kinematic data that were followed for both groups in the study:

STEP 1: The standard reporting template contained standardised terms organised into four boxes based on three themes: amount, nature and timing (see Figure 10). A single term from each of these themes was selected to describe the observed altered movement patterns.

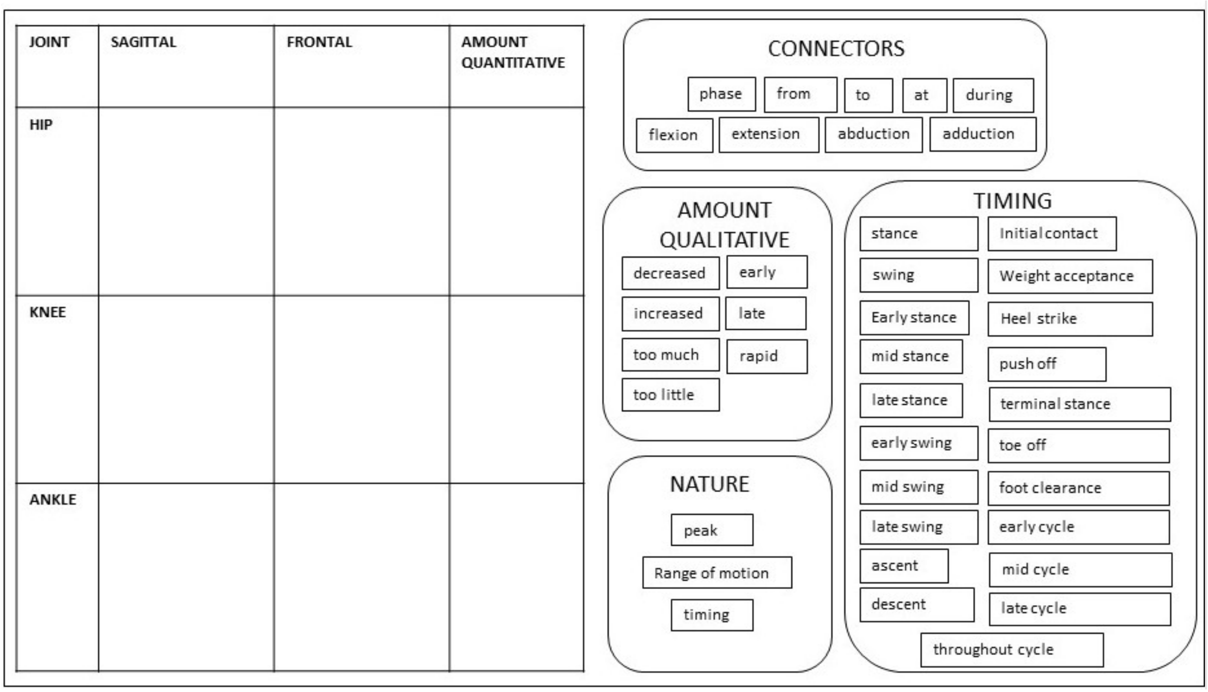


Figure 10: The standardised reporting template adapted from Button et al. (2022)

STEP 2: Integrating and writing the chosen terms in a prepared Excel sheet according to the joint and plane of movement analysed (see Appendix H). All of the identified alterations were written for each individual on a separate spreadsheet.

STEP 3: The researcher (RA) read through the data many times to become familiar with it.

STEP 4: Once the researcher was familiar with the data, all of the identified movement alterations were copied into a Microsoft Word document for each task, joint and plane of movement. Then a colour-coding technique was used to identify commonalities (Bianco et al. 2015). The coding process involved searching the text for similar themes (similar movement alteration from the participants) and then marking those descriptions with a code colour (Bianco et al. 2015). This makes it easier to identify common patterns, quantify the number of identified alterations and enhance comparisons (see Appendix I).

STEP 5: All of the colour-coded altered movement patterns were organised in tables for each activity, joint and plane of movement for each group. Furthermore, the frequency (number of identified alterations) and percentage (frequency of the identified alterations divided by the total number of participants who performed the activity in each group X 100) of each alteration were reported and compared between groups and limbs.

3.2.13.2 Standard quantitative analysis of kinematic data

In this SQA analysis, the data were analysed at discrete time points of the movement cycle using the usual standard statistical tests. An explanation for the statistical tests undertaken for the current analysis is provided in the following sub-sections.

3.2.13.2.1 Descriptive statistics

Descriptive statistics were calculated using Microsoft Excel software (Microsoft Office, Excel software, version 2013) and are presented as the means and standard deviations (mean ± SD) for demographic data (age, gender, height, weight and BMI) for both groups. Data for the patient-reported outcome measures (PROMs), KOOS and NPRS were also presented as mean ± SD for the CKP group only.

The kinematic variables (ROM during the whole cycle, the joint angle at PKF, and the joint angle at HS for the hip, knee and ankle joints on both sides of the body in the sagittal and frontal planes) were calculated as means ± SD for each limb. This was based on the sensor data and a series of time points and variables which were predetermined according to the existing movement analysis literature. First, the average scores for each participant's joint angular kinematics (across all repetitions) for each task were determined. Descriptive analysis was then conducted to determine the mean, standard deviation and 95% confidence interval. Subsequently, data for all of the participants in a group were averaged to calculate the group mean.

3.2.13.2.2 Inferential statistics

All of the data collected were analysed using the Statistical Package for Social Sciences (SPSS) version 27 (IBM Corp. in Armonk, NY). Because the aim of the current study was to explore between-group and within-subject kinematic differences of those with and without CKP during various functional tasks including gait, DLS, SLS, VJ, SA and SD in the sagittal and frontal planes for the hip, knee and ankle joints using clinically available IMUs, t-tests were chosen for the purpose of comparison in case the following assumptions were met:

- The data are independent.
- They are approximately normally distributed.
- There is an equal amount of variance (homogeneity of variance) (Kim and Park 2019).

Thus, the normal distribution of data was first assessed using the Shapiro-Wilk test, Q-Q plots and histograms (see Appendix J). The Shapiro-Wilk test has the advantage of objectively determining the normality of the data but it might be insensitive to small sample numbers or overly sensitive to large sample sizes (Mishra et al. 2019). Therefore, Q-Q plots and histograms were investigated to better visualise the data distribution, as recommended by Field (2009). If data were normally distributed, a parametric paired-sample t-test was used for within-subject comparison; otherwise, the non-parametric Wilcoxon signed-rank test was used. For between-group comparison, parametric independent t-tests were performed to determine differences in primary outcome measures between groups in the normally distributed data. Alternatively, the non-parametric Mann-Whitney U test was applied if the normality assumption was violated.

The independent t-test assumes that the variances of the two groups are equal in the population. The assumption of homogeneity of variance was tested for between-group comparisons using Levene's Test of Equality of Variances which is produced in SPSS Statistics when running the independent t-test procedure. The test for homogeneity of variance provides the F-statistic and a significance value (p-value) but the p-value is the one that should be investigated. If it was greater than 0.05 (i.e., $p > .05$), the group variances were treated as equal and the independent t-test score was taken. However, if $p < 0.05$, this indicates that the variances were unequal and the assumption of homogeneity of variances was violated. In this case, the welch t-test score was considered (Kim 2019).

A comparison was performed for the outcome variables for each task (gait, DLS, SLS, VJ, SA and SD), each lower limb's joint (hip, knee and ankle) and each plane of movement (sagittal and frontal). For within-subject comparisons, the painful limb was compared to the non-painful limb in the CKP group, whereas the dominant limb was compared to the non-dominant limb in the healthy group (Sadeghi et al. 2000) and the significance level (*p* value) was set at $p < 0.05$.

In the between-group comparison, each limb of the CKP group was compared to the dominant limb only of the healthy group. The decision to choose the dominant limb of the healthy group for comparison was because previous research supported using any healthy limb as a reference limb for the diseased group (Abu El Kasem et al. 2020). This was also supported by other investigations claiming that, although statistically significant changes presented between the dominant and non-dominant sides of the healthy group, they could be clinically disregarded (Cocchiarella and Andersson 2001; Hallajeli et al. 2014; Macedo and Magee 2008). The current study therefore supports the use of the dominant side of the healthy group as a reference for the CKP group.

The significance level in the between-group analysis was adjusted for three multiple comparisons (KPPL, KPNPL and HDL) using Bonferroni correction, which resulted in a significance level of $p < 0.017$. Adjusting the *p*-value for multiple comparisons was advocated to reduce the possibility of type I errors and the Bonferroni method is one of the most widely used approaches for adjusting for t-tests (Lee and Lee 2018). The significance level is therefore divided into the number of comparisons being tested based on the following equation:

$$\textit{Adjusted alpha } (\alpha) = \alpha / k \textit{ (number of comparisons tested)}$$

Thus, type I error can be reduced. In other words, the greater the number of comparisons to be tested, the stricter the criterion and the lower the likelihood of producing type I errors (Lee and Lee 2018).

For all comparisons, effect sizes were calculated as Cohen's d only when statistically significant differences were identified and in order to avoid drawing conclusions based solely on *p*-values. Effect size was interpreted as follows: Cohen's d of 0-0.19 = trivial effect; 0.2-0.49 = small effect; 0.50-0.79 = moderate effect; > 0.8 = large effect (Cohen 1992). The following flowchart (see Figure 11) explains the statistical analysis process conducted for this section:

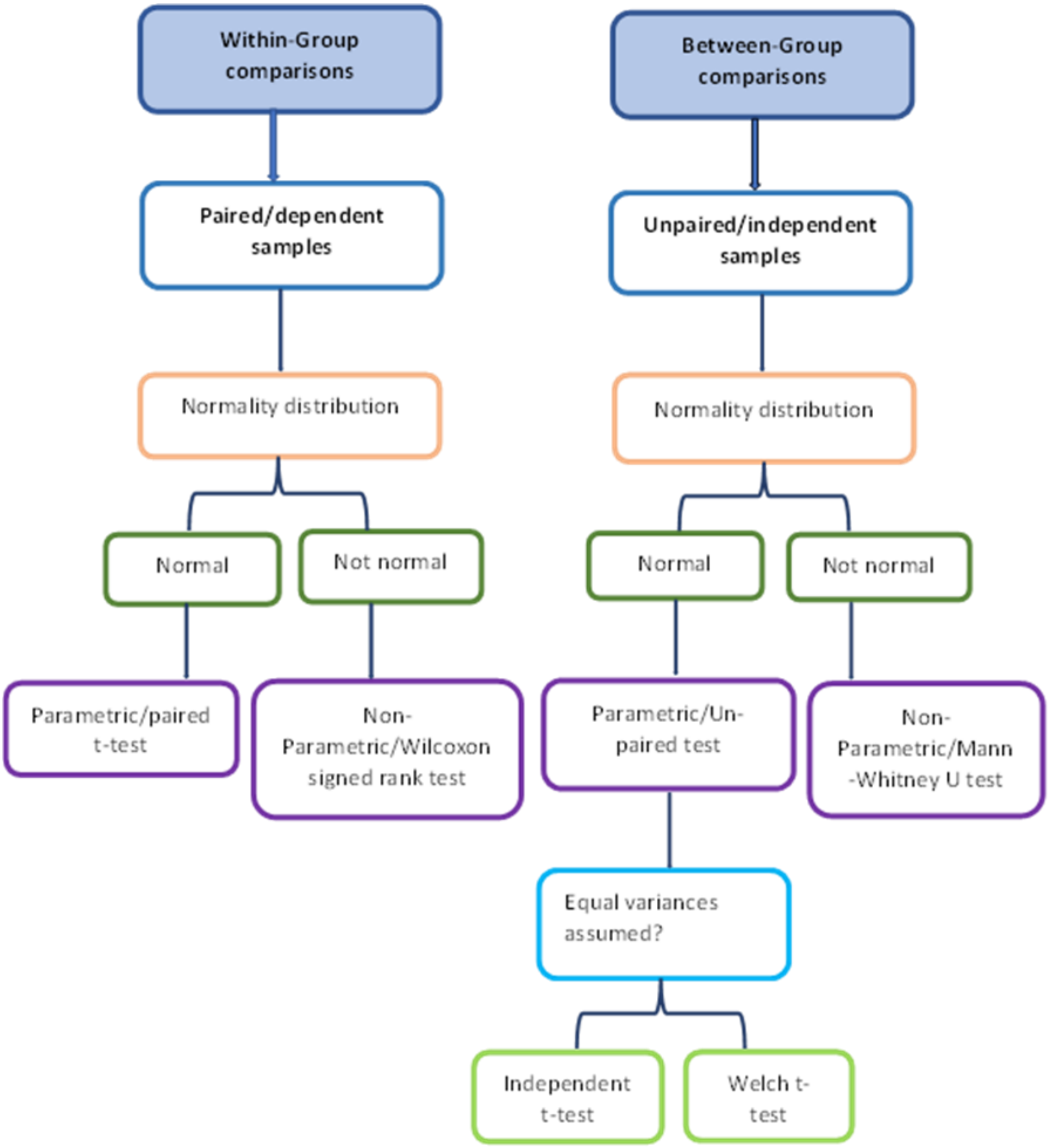


Figure 11: Flowchart explaining the SQA for within-subject and between-group comparisons

3.2.14 Ethical considerations

With regards to risk assessment, the classroom and corridor were checked prior to data collection to avoid any possibility of colliding with objects and causing injury to the participants. In addition, the participants were assured about the safety of the device (IMU-sensors). It was also made clear to the participants that the IMUs are attached using sticky tape for the sacral tracker or elastic straps for the other body parts. The removal of these items may cause some mild discomfort, similar to that experienced when removing a sticky plaster. The participants were also notified that they may experience some temporary pain within the affected joint or muscle soreness during or after performing the activities. This discomfort, however, was reduced by allowing breaks between the activities and only performing the tasks if pain in the knee joint was manageable at levels they would normally experience during activities of daily living.

In addition, all of the participants were supervised whilst performing the activities by a qualified physiotherapist for safety purposes and to prevent any unforeseen events. The classroom was booked for research purposes only and locked off during the experimental tests. In addition, a sign was posted in front of the door indicating that "participant research is ongoing" to help ensure privacy during the data collection process. There was an area in the room dedicated to the changing of clothing and this was protected by a privacy screen.

With regards to data management and the processing of the participants' personal information, it was stored securely on a password protected university computer. Access to this information was restricted to members of the research team. All of the participants signed a written consent sheet and each was assigned a unique ID number. From then on, this number was used to identify each participant throughout the study. For confidentiality and security purposes, electronic data were saved in an electronic record system using a protected password on Cardiff University's servers. A digital copy of the anonymised data was stored on OneDrive with a password known only by the researcher and a hard copy also was securely saved in a locked cupboard which could only be accessed by the researcher. The data will be reserved for 15 years following completion of the study and will then be deleted. Cardiff University’s Guidelines for Research Governance, the General Data Protection Regulation (GDPR 2018), and the procedures for good clinical practice in research were followed.

It is of utmost importance to ensure that participants are not obliged to take part in the study and, therefore, they were given 2-3 days to decide whether or not they would like to participate in the study after they had received the information sheet. The participants had the right to ask questions at any time and to withdraw from the study if they did not wish to continue.

Chapter 4: Results of part 1

4.1 Overview

The aim of this study was to **explore the between and within-subject kinematic differences of people with CKP and healthy people during various functional tasks, including gait, DLS, SLS, VJ, and SA and SD in the sagittal and frontal planes for the hip, knee, and ankle joints using clinically available IMUs.** This was accomplished by pursuing the following objectives:

- **Performing a structured clinical interpretation (SCI) of kinematic data** by exploring kinematic movement alterations of waveform data for gait, DLS, SLS, VJ, SA and SD for people with and without CKP in the sagittal and frontal planes of movement using IMU kinematic reports and a standardised reporting template.

- **Conducting a standard quantitative analysis (SQA) of kinematic data** by statistically assessing differences in kinematics at discrete time points among people with and without CKP for gait, DLS, SLS, VJ, SA and SD in the sagittal and frontal planes of movement.

4.2 Participants

Data were collected for 38 healthy participants including four from the pilot study and 21 participants with CKP. However, data of the four healthy participants from the pilot were excluded in addition to the data of three other healthy participants due to issues with the quality of that data. Accordingly, a total of 31 healthy participants were included in the study. For the CKP group, the data collection process had to stop due to the events of the Covid-19 pandemic and the target sample size of 28 participants was unachievable, thereby representing a limitation of this study. Thus, a total of 21 participants with CKP were included. In addition, some of the participants were unable to perform certain activities including SLS, SA and SD due to the pain that they experienced. Full details of the number of participants that completed each task are presented in Table 8.

Table 8: Number of participants included in the analysis for each task

Task	**Healthy group**		**Chronic knee pain group**	
	HDL	HNDL	KPPL	KPNPL
DLS	31	31	21	21
SLS	31	31	16	20
VJ	31	31	21	21
SA	31	31	20	20
SD	31	31	20	20
Gait	31	31	21	21

The number of participants is given for each limb because some of the activities (e.g., SLS) needed to be performed in each limb separately and some of the participants were only able to perform it on one leg but not on the other. HDL refers to the healthy dominant limb in the healthy group, HNDL refers to the healthy non-dominant limb in the healthy group, KPPL refers to the knee pain painful limb in the CKP group, and KPNPL refers to the knee pain non-painful limb in the CKP group.

4.3 Demographics, knee injuries and osteoarthritis outcome score and numeric pain rating scale

The participants' demographics, in addition to the self-reported outcome measures of pain (NPRS) and function (KOOS) are summarised in Table 9. The independent sample t-test was used to compare the demographic data and the results indicated no statistically significant difference between groups in terms of their gender, height, weight or BMI ($p > 0.05$). Indeed, a statistically significant difference ($p < 0.001$) was only found for the age between the CKP and healthy groups.

Table 9: Participant demographics, knee injury, osteoarthritis outcome and numeric pain rating scale scores

Demographic, KOOS and NPRS data	Healthy group mean ± SD	Chronic knee pain group mean ± SD
Age (years)*	30 ± 6.3	45 ± 16.4
Gender	13M:18F	8M:13F
Height (cm)	165.74 ± 10.33	170.28 ± 11.33
Weight (kg)	72.80 ± 15.05	77.34 ± 15.83
Body mass index (kg/m^2)	26.52 ± 5.23	26.85 ± 5.83
KOOS pain score	N/A	65 ± 16
KOOS symptoms score	N/A	63 ± 15
KOOS ADL score	N/A	76 ± 14
KOOS sport/rec score	N/A	59 ± 17
KOOS QoL score	N/A	49 ± 16
Average NPRS score	N/A	3.33 ± 2.05
Pain right now (NPRS)	N/A	2.19 ± 2.13
Usual pain (NPRS)	N/A	3.76 ± 2.47
Best pain (NPRS)	N/A	1.76 ± 1.7

Worst pain (NPRS)	N/A	5.62 ± 1.88
M: male, **F:** female, **cm:** centimetres, **Kg:** kilograms, **KOOS:** knee pain and osteoarthritis outcome score, **ADL:** activities of daily living, **QoL:** quality of life, **NPRS:** numeric pain rating scale ***:** statistically significant difference ($p < 0.05$).		

KOOS and NPRS scores were only collected for those with knee pain. Each KOOS subscale score could range from zero to 100, with a score of zero indicating extreme knee problems and a score of 100 indicating no knee problems. The highest average score was reported for the KOOS daily living functions subscale (ADL) (76/100), and the lowest score for the KOOS QoL subscale (49/100). The results for each subscale are presented in Table 9.

The scores for the level of pain were reported by the CKP individuals using the NPRS. The total average NPRS for the CKP group was 3.33/10. The average rating for the (best) level of pain was 1.76/10, whereas the average rating for the (worst) level of pain was 5.62/10. Goulet et al. (2015) reported that scores ranging from 1 to 3 were categorised as mild, scores of 4 to 6 were moderate, and 7 to 10 were severe pain. Thus, the average NPRS for the CKP group in the current study is considered to be mild. Further details for each category of the NPRS are presented in Table 9.

4.4 Results for the structured clinical interpretation and standard quantitative analysis of the kinematic data

4.4.1 Results for the SCI of the kinematic data

In the SCI results, altered movement patterns were identified using the standardised reporting template and all of the identified alterations are displayed in the tables on the basis of the percentage of the total number of participants who performed this alteration in each group: 21 participants in the CKP group and 31 participants in the healthy group (except for some activities such as SLS, SA and SD). It should be noted that the data included in the tables are the result of within-subject comparisons. Thus, for those subjects with CKP, the KPPL was compared to the KPNPL for gait, DLS, SLS, VJ, SA and SD in the sagittal and frontal planes for the hip, knee and ankle. The number of different movement patterns that the KPPL limb showed compared to the KPNPL is reported. The data are represented as a percentage of the total number of participants in the CKP group (21 participants).

For the healthy group, the HDL was compared to the HNDL for gait, DLS, SLS, VJ, SA and SD in the sagittal and frontal plane for the hip, knee and ankle. The number of different types of movement patterns that the HDL limb showed compared to the HNDL is reported. Again, the data are presented as a percentage of the total number of participants in the healthy group (31 participants).

Importantly, in this SCI of the kinematic data, differences are between the limbs in terms of kinematic movement patterns, so no limb was superior to the other. Consequently, no limb was favoured over another in terms of movement patterns.

4.4.2 Results for the SQA of the kinematic data

The results for the SQA for the sagittal and frontal planes of movement for within-subjects and between-groups are presented as the mean and SD for the hip, knee and ankle joints for the following variables: the ROM throughout the whole movement cycle, joint angles at PKF and joint angles at HS (only for gait, SA and SD).

Within-subject comparisons were conducted to identify differences in movement patterns in the sagittal and frontal planes among CKP subjects (KPPL versus KPNPL) and within healthy subjects (HDL versus HNDL). For this, the statistical significance level was set at $p< 0.05$.

Between-group comparisons were also conducted to identify differences in altered movement patterns in the sagittal and frontal planes between the CKP group and healthy individuals during the execution of the selected functional tasks. Thus, both limbs in the CKP group (KPPL and KPNPL) were compared to the dominant limb (HDL) of the healthy group. The statistical significance level for between-group comparisons was set at $p < 0.017$ and was adjusted for multiple comparisons according to the Bonferroni corrections.

In the following sections of this chapter, the results for the SCI and SQA are introduced and started with a short description of the movement cycle for each activity and each plane of movement. For example, the gait movement cycle and results for the SCI in the sagittal plane are presented first, followed by the SQA results for within-subject and between-group comparisons. Subsequently, the frontal plane results for the same activity are introduced. This is applied to all of the activities analysed in the current study.

In the SQA, positive values indicate flexion, abduction or dorsiflexion, whereas negative values indicate extension, adduction or plantarflexion.

4.4.3 Gait sagittal plane results

Gait waveform graphs (see Appendix K) indicate that the stance phase starts with the first foot contact (HS) on the ground. The mid-stance then places weight over the stance leg and foot on the ground. Late stance ends when the body advances forwards and the stance limb pushes off the ground, commencing the swing phase. The early swing phase begins with the foot rising and the knee and hip joints flexing for the forward swing. The **PKF joint angle** occurs **mid-swing** when the limb swings forwards, the knee reaches maximum flexion and the foot clears the ground. Last is the late swing which prepares the foot for ground contact. Knees and hips should be extended for stance.

In Table 10, altered movement patterns are described according to their order in the gait movement cycle, starting from movement throughout the whole cycle, then the stance phase and, finally, the swing phase.

4.4.3.1 Gait sagittal plane within-subject (KPPL vs KPNPL and HDL vs HNDL) kinematic results

Based on the criteria developed to identify the presence of movement alterations for the **SCI** in the sagittal plane, there were 17 observable kinematic movement alterations in the KPPL compared to the KPNPL and 19 in the HDL compared to the HNDL across individuals. All movement alterations for the gait sagittal plane are presented in Table 10.

At the hip, knee and ankle joints, various movement alterations were observed between the KPPL and KPNPL and between the HDL and HNDL. The low number of participants using each strategy suggests that various alterations were used between limbs, regardless of pain. At the hip there was no consistency in the alterations observed between the KPPL and KPNPL and the HDL and HNDL. At the knee joint, reduced flexion during stance was the most widely observed between limb difference for the KPPL versus KPNPL and less frequently observed between HDL and HNDL. At the ankle, the most common strategy for both KPPL and KPNPL as well as HDL and HNDL was altered plantarflexion ROM (both increased and decreased) during the swing phase.

All of the data for the sagittal plane gait analysis for **SQA** are presented in Table 11. For the CKP group, the results of the within-group differences between the KPPL and KPNPL demonstrated that there were no significant findings in any of the outcome variables at the hip, knee or ankle joints (*P*> 0.05). With regards to the healthy group, a statistically significant finding was presented between the HDL and the HNDL only at the hip joint at PKF, with reduced hip flexion ROM for the HDL compared to the HNDL (*p*= 0.041, mean ± SD= 12.28 ± 3.74 HDL vs 13.24 ± 3.19 HNDL, d= 0.383).

4.4.3.2 Gait sagittal plane between-group (KPPL vs HDL and KPNPL vs HDL) kinematic results

Joint angle at HS

The CKP group demonstrated a significant reduction in knee flexion angle at HS in the KPPL compared to the HDL (*p*= 0.016, mean ± SD -1.29 ± 5.49 KPPL, 2.20 ± 3.73 HDL, d= 0.743). No other significant between-group differences presented at the hip or ankle joints (*p*> 0.017).

Joint angle at PKF

Sagittal plane hip and knee angles at PKF indicated no statistically significant differences between groups (*p*> 0.017). With regards to the ankle joint at PKF, a statistically significant difference was observed between the KPPL and the HDL with reduced ankle plantarflexion in the KPPL (*p*= 0.006, mean ± SD -10.06 ± 4.78 KPPL, -14.17 ± 5.28 HDL, d= 0.810).

ROM during the whole cycle

No significant differences in the ROM during the whole cycle were identified for the hip or knee joints during gait ($p > 0.017$). At the ankle joint, a statistically significant difference was observed between the KPPL and the HDL with reduced ankle dorsiflexion ROM in the KPPL compared to the HDL ($p = 0.011$, mean ± SD 38.99 ± 8.36 KPPL, 44.48 ± 6.69 HDL, d= 0.741).

In summary, both analyses underscore gait movement alterations in the sagittal plane, with most alterations occurring at the ankle. For the SCI, the most common between limb alteration among the CKP and healthy groups was an altered range of plantarflexion during the swing phase. The CKP group frequently demonstrated reduced knee flexion during the stance phase in the KPPL compared to the KPNPL. However, the SCI demonstrated the complexity and individual variability of altered movement patterns in CKP. The SQA results indicated reduced ankle dorsiflexion ROM throughout the cycle and plantarflexion joint angle at PKF in the KPPL limb.

Table 10: Gait sagittal plane SCI for HDL (n= 31) and KPPL (n= 21)

Joint	* Limb	Altered movement pattern	Number of participants	Percentage of participants
Hip	HDL	Decreased flexion ROM throughout cycle	1	3%
		Decreased flexion ROM during the stance phase	2	6%
		Decreased extension ROM during the stance phase	2	6%
		Decreased peak extension at late stance	1	3%
		Increased peak flexion at early swing	1	3%
		Early peak flexion at early swing	1	3%
		Decreased flexion ROM at late swing	1	3%
	KPPL	Decreased flexion ROM during early stance	1	4%
		Increased peak extension at late stance	1	4%
		Decreased flexion ROM at late swing	1	4%
	HDL	Increased flexion ROM throughout cycle	1	3%
		Decreased flexion ROM throughout cycle	1	3%
		Increased flexion ROM during stance	1	3%
		Decreased flexion ROM during early stance	2	6%

Knee		Increased peak flexion at mid-swing	4	12%
		Decreased peak flexion at mid-swing	4	12%
	KPPL	Decreased flexion ROM throughout cycle	1	4%
		Increased extension at early stance	1	4%
		Decreased flexion ROM from mid-to-late stance	3	14%
		Decreased flexion ROM during swing phase	1	4%
		Increased peak flexion at mid-swing	2	9%
		Decreased peak flexion at mid-swing	2	9%
Ankle	**HDL**	Decreased peak dorsiflexion at late stance	1	3%
		Decreased plantarflexion ROM at early stance and late swing	5	16%
		Increased peak plantarflexion ROM at mid-swing	5	16%
		Decreased peak plantarflexion at mid-swing	8	25%
		Early peak plantarflexion at mid-swing	1	3%
		Late peak plantarflexion at mid-swing	1	3%
	KPPL	Increased plantarflexion ROM during early stance	1	4%
		Increased dorsiflexion ROM from mid-to-late stance	2	9%
		Decreased dorsiflexion ROM from mid-to-late stance	2	9%

		Decreased plantarflexion ROM during swing phase	2	9%
		Increased peak plantarflexion at mid-swing	6	28%
		Decreased peak plantarflexion at mid-swing	6	28%
		Early peak plantarflexion at early swing	1	4%
		Increased plantarflexion ROM during late swing phase	1	4%
*** In the limb section, HDL was compared to the HNDL and the KPPL was compared to the NPNPL for each joint, each task and each plane of movement.**				

Table 11: Summary statistics for gait sagittal plane within and between group comparisons

Joint	**Time point**	**Within chronic knee pain group ($p<0.05$)**		**Sig-**	**Within healthy group ($p<0.05$)**		**Sig-**	**Between-groups ($p<0.017$)**	
		KPPL Mean ± SD	KPNPL Mean ± SD		HDL Mean ± SD	HNDL Mean ± SD		**KPPL vs HDL**	**KPNPL vs HDL**
Gait									
Hip	HS (◦)	24.11 ± 4.01	24.32 ± 4.12	0.684	23.43 ± 4.37	23.56 ± 3.89	0.794	0.577	0.466
	PKF (◦)	12.81 ± 5.31	13.55 ± 4.09	0.327	12.28 ± 3.74	13.24 ± 3.19	*0.041	0.675	0.252
	ROM (◦)	36.01 ± 3.87	35.92 ± 4.71	0.877	37.84 ± 3.74	38.16 ± 3.810	0.468	0.095	0.110
Knee	HS (◦)	-1.29 ± 5.49	-0.08 ± 4.64	0.203	2.20 ± 3.73	1.84 ± 4.11	0.595	*0.016	0.056
	PKF (◦)	58.10 ± 6.63	59.210 ± 6.52	0.476	57.85±4.65	58.09 ± 4.97	0.570	0.589	0.355
	ROM (◦)	61.48 ± 10.13	61.47 ± 6.51	0.995	58.41 ± 3.84	58.63 ± 4.11	0.745	0.197	0.038
Ankle	HS (◦)	-2.57 ± 3.03	-1.83 ± 3.13	0.210	-3.21 ± 4.02	-4.28 ± 3.98	0.173	0.535	0.191
	PKF (◦)	-10.06 ± 4.78	-10.72 ± 4.33	0.503	-14.17 ± 5.28	-14.710 ± 5.66	0.395	*0.006	*0.016
	ROM (◦)	38.99 ± 8.36	39.610 ± 7.28	0.503	44.48 ± 6.61	44.93 ± 6.72	0.517	*0.011	0.018

KPPL: knee pain painful limb; **KPNPL:** knee pain non-painful limb; **HDL:** healthy dominant limb; **HNDL**: healthy non-dominant limb; **HS:** angle at heel-strike; **PKF:** joint angle at peak knee flexion; **ROM**: range of motion during the whole cycle; ***** statistically significant findings (**$p<0.05$** for within-group and **$p<0.017$** for between-group); **(◦)**: measurement unit in degrees**. Positive values** indicate flexion, abduction or dorsiflexion, whereas **negative values (-)** indicate extension, adduction or plantarflexion.

4.4.4 Gait frontal plane results

In Table 12, altered movement patterns are described according to their order in the gait movement cycle, starting with movement throughout the entire cycle, then the stance phase and, finally, the swing phase.

4.4.4.1 Gait frontal plane within-subject (KPPL vs KPNPL and HDL vs HNDL) kinematic results

For the frontal plane **SCI** of the kinematic data, 26 lower-limb movement alterations were identified in the KPPL compared to the KPNPL, whilst there were 25 in the HDL compared to the HNDL. All between-limb alterations are presented in Table 12.

At the hip joint, range of movement alterations were used across the participants and there was little consistency. Increased hip abduction ROM at early stance was more commonly observed in the HDL than in the HNDL. Also, altered abduction/adduction ROM during the stance phase was the most frequent alteration identified between limbs (KPPL vs KPNPL and HDL vs HNDL). At the knee, altered (increased or decreased) peak adduction during the swing phase was the most commonly identified alteration in the KPPL compared to the KPNPL and in the HDL compared to the HNDL. In both groups, most alterations were evident in the swing phase of the gait cycle. With regards to the ankle, increased peak adduction during the swing phase was the most identified alteration in the KPPL compared to the KPNPL and in the HDL compared to the HNDL. Altered adduction ROM during the swing phase was also identified in the KPPL compared to the KPNPL and in the HDL compared to the HNDL.

For the gait **SQA** (Table 13), the CKP group demonstrated no statistically significant differences across all three joints between the KPPL versus the KPNPL. However, there was a statistically significant difference within the healthy group. At the hip joint, there was increased hip abduction at heel strike in the HDL compared to the HNDL (*p*= 0.007, mean ± SD= 5.25 ± 2.43 vs 3.09 ± 3.43, d= 0.522). At the ankle, there was increased abduction ROM across the whole cycle of the HDL compared to the HNDL (*p*= 0.001, mean ± SD= 17.95 ± 4.24 vs15.26 ± 2.69, d= 0.639).

4.4.4.2 Gait frontal plane between-group (KPPL vs HDL and KPNPL vs HDL) kinematic results

Joint angle at HS

The hip and ankle joints demonstrated no statistically significant differences between groups in the frontal plane of movement (*p*> 0.017). With regards to the knee joint, a statistically significant difference was presented in the CKP group with a decreased knee adduction angle at HS in the KPPL compared to the HDL (*p*= 0.013, mean ± SD -0.47 ± 1.53 KPPL vs -2.13 ± 2.44 HDL, d= 0.783).

Joint angle at PKF

There were no statistically significant differences between groups in the frontal plane hip, knee and ankle joint angles at PKF (*p*> 0.017).

ROM during the whole cycle

There were no statistically significant differences in the ROM across the whole cycle in the frontal plane, between the groups at the hip, knee or ankle joints (*p*> 0.017).

In summary, the SCI demonstrated many different combinations of movement alterations between limbs in both the CKP and healthy groups in the frontal plane, with low numbers of participants using each alteration. This was reflected in the SQA because no statistically significant differences were found between limbs within the CKP. However, SQA presented a statistically significant difference at the knee joint at HS between the painful limb of CKP and the HDL of the healthy group. This finding did not appear in the SCI and most of the alterations existed during the swing phase of the gait cycle. For the HDL of the healthy group, there was limited occurrence of increased hip abduction during gait based on the SCI and SQA.

Table 12: Gait frontal plane SCI for HDL (n= 31) and KPPL (n= 21)

Joint	*Limb	Altered movement pattern	Number of participants	Percentage of participants
Hip	**HDL**	Increased abduction ROM throughout cycle	2	6%
		Decreased abduction ROM throughout cycle	1	3%
		Decreased adduction ROM throughout cycle	1	3%
		Increased abduction ROM during early stance	12	38%
		Increased adduction ROM from mid-to-late stance	3	9%
		Increased adduction ROM from mid-stance to mid-swing	1	3%
		Increased peak abduction at mid-swing	1	3%
		Increased abduction ROM at late swing	9	29%
	KPPL	Increased abduction ROM throughout cycle	2	9%
		Decreased adduction ROM during stance phase	3	14%
		Decreased abduction ROM at early stance	2	9%
		Increased adduction ROM during mid and late stance phase	1	4%
		Decreased peak abduction at early swing	4	19%
		Increased peak abduction at early swing	1	4%
		Decreased peak adduction at early swing	1	4%
		Early peak abduction at early swing	1	4%
		Late peak abduction at mid-swing	1	4%
		Decreased abduction ROM at late swing phase	2	9%

Knee	**HDL**	Decreased adduction ROM at early stance	1	3%
		Decreased abduction ROM at early swing	1	3%
		Increased peak abduction at mid-swing	1	3%
		Decreased peak abduction at mid-swing	2	6%
		Late peak abduction at mid-swing	1	3%
		Decreased peak adduction at late swing	4	12%
		Increased peak adduction at late swing	4	12%
	KPPL	Increased abduction ROM during swing phase	1	4%
		Increased abduction ROM at early swing	1	4%
		Increased peak adduction at mid-swing	4	19%
		Decreased peak abduction at early swing	4	19%
		Early peak abduction at early swing	1	4%
		Late peak abduction at mid-swing	1	4%
		Early peak adduction at late swing	2	9%
		Late peak adduction at late swing	1	4%
Ankle	**HDL**	Increased adduction ROM throughout cycle	3	9%
		Decreased adduction ROM throughout cycle	4	12%
		Increased abduction ROM during stance phase	4	12%
		Decreased abduction ROM during stance phase	1	3%
		Increased adduction ROM during early stance	3	9%
		Decreased adduction ROM from early to mid-stance	1	3%

		Decreased adduction ROM at early stance and during swing	2	6%
		Increased adduction ROM during swing phase	4	12%
		Increased peak adduction at mid-swing	6	19%
		Decreased peak adduction at mid-swing	3	9%
	KPPL	Increased adduction ROM throughout cycle	2	9%
		Decreased adduction ROM throughout cycle	1	4%
		Decreased adduction ROM during early stance	3	14%
		Increased adduction ROM during early stance and swing phase	2	9%
		Decreased peak abduction at late stance	1	4%
		Decreased adduction ROM during swing phase	4	19%
		Increased peak adduction at mid-swing	4	19%
		Decreased peak adduction at mid-swing	2	9%
*** In the limb section, HDL was compared to HNDL and KPPL was compared to KPNPL for each joint, each task and each plane of movement.**				

Table 13: Summary statistics for gait frontal plane within and between group comparisons

Joint	**Time point**	**Within chronic knee pain group ($p < 0.05$)**		**Sig-**	**Within healthy group ($p < 0.05$)**		**Sig-**	**Between-groups ($p < 0.017$)**	
		KPPL Mean ± SD	KPNPL Mean ± SD		HDL Mean ± SD	HNDL Mean ± SD		NPPL vs HDL	KPNPL vs HDL
Gait									
Hip	HS (◦)	3.89 ± 2.86	4.00 ± 2.66	0.972	5.25 ± 2.43	3.09 ± 3.43	*0.007	0.020	0.086
	PKF (◦)	7.79 ± 3.56	7.89 ± 2.78	0.702	8.28 ± 2.25	7.41 ± 3.08	0.113	0.279	0.580
	ROM (◦)	13.79 ± 2.75	14.21 ± 3.57	0.390	15.27 ± 2.501	14.63 ± 2.30	0.136	0.049	0.216
Knee	HS (◦)	-0.47 ± 1.53	-0.98 ± 1.65	0.216	-2.13 ± 2.44	-1.97 ± 1.76	0.685	*0.008	0.064
	PKF (◦)	-0.02 ± 2.49	-0.30 ± 3.26	0.696	2.30 ± 4.44	3.12 ± 4.77	0.362	0.034	0.025
	ROM (◦)	9.06 ± 2.84	9.00 ± 3.02	0.947	9.75 ± 4.88	10.28 ± 4.88	0.185	0.948	0.874
Ankle	HS (◦)	-6.51 ± 5.28	-6.27 ± 4.74	0.846	-7.86 ± 5.58	-7.65 ± 4.49	0.821	0.386	0.288
	PKF (◦)	-5.31 ± 4.34	-5.03 ± 4.87	0.850	-5.70 ± 5.61	-4.99 ± 4.76	0.467	0.789	0.660
	ROM (◦)	18.25 ± 4.46	17.17 ± 4.25	0.356	17.95 ± 4.24	15.26 ± 2.69	*0.001	0.805	0.517

KPPL: knee pain painful limb; **KPNPL:** knee pain non-painful limb; **HDL:** healthy dominant limb; **HNDL**: healthy non-dominant limb; **HS:** angle at heel-strike; **PKF:** angle at peak knee flexion; **ROM**: range of motion during the whole cycle; ***** statistically significant findings (**$p < 0.05$** for within-group and **$p < 0.017$** for between-group); **(◦)**: the measurement unit in degrees. **Positive values** indicate flexion, abduction or dorsiflexion, whereas **negative values (-)** indicate extension, adduction or plantarflexion.

4.4.5 Double leg squat sagittal plane results

According to the DLS waveform graphs (see Appendix K), DLS consists of two main phases: the descent phase and the ascent phase. From a standing position, the individual starts bending their hips and knees as far as possible to reach their **maximum squat** which is the point of **PKF**. Subsequently, the individual starts to extend their hips and knees and move their body upwards.

In Table 14, movement alterations are presented according to the DLS movement cycle, starting from movement throughout the cycle, the descending phase, maximum squat and then the ascent phase.

4.4.5.1 DLS sagittal plane within-subject (KPPL vs KPNPL and HDL vs HNDL) kinematic results

The interpretations of the sagittal plane **SCI** graphs of DLS for both groups demonstrated several different alterations: 10 in the KPPL compared to the KPNPL and 11 in the HDL compared to the HNDL. All between-limb alterations are presented in Table 14.

Based on the **SCI** of the CKP group (KPPL vs KPNPL) and healthy group (HDL vs HNDL), only a few participants demonstrated any differences between limbs. There was no consistency in the alteration used. At the hip and knee, there was evidence of both an increased or decreased flexion angle, most commonly at maximum squat and at the ankle decreased or increased dorsiflexion ROM throughout the cycle or at maximum squat.

For within-subject **SQA** (Table 15), there were no statistically significant findings in the CKP group or the healthy group in the ROM during the whole cycle or in the lower limb joint angles at PKF in the hip, knee or ankle joints ($p > 0.05$).

4.4.5.2 DLS sagittal plane between-group (KPPL vs HDL and KPNPL vs HDL) kinematic results

Joint angle at PKF

The were no statistically significant between group (KPPL vs HDL and KPNPL vs HDL) differences in the hip, knee or ankle peak joint angles in the sagittal plane of movement ($p > 0.017$ for all three joints).

ROM during the whole cycle

There was no statistically significant difference in the ROM during the whole cycle at the hip, knee or ankle joints between the groups (KPPL vs HDL and KPNPL vs HDL) in the sagittal plane ($p > 0.017$).

In summary, for the DLS task in the **sagittal** plane, there was no consistency in terms of increased or decreased hip and/or knee flexion or ankle dorsiflexion between limbs for either group.

Table 14: DLS sagittal plane SCI for HDL (n= 31) and KPPL (n= 21)

Joint	* Limb	Altered movement pattern	Number of participants	Percentage of participants
Hip	**HDL**	Decreased flexion ROM throughout cycle	1	3%
		Increased peak flexion at maximum squat	4	12%
		Decreased peak flexion at maximum squat	5	16%
	KPPL	Decreased ROM throughout cycle	1	4%
		Decreased peak flexion at maximum squat	2	9%
		Increased peak flexion at maximum squat	3	14%
Knee	**HDL**	Increased peak flexion at maximum squat	2	6%
		Decreased peak flexion at maximum squat	1	3%
	KPPL	Increased peak flexion at maximum squat	3	14%
		Increased flexion ROM at early descent and late ascent	1	4%
		Decreased flexion ROM during early descent phase	1	4%
Ankle	**HDL**	Increased dorsiflexion ROM throughout cycle	5	16%
		Decreased dorsiflexion ROM throughout cycle	3	9%
		Increased peak dorsiflexion at maximum squat	4	12%
		Decreased peak dorsiflexion at maximum squat	1	3%

		Late peak dorsiflexion at maximum squat	1	3%
		Decreased dorsiflexion ROM during descent phase	1	3%
	KPPL	Increased dorsiflexion ROM throughout cycle	3	14%
		Decreased dorsiflexion ROM throughout cycle	4	19%
		Increased peak dorsiflexion at maximum squat	3	14%
		Decreased peak dorsiflexion at maximum squat	2	9%
*** In the limb section, HDL was compared to the HNDL, whereas the KPPL was compared to the KPNPL for each joint, each task and each plane of movement.**				

Table 15: Summary statistics for double leg squat sagittal plane within and between group comparisons

Joint	**Time point**	**Within chronic knee pain group (*p*< 0.05)**		**Sig-**		**Within healthy group (*p*< 0.05)**		**Sig-**	**Between-groups (*p*< 0.017)**	
		KPPL Mean ± SD	KPNPL Mean ± SD			HDL Mean ± SD	HNDL Mean ± SD		KPPL vs HDL	KPNPL vs HDL
DLS										
Hip	PKF (◦)	94.18 ± 22.08	93.47 ± 20.16	0.351		87.85 ± 22.76	87.96 ± 21.82	0.724	0.366	0.396
	ROM (◦)	86.41 ± 22.45	86.03 ± 20.96	0.614		80.84 ± 22.01	80.29 ± 21.09	0.704	0.379	0.400
Knee	PKF (◦)	94.21 ± 23.05	93.84 ± 23.02	0.532		103.86 ± 20.77	103.77 ± 20.57	0.837	0.122	0.108
	ROM (◦)	89.68 ± 24.94	89.65 ± 23.57	0.972		99.95 ± 18.92	99.69 ± 18.67	0.617	0.098	0.087
Ankle	PKF (◦)	29.73 ± 8.72	29.32 ± 9.39	0.698		28.74 ± 12.4	28.49 ± 10.43	0.830	0.752	0.855
	ROM (◦)	28.29 ± 8.14	28.60 ± 7.91	0.591		27.66 ± 6.56	28.32 ± 7.23	0.327	0.759	0.642

KPPL: knee pain painful limb; **KPNPL:** knee pain non-painful limb; **HDL:** healthy dominant limb; **HNDL**: healthy non-dominant limb; **PKF:** joint angle at peak knee flexion; **ROM**: range of motion during the whole cycle; **DLS:** double leg squat; ***** statistically significant findings (***p*< 0.05** for within-group and ***p*< 0.017** for between-group); **(◦)**: measurement unit in degrees. **Positive values** indicate flexion, abduction or dorsiflexion, whereas **negative values (-)** indicate extension, adduction or plantarflexion.

4.4.6. Double leg squat frontal plane results

In Table 16, movement alterations are presented according to the DLS movement cycle, starting from movement throughout the cycle, then the descending phase, maximum squat and, finally, the ascent phase.

4.4.6.1 DLS frontal plane within-subject (KPPL vs KPNPL and HDL vs HNDL) kinematic results

In the **SCI** of kinematic data, 17 movement alterations were identified in the KPPL compared to the KPNPL and 17 movement alterations in the HDL compared to the HNDL in the frontal plane across the hip, knee and ankle joints. All between-limb alterations are presented in Table 16.

Most frontal plane movement alterations identified in the CKP group (KPPL vs KPNPL) were found at the hip level, with an overall trend of increased hip abduction ROM throughout the cycle which was identified in the KPPL compared to the KPNPL and in the HDL compared to the HNDL. With regards to the knee joint, altered adduction ROM throughout the cycle was most commonly identified with an overall trend of increased knee adduction in both groups (KPPL vs KPNPL and HDL vs HNDL). The CKP group also demonstrated increased peak adduction at maximum squat in the KPPL compared to the KPNPL. At the ankle, altered adduction (increased or decreased) ROM throughout the cycle was identified in both groups (KPPL vs KPNPL and HDL vs HNDL).

For within-subject **SQA** (Table 17), both groups demonstrated significant differences at the knee joint during PKF, with an increased knee adduction angle in the KPPL compared to the KPNPL in the knee pain group (*p*= 0.029, mean ± SD= -3.90 ± 6.57 KPPL vs -1.83 ± 6.55 KPNPL, d= 0.515) and decreased abduction angle in the HDL compared to the HNDL in the healthy group (*p*= 0.007, mean ± SD= 1.55 ± 4.75 HDL vs 4.54 ± 4.74 HNDL, d= 0.48). The healthy participants exhibited another significant difference in the ankle joint at PKF with a decreased ankle adduction angle of the

HDL compared to the HNDL (*p*= 0.022, mean ± SD= -4.39 ± 10.39 HDL vs -7.18 ± 12.65 HNDL, d=0.411).

4.4.6.2 DLS frontal plane between-group (KPPL vs HDL and KPNPL vs HDL) kinematic results

Joint angle at PKF

There was no statistically significant difference in the hip and ankle abduction/adduction joint angles at PKF (*p*> 0.017). At the knee joint, the frontal plane presented a statistically significant increase in the knee adduction angle in the KPPL in the CKP group and the HDL in the healthy group (*p*< 0.001, mean ± SD – 3.90 ± 6.57 KPPL vs 1.55 ± 4.75 HDL, d= 0.982).

ROM during the whole cycle

ROM at the hip, knee and ankle joints exhibited no statistically significant difference between the groups (*p*> 0.017 for all joints).

In summary, the **frontal** plane presented an increase in knee adduction angle at maximum squat (dynamic knee valgus) which was the most recurrent alteration identified within-subjects in both the SCI and the SQA. This finding for the knee joint angle at PKF was confirmed by the SQA of within-subjects and between-groups but the mean differences between the limbs of the CKP group were very small, with a small effect size, thereby indicating a lack of clinical significance.

Table 16: DLS frontal plane SCI for HDL (n=31) and KPPL (n=21)

Joint	***Limb**	**Altered movement pattern**	**Number of participants**	**Percentage of participants**
Hip	**HDL**	Increased abduction ROM throughout cycle	10	32%
		Decreased abduction ROM throughout cycle	6	19%
		Increased peak abduction at maximum squat	4	12%
		Decreased peak abduction at maximum squat	2	6%
		Increased peak adduction at maximum squat	2	6%
	KPPL	Increased abduction ROM throughout cycle	7	33%
		Decreased abduction ROM throughout cycle	2	9%
		Increased peak abduction at maximum squat	2	9%
		Increase peak adduction at maximum squat	1	4%
		Late peak adduction at maximum squat	1	4%
		Early peak abduction at maximum squat	1	4%
		Increase abduction ROM at early descent	2	9%
		Decreased abduction ROM at early descent	1	4%
	HDL	Increased abduction ROM throughout cycle	1	3%
		Decreased abduction ROM throughout cycle	3	9%
		Increased adduction ROM throughout cycle	8	25%

Knee		Increased peak adduction at maximum squat	2	6%
		Decreased peak adduction at maximum squat	1	3%
		Decreased peak abduction at maximum squat	4	12%
	KPPL	Increased adduction ROM throughout cycle	5	23%
		Decreased adduction ROM throughout cycle	3	14%
		Increased peak adduction at maximum squat	6	28%
		Decreased peak adduction at maximum squat	1	4%
		Early peak abduction at maximum squat	1	4%
Ankle	**HDL**	Increased adduction ROM throughout cycle	4	12%
		Decreased adduction ROM throughout cycle	8	25%
		Increased abduction ROM throughout cycle	5	16%
		Decreased abduction ROM throughout cycle	1	3%
		Increased peak adduction at maximum squat	1	3%
		Decreased peak adduction at maximum squat	4	12%
	KPPL	Increased adduction ROM throughout cycle	8	38%
		Decreased adduction ROM throughout cycle	5	23%
		Decreased peak adduction at maximum squat	1	4%
		Decreased peak abduction at maximum squat	1	4%

*** In the limb section, HDL was compared to the HNDL, while the KPPL was compared to the KPNPL for each joint, each task and each plane of movement.**

Table 17: Summary statistics for double leg squat frontal plane within and between group comparisons

Joint	Time point	Within chronic knee pain group ($p< 0.05$)		Sig-	Within healthy group ($p< 0.05$)		Sig-	Between-groups ($p< 0.017$)	
		KPPL ± Mean SD	KPNPL Mean ± SD		HDL Mean ± SD	HNDL Mean ± SD		NPPL vs HDL	KPNL vs HDL
DLS									
Hip	PKF (◦)	9.510 ± 9.62	8.07 ± 10.11	0.354	11.04 ± 9.87	8.56 ± 8.63	0.236	0.603	0.297
	ROM (◦)	9.21 ± 5.71	8.60 ± 4.91	0.614	9.69 ± 5.96	8.79 ± 4.234	0.531	0.780	0.544
Knee	PKF (◦)	-3.90 ± 6.57	-1.83 ± 6.55	*0.029	1.55 ± 4.75	4.54 ± 4.74	*0.007	*0.001	0.035
	ROM (◦)	9.96 ± 5.47	9.59 ± 4.34	0.538	9.37 ± 3.18	9.85 ± 4.95	0.945	0.758	0.859
Ankle	PKF (◦)	-4.49 ± 9.76	-2.88 ± 9.38	0.281	-4.39 ± 10.39	-7.18 ± 12.65	*0.022	0.816	0.730
	ROM (◦)	7.310 ± 5.42	8.28 ± 5.17	0.156	9.25 ± 5.41	9.31 ± 7.210	0.938	0.081	0.407

KPPL: knee pain painful limb; **KPNPL:** knee pain non-painful limb; **HDL:** healthy dominant limb; **HNDL**: healthy non-dominant limb; **PKF:** joint angle at peak knee flexion; **ROM**: range of motion during the whole cycle; **DLS:** double leg squat; ***** statistically significant findings (**$p< 0.05$** for within-group and **$p< 0.017$** for between-group); **(◦)**: measurement unit in degrees. **Positive values** indicate flexion, abduction or dorsiflexion, whereas **negative values (-)** indicate extension, adduction or plantarflexion.

4.4.7 Single leg squat sagittal plane results

According to the SLS waveform graphs (see Appendix K), SLS consists of two main phases: the descent phase and the ascent phase. SLS begins by standing on one leg, with the other leg slightly lifted off the ground. The individual then starts bending their hips and knees as far as possible to reach their **maximum squat**, which is the point of **PKF**. Subsequently, individuals start extending their hip and knee and moving their body upwards. The descending phase is the start of the movement cycle and it is followed by the ascending phase.

In Table 18, movement alterations are presented according to the SLS movement cycle starting with movement throughout the cycle, then the descending phase, maximum squat and, finally, the ascent phase.

4.4.7.1 SLS sagittal plane within-subject (KPPL vs KPNPL and HDL vs HNDL) kinematic results

Analysis of SLS sagittal plane **SCI** of the hip, knee and ankle resulted in the identification of various alterations in both groups: 21 in the KPPL compared to the KPNPL and 28 in the HDL compared to the HNDL. All between limb alterations are presented in Table 18.

At the hip joint, the CKP group demonstrated a trend of lower peak hip flexion at maximum squat in the KPPL compared to the KPNPL. In contrast, in the healthy group (HDL vs HNDL), there was a trend for greater peak hip flexion at maximum squat in addition to increased flexion ROM during the whole cycle. At the knee joint, lower peak flexion at maximum squat was most commonly identified among the CKP participants (KPPL vs KPNPL) but in the healthy group (HDL vs HNDL), increased peak flexion at maximum squat was identified. At the ankle joint, the CKP group (KPPL vs KPNPL) demonstrated altered (increased or decreased) dorsiflexion ROM throughout the cycle or at maximum squat. The HDL exhibited a trend towards increased dorsiflexion ROM throughout the cycle.

For the **SQA** within the CKP group (Table 19), no statistically significant difference was identified in the KPPL compared to the KPNPL across the three joints (*p*> 0.05). The SLS only exhibited statistically significant findings in the healthy group at the ankle with decreased ankle dorsiflexion ROM in the HDL compared to the HNDL during the entire cycle (*p*= 0.013, mean ± SD= 24.46 ± 6.02 HDL vs 26.34 ± 5.8 HNDL, d= 0.474).

4.4.7.2 SLS sagittal plane between-group (KPPL vs HDL and KPNPL vs HDL) kinematic results

Joint angle at PKF

There were no statistically significant differences between groups in the hip and ankle peak joint angles in the SLS sagittal plane of movement (*p*> 0.017). The knee joint presented a statistically significant difference between groups at PKF, with a decreased peak flexion angle in both limbs of the CKP group compared to the HDL of the healthy group (*p*= 0.003, mean ± SD 57.15 ± 23.05 KPPL, 72.99 ± 20.77 HDL, d= 0.43; and *p*= 0.009, mean ± SD 61.03 ± 23.02 KPNPL vs 72.99 ± 20.77 HDL, d= 0.36, respectively).

ROM during the whole cycle

There was no statistically significant difference between groups in the ROM at the hip and ankle joints. Sagittal plane knee ROM presented a statistically significant difference between KPPL in the CKP group and the HDL in the healthy group with decreased knee flexion ROM in the KPPL compared to the HDL (*p*= 0.006, mean ± SD 48.90 ± 19.13 KPPL vs 63.39 ± 14.41 HDL, d= 0.477).

In summary, in the SLS **sagittal** plane of movement, the CKP group presented with a lower knee flexion angle at PKF and lower knee flexion ROM during the entire cycle compared to the HDL, which was identified in both the SCI and the SQA. Further alterations were identified in the SCI between limbs (KPPL vs KPNPL and

HDL vs HNDL) with the CKP group exhibiting a trend toward decreased flexion during the movement cycle among the three joints.

Table 18: SLS sagittal plane SCI for HDL (n=31) and KPPL (n=16)

Joint	* Limb	Altered movement pattern	Number of participants	Percentage of participants
Hip	HDL	Increased flexion ROM throughout cycle	4	12%
		Decreased flexion ROM throughout cycle	2	6%
		Increased flexion ROM during descent phase	4	12%
		Decreased flexion ROM during descent phase	3	9%
		Increased flexion ROM during ascent phase	1	3%
		Decreased flexion ROM during ascent phase	1	3%
		Increased peak flexion at maximum squat	15	48%
		Decreased peak flexion at maximum squat	8	25%
		Early peak flexion at maximum squat	1	3%
		Late peak flexion at maximum squat	1	3%
	KPPL	Increased flexion ROM throughout cycle	1	6%
		Decreased flexion ROM throughout cycle	1	6%
		Increased flexion ROM during descent phase	3	18%
		Increased peak flexion at maximum squat	1	6%
		Decreased peak flexion at maximum squat	6	37%
		Early peak flexion at maximum squat	2	12%

		Late peak flexion at maximum squat	1	6%
Knee	**HDL**	Increased flexion ROM throughout cycle	2	6%
		Decreased flexion ROM throughout cycle	2	6%
		Increased flexion ROM at early descent	6	19%
		Decreased flexion ROM during descent phase	3	9%
		Increased flexion ROM during ascent phase	1	3%
		Decreased flexion ROM during ascent phase	1	3%
		Increased peak flexion at maximum squat	10	32%
		Decreased peak flexion at maximum squat	6	19%
		Early peak flexion at maximum squat	2	6%
	KPPL	Increased flexion ROM throughout cycle	1	6%
		Increased flexion ROM during descent phase	3	18%
		Decreased flexion ROM during descent phase	2	12%
		Decreased flexion ROM during ascent phase	2	12%
		Decreased peak flexion at maximum squat	6	37%
		Early peak flexion at maximum squat	2	12%
Ankle	**HDL**	Increased dorsiflexion ROM throughout cycle	6	19%
		Decreased dorsiflexion ROM throughout cycle	2	6%
		Increased dorsiflexion during descent phase	2	6%

		Increased dorsiflexion at early descent	2	6%
		Decreased dorsiflexion at early descent	2	6%
		Increased dorsiflexion at late ascent	1	3%
		Decreased dorsiflexion at late ascent	1	3%
		Decreased peak dorsiflexion at maximum squat	2	6%
		Early peak dorsiflexion at maximum squat	1	3%
	KPPL	Increased dorsiflexion ROM throughout cycle	1	6%
		Decreased dorsiflexion ROM throughout cycle	2	12%
		Increased dorsiflexion ROM during descent phase	2	12%
		Decreased dorsiflexion ROM during ascent phase	1	6%
		Increased dorsiflexion at late ascent	1	6%
		Increased peak dorsiflexion at maximum squat	1	6%
		Decreased peak dorsiflexion at maximum squat	3	18%
		Early peak dorsiflexion at maximum squat	1	6%

*** In the limb section, HDL was compared to the HNDL and the KPPL was compared to the KPNPL for each joint, each task and each plane of movement.**

Table 19: Summary statistics for single leg squat sagittal plane within and between group comparisons

Joint	**Time point**	**Within chronic knee pain group (*$p < 0.05$*)**		**Sig-**	**Within healthy group (*$p < 0.05$*)**		**Sig-**	**Between-groups (*$p < 0.017$*)**	
		KPPL Mean ± SD	KPNPL Mean ± SD		HDL Mean ± SD	HNDL Mean ± SD		KPPL vs HDL	KPNPL vs HDL
SLS									
Hip	PKF (◦)	51.79 ± 21.27	52.74 ± 24.08	0.814	57.95 ± 21.29	55.05 ± 20.06	0.098	0.352	0.421
	ROM (◦)	41.88 ± 23.68	42.86 ± 23.24	0.642	49.98 ± 19.86	47.85 ± 18.70	0.185	0.138	0.140
Knee	PKF (◦)	57.15 ± 23.05	61.03 ± 23.02	0.552	72.99 ± 20.77	71.42 ± 20.57	0.115	*0.003	*0.009
	ROM (◦)	48.90 ± 19.13	53.58 ± 17.51	0.399	63.39 ± 14.41	62.67 ± 14.54	0.521	*0.006	0.034
Ankle	PKF (◦)	27.88 ± 7.35	29.09 ± 6.28	0.746	30.85 ± 6.28	30.74 ± 6.24	0.900	0.154	0.332
	ROM (◦)	22.86 ± 8.80	24.83 ± 6.85	0.490	24.46 ± 6.02	26.34 ± 5.83	*0.013	0.520	0.839

KPPL: knee pain painful limb; **KPNPL:** knee pain non-painful limb; **HDL:** healthy dominant limb; **HNDL**: healthy non-dominant limb; **PKF:** angle at peak knee flexion; **ROM**: range of motion during the whole cycle; **SLS:** single leg squat; ***** statistically significant findings (**$p < 0.05$** for within-group and **$p < 0.017$** for between-group); **(◦)**: measurement unit in degrees. **Positive values** indicate flexion, abduction or dorsiflexion, whereas **negative values (-)** indicate extension, adduction or plantarflexion.

4.4.8. Single leg squat frontal plane results

In Table 20, movement alterations are presented according to SLS movement cycle starting with movement throughout the cycle, then the descending phase, maximum squat and, finally, the ascent phase.

4.4.8.1 SLS frontal plane within-subject (KPPL vs KPNPL and HDL vs HNDL) kinematic results

In the **SCI** frontal plane of movement, 15 movement alterations were identified in the KPPL compared to the KPNPL and 17 in the HDL compared to the HNDL across the hip, knee and ankle joints. All between-limb alterations are presented in Table 20.

Overall, in both groups there was a trend for reduced adduction ROM at the hip throughout the cycle in both KPPL vs KPNPL and HDL vs HNDL. The opposite occurred at the knee joint for both groups between limbs and there appeared to be a trend overall for increased adduction (dynamic knee valgus). At the ankle, a large range of alterations were used in both KPPL vs KPNPL and HDL vs HNDL and there was no dominant pattern; people used a combination of increased or decreased abduction ROM throughout the cycle.

Regarding within-subject **SQA** (Table 21), the healthy group was found to have a statistically significant decrease in hip adduction angle at PKF in the HDL compared to the HNDL (*p*= 0.007, mean ± SD= -8.23 ± 5.85 HDL vs -11.97 ± 5.88 HNDL, d= 0.522).

4.4.8.2 SLS frontal plane between-group (KPPL vs HDL and KPNPL vs HDL) kinematic results

Joint angle at PKF

At PKF, the KPNPL of the CKP group compared to the HDL of the healthy group demonstrated a statistically significant increase in mean hip adduction angle ($p < 0.010$, mean ± SD -14.37 ± 7.03 KPNPL vs -8.23 ± 5.85 HDL, d= 0.773). However, knee and ankle abduction/adduction joint angles at PKF presented no statistically significant difference between the groups ($p > 0.017$).

ROM during the whole cycle

There was no statistically significant difference between the groups either at the hip joint or in the knee joint ($p > 0.017$). However, the ankle frontal plane ROM depicted a statistically significant difference between groups with decreased ankle abduction ROM in the KPNPL of the CKP group compared to the HDL in the healthy group ($p < 0.008$, mean ± SD 12.52 ± 6.45 KPNPL vs 15.52 ± 4.59 HDL, d= 0.799).

In summary, **frontal** plane SLS findings at the individual level (based on SCI) revealed that a range of individual alterations were present at each joint. There was a trend for the HDL and KPPL to demonstrate decreased hip adduction and increased knee adduction compared to their respective limbs. At the ankle, there was no dominant trend. Meanwhile, for the averaged data (SQA), these alterations were not found to be statistically significant. At the hip and ankle joint for the non-painful limb in the CKP group, the hip was found to have significantly increased adduction at PKF and the ankle significantly decreased abduction throughout the SLS.

Table 20: SLS frontal plane SCI for HDL (n= 31) and KPPL (n=16)

Joint	*Limb	Altered movement pattern	Number of participants	Percentage of participants
Hip	**HDL**	Increased adduction ROM throughout cycle	3	9%
		Decreased adduction ROM throughout cycle	13	41%
		Decreased adduction ROM during descent phase	3	9%
		Increased peak adduction at maximum squat	4	12%
		Decreased peak adduction at maximum squat	7	22%
		Late peak adduction at maximum squat	1	3%
	KPPL	Increased adduction ROM throughout cycle	3	18%
		Decreased adduction ROM throughout cycle	8	50%
		Increased peak adduction at maximum squat	3	18%
		Decreased peak adduction at maximum squat	3	18%
		Early peak adduction at maximum squat	1	6%
Knee	**HDL**	Increased adduction ROM throughout cycle	7	22%
		Increased abduction ROM throughout cycle	1	3%
		Increased peak adduction at maximum squat	4	12%
		Decreased peak adduction at maximum squat	2	6%

	KPPL	Increased adduction ROM throughout cycle	2	12%
		Decreased adduction ROM throughout cycle	1	6%
		Increased peak adduction at maximum squat	3	18%
		Decreased peak adduction at maximum squat	1	6%
		Early peak adduction at maximum squat	1	6%
Ankle	**HDL**	Increased abduction ROM throughout cycle	5	16%
		Decreased abduction ROM throughout cycle	3	9%
		Increased adduction ROM throughout cycle	1	3%
		Increased abduction ROM during descent phase	1	3%
		Increased abduction ROM at early descent	1	3%
		Decreased abduction ROM at early descent	5	16%
		Increased peak abduction at maximum squat	3	9%
	KPPL	Increased abduction ROM throughout cycle	3	18%
		Decreased abduction ROM throughout cycle	3	18%
		Decreased abduction during early descent	1	6%
		Decreased abduction at late ascent	1	6%
		Decreased peak abduction at maximum squat	1	6%

*** In the limb section, HDL was compared to the HNDL and the KPPL was compared to the KPNPL for each joint, each task and each plane of movement.**

Table 21: Summary statistics for single leg squat frontal plane within and between group comparisons

Joint	**Time point**	**Within chronic knee pain group (*p*< 0.05)**		**Sig-**		**Within healthy group (*p*< 0.05)**		**Sig-**	**Between-groups (*p*< 0.017)**	
		KPPL Mean SD	KPNPL Mean SD			HDL Mean SD	HNDL Mean SD		NPPL vs HDL	KPNPL vs HDL
SLS										
Hip	PKF (◦)	-10.53 ± 6.013	-14.37 ± 7.03	0.177		-8.23 ± 5.85	-11.97 ± 5.88	*0.007	0.212	*0.010
	ROM (◦)	11.04 ± 5.09	12.52 ± 6.45	0.453		11.14 ± 3.84	12.57 ± 5.42	0.138	0.939	0.647
Knee	PKF (◦)	-4.35 ± 4.77	-2.66 ± 4.86	0.423		-2.81 ± 5.28	-1.14 ± 5.32	0.085	0.333	0.743
	ROM (◦)	7.71 ± 3.91	7.46 ± 3.42	0.851		11.14 ± 3.84	12.57 ± 5.42	0.487	0.857	0.964
Ankle	PKF (◦)	11.81 ± 4.71	11.60 ± 4.84	0.905		8.52 ± 6.26	7.11 ± 5.51	0.098	0.071	0.109
	ROM (◦)	11.04 ± 5.09	12.52 ± 6.45	0.642		15.52 ± 4.59	14.35 ± 4.26	0.145	0.041	*0.008

KPPL: knee pain painful limb; **KPNPL:** knee pain non-painful limb; **HDL:** healthy dominant limb; **HNDL**: healthy non-dominant limb; **PKF:** joint angle at peak knee flexion; **ROM**: range of motion during the whole cycle; **SLS:** single leg squat; ***** statistically significant findings (***p*< 0.05** for within-group and ***p*< 0.017** for between-group); **(◦)**: measurement unit in degrees. **Positive values** indicate flexion, abduction or dorsiflexion, whereas **negative values (-)** indicate extension, adduction or plantarflexion.

4.4.9 Vertical jump sagittal plane results

In the VJ waveform graphs (see Appendix K), the movement cycle entails a preparatory phase in which the individual flexes their hips and knees, followed by an explosive upward motion as they extend their lower body muscles, propelling themselves off the ground. This take-off phase leads to an ascent, reaching the peak height of the jump before transitioning to the landing phase. The landing phase involves the individual absorbing the impact by flexing their lower body joints, stabilising their body to regain their balance and preparing for subsequent movements. In this movement cycle, the point of **PKF** signifies **the completion of the landing phase and the initiation of the take-off phase**. This is applied for the sagittal and frontal planes.

In Table 22, movement alterations are described according to the sequence of the movement cycle, starting with movement throughout the cycle, then the take-off phase and, finally, the landing phase.

4.4.9.1 VJ sagittal plane within-subject (KPPL vs KPNPL and HDL vs HNDL) kinematic results

There were 13 movement alterations in the KPPL compared to the KPNPL and 13 in the HDL compared to the HNDL in the sagittal plane across the hip, knee and ankle joints. All between-limb alterations are presented in Table 22.

Regarding the **SCI** at the hip joint, a very symmetrical pattern between limbs was identified because there are not many alterations between limbs (KPPL vs KPNPL and HDL vs HNDL) in these groups. At the knee joint, the most prevalent alteration appeared to be in the CKP group (KPPL vs KPNPL) which demonstrated less knee flexion ROM during take-off. At the ankle joint, there was a trend towards decreased peak dorsiflexion at the end of landing in the KPPL compared to the KPNPL. During take-off there was a trend for reduced plantarflexion in the KPPL compared to the KPNPL. The healthy people demonstrated no consistent alterations.

The results for the within-subject **SQA** between the KPPL compared to the KPNPL demonstrated no significant findings for the joint angles at PKF (end of landing) and the ROM during the entire cycle at the hip, knee or ankle joints (*p*> 0.05) (Table 23). However, the healthy group demonstrated a statistically significant difference at the hip joint at PKF (end of landing) with decreased hip flexion in the HDL compared to the HNDL (*p*= 0.017, mean ± SD= 42.97 ± 20.502 HDL vs 44.4 ± 19.98 HNDL, d= 0.455).

4.4.9.2 VJ sagittal plane between-group (KPPL vs HDL and KPNPL vs HDL) kinematic results

Joint angle at PKF

In the CKP group, the hip joint exhibited a significant increase in peak flexion angle for both limbs compared to the HDL (*p*= 0.004, mean ± SD 66.75 ± 30.75 KPPL vs 42.97 ± 20.502HDL, d=0.947; and *p*= 0.004, mean ± SD 65.79 ± 29.43 KPNPL vs 42.97 ± 20.502 HDL, d=0.932, respectively).

ROM during the whole cycle

The hip joint presented statistically significant increased hip flexion ROM during the entire cycle for both limbs in the CKP group compared to the HDL (*p*= 0.017, Mean ± SD 53.34 ± 28.57 KPPL vs 35.64 ± 18.18 HDL, d= 0.773; and *p*= 0.017, 52.65 ± 27.10 KPNPL vs 35.64 ± 18.18 HDL, d= 0.767, respectively). No other statistically significant difference was identified in the knee or ankle joints.

In summary, sagittal plane analysis only revealed decreased knee flexion ROM during take-off in the CKP group at the individual level and not in averaged data. Minimal sagittal plane differences were observed in the hip joints between limbs in both groups, thereby suggesting symmetrical patterns. SQA averaged data revealed significant alterations at PKF and in ROM throughout the cycle between the CKP and healthy groups, with a small clinically relevant decrease in hip flexion during healthy group landing. Individual-level analysis using SCI revealed detailed waveform alterations including joint angles and ROM during take-off and/or landing which were not captured by SQA.

Table 22: VJ sagittal plane SCI for HDL (n= 31) and KPPL (n=21)

Joint	*Limb	Altered movement pattern	Number of participants	Percentage of participants
Hip	**HDL**	Decreased flexion ROM throughout cycle	1	3%
		Decreased flexion ROM during take-off	2	6%
		Increased peak flexion at end of landing	1	3%
		Decreased peak flexion at end of landing	3	9%
	KPPL	Increased flexion ROM during take-off	1	4%
		Increased peak flexion at end of landing	1	4%
		Decreased peak flexion at end of landing	2	9%
Knee	**HDL**	Decreased flexion ROM throughout cycle	2	6%
		Decreased flexion ROM during take-off	3	9%
		Decreased flexion ROM during landing	1	3%
		Decreased peak flexion at end of landing	4	12%
		Increased peak flexion at end of landing	1	3%
	KPPL	Increased flexion ROM throughout cycle	1	4%
		Decreased flexion ROM throughout cycle	1	4%
		Increased flexion ROM during take-off	2	9%
		Decreased flexion ROM during take-off	5	23%
		Increased peak flexion at end of landing	1	4%
		Decreased peak flexion at end of landing	2	9%
Ankle	**HDL**	Increased plantarflexion ROM during take-off	6	19%
		Decreased plantarflexion ROM during take-off	7	22%
		Increased peak dorsiflexion at end of landing	7	22%

		Decreased peak dorsiflexion at end of landing	5	16%
	KPPL	Decreased dorsiflexion ROM throughout cycle	1	4%
		Increased plantarflexion ROM during take-off	4	19%
		Decreased plantarflexion ROM during take-off	6	28%
		Decreased peak dorsiflexion at end of landing	5	23%
*** In the limb section, the HDL was compared to the HNDL and the KPPL was compared to the KPNPL for each joint, each task and each plane of movement.**				

Table 23: Summary statistics for vertical jump sagittal plane within and between group comparisons

Joint	**Time point**	**Within chronic knee pain group (*p*< 0.05)**		**Sig-**	**Within healthy group (*p*< 0.05)**		**Sig-**	**Between-groups (*p*< 0.017)**	
		KPPL Mean ± SD	KPNPL Mean ± SD		HDL Mean ± SD	HNDL Mean ± SD		KPPL vs HDL	KPNPL vs HDL
VJ									
Hip	PKF (◦)	66.75 ± 30.75	65.79 ± 29.43	0.170	42.97 ±20.502	44.4 ±19.98	*0.017	*0.004	*0.004
	ROM (◦)	53.34 ± 28.57	52.65 ± 27.10	0.322	35.64 ±18.18	35.41 ±18.13	0.691	*0.017	*0.017
Knee	PKF (◦)	74.99 ± 20.01	75.110 ± 19.57	0.814	72.16 ± 17.75	72.7 ± 17.17	0.337	0.594	0.564
	ROM (◦)	66.96 ± 21.88	68.24 ± 21.44	0.198	64.85 ±17.56	64.37 ± 17.28	0.539	0.702	0.534
Ankle	PKF (◦)	27.84 ± 7.05	28.96 ± 8.87	0.385	27.93 ± 10.76	27.5 ± 10.73	0.609	0.975	0.718
	ROM (◦)	71.210 ± 15.56	73.53 ± 15.010	0.152	73.03 ±8.85	73.64 ±9.69	0.510	0.647	0.893

KPPL: knee pain painful limb; **KPNPL:** knee pain non-painful limb; **HDL:** healthy dominant limb; **HNDL**: healthy non-dominant limb; **PKF:** joint angle at peak knee flexion; **ROM**: range of motion during the entire cycle; **VJ:** vertical jump; ***** statistically significant findings (***p*< 0.05** for within-group and ***p*< 0.017** for between-group); **(◦)**: measurement unit in degrees. **Positive values** indicate flexion, abduction or dorsiflexion, whereas **negative values (-)** indicate extension, adduction or plantarflexion.

4.4.10 VJ frontal plane results

In Table 24, movement alterations are described according to the sequence of the movement cycle, starting with movement throughout the cycle, then the take-off phase and, finally, the landing phase.

4.4.10.1 VJ frontal plane within-subject (KPPL vs KPNPL and HDL vs HNDL) kinematic results

In the **SCI** of kinematic data, many altered movement patterns were observed in the frontal plane of the jumping task among all of the participants in both groups. A total of 17 movement alterations were identified in the KPPL compared to the KPNPL and 21 were identified in the HDL compared to the HNDL in the frontal plane among the hip, knee and ankle joints. All of the between limb alterations are presented in Table 24.

At the hip joint, neither group (KPPL vs KPNPL and HDL vs HNDL) presented consistency of movement at the hip and there was a trend for both increased or decreased abduction and adduction ROM throughout the cycle and also during the landing phase. At the knee joint, an overall trend of reduced knee abduction at the end of landing was identified in the KPPL compared to the KPNPL. However, no dominant alteration was identified between limbs in the healthy group. At the ankle joint, both the healthy group (HDL vs HNDL) and the CKP group (KPPL vs KPNPL) exhibited altered adduction and abduction ROM at the end of landing and during take-off.

For the **SQA,** no significant differences were identified in any of the outcome variables within-subjects in the CKP group (Table 25). On the other hand, healthy participants presented some significant findings, mainly at the knee and ankle joints. There was a decrease in the knee abduction angle at PKF (end of landing) in the HDL compared to the HNDL (*p*= 0.013, mean ± SD= 1.47 ± 5.25 HDL vs 3.62 ± 5.47 HNDL, d= 0.475). With regards to the ankle, there was an increase in ankle abduction ROM during the entire cycle in the HDL compared to the HNDL *(p*= 0.007, mean ± SD= 26.60 ± 8.76 HDL vs 21.77 ± 7.41 HNDL, d= 0.525). Another significant result was found at PKF (end of landing) with a decreased ankle adduction angle in the HDL compared to the HNDL *(p*= 0.004, mean ± SD= 0.97 ± 6.43 HDL vs -2.10 ± 6.09 HNDL, d= 0.568).

4.4.10.2 VJ frontal plane between-group (KPPL vs HDL and KPNPL vs HDL) kinematic results

Joint angle at PKF

There was no significant difference in the hip and ankle joints between groups at PKF. However, a significant increase in knee adduction was identified between the KPPL in the CKP group and the HDL in the healthy group (*p*< 0.015, mean ± SD -2.40 ± 5.70 KPPL vs 1.47 ± 5.25 HDL, d= 0.713).

ROM during the whole cycle

There were no statistically significant differences in the ROM between the groups at the hip, knee or ankle joint ROM during the whole cycle (*p*> 0.017).

In summary, in the **frontal** plane, the SCI of within-subjects were more consistent in the CKP group than in the healthy group, especially at the knee and ankle joints, which was also identified in the SQA. More alterations at the knee and ankle were identified between the limbs of the healthy group but these findings were not clinically significant. Between the two groups, increased knee adduction at end of landing phase (at PKF) was observed in the KPPL compared to the HDL in both analyses.

Table 24: VJ frontal plane SCI for HDL (n= 31) and KPPL (n=21)

Joint	*Limb	Altered movement pattern	Number of participants	Percentage of participants
Hip	**HDL**	Increased abduction ROM throughout cycle	5	16%
		Increased adduction ROM throughout cycle	3	9%
		Decreased adduction ROM throughout cycle	1	3%
		Increased abduction ROM during take-off	2	6%
		Increased adduction ROM during landing	5	16%
		Increased abduction ROM during landing	1	3%
		Increased peak abduction at end of landing	5	16%
		Decreased peak abduction at end of landing	1	3%
	KPPL	Increased abduction ROM throughout cycle	7	33%
		Decreased abduction ROM throughout cycle	4	19%
		Increased adduction ROM during landing	1	4%
		Increased peak adduction at end of landing	2	9%
		Decreased peak adduction at end of landing	2	9%
Knee	**HDL**	Increased abduction ROM throughout cycle	1	3%
		Increased peak adduction at maximum squat	3	9%
		Increased adduction ROM during landing	2	6%
		Decreased peak abduction at end of landing	3	9%
		Decreased peak adduction at end of landing	1	3%
	KPPL	Increased adduction ROM throughout cycle	1	4%
		Increased adduction ROM during landing	4	19%

		Decreased peak abduction at end of landing	7	33%
		Decreased peak adduction at end of landing	4	19%
Ankle	**HDL**	Increased adduction ROM throughout cycle	1	3%
		Decreased adduction ROM throughout cycle	1	3%
		Increased adduction ROM during take-off	13	41%
		Decreased adduction ROM during take-off	5	16%
		Increased adduction ROM during take-off to mid-landing	9	29%
		Increased abduction ROM during landing	8	25%
		Increased peak abduction at end of landing	15	48%
		Increased peak adduction at end of landing	3	9%
	KPPL	Increased adduction ROM throughout cycle	3	14%
		Decreased adduction ROM throughout cycle	2	9%
		Increased adduction ROM during take-off	5	23%
		Increased abduction during landing	3	14%
		Increased peak adduction at end of landing	4	19%
		Decreased peak adduction at end of landing	1	4%
		Increased peak abduction at end of landing	1	4%
		Decreased peak abduction at end of landing	3	14%

*** In the limb section, HDL was compared to the HNDL and the KPPL was compared to the KPNPL for each joint, each task and each plane of movement.**

Table 25: Summary statistics for vertical jump frontal plane within and between group comparisons

Joint	Time point	**Within chronic knee pain group (*p*< 0.05)**		Sig-		**Within healthy group (*p*< 0.05)**		Sig-	**Between-groups (*p*< 0.017)**	
		KPPL Mean ± SD	KPNP Mean ± SD			HDL Mean ± SD	HNDL Mean ± SD		NPPL vs HDL	KPNPL vs HDL
VJ										
Hip	PKF (◦)	5.83 ± 5.68	3.71 ± 5.66	0.194		2.42 ± 6.14	1.82 ± 5.87	0.814	0.048	0.445
	ROM (◦)	8.07 ± 3.44	6.91 ± 2.74	0.088		8.20 ± 4.3	7.95 ± 4.29	0.806	0.905	0.234
Knee	PKF (◦)	-2.40 ± 5.70	-1.39 ± 5.16	0.280		1.47 ± 5.25	3.62 ± 5.47	*0.013	*0.015	0.058
	ROM (◦)	9.65 ± 3.71	9.32 ± 3.03	0.698		8.79 ± 4.44	9.85 ± 5.08	0.342	0.470	0.637
Ankle	PKF (◦)	-0.45 ± 4.58	0.36 ± 6.45	0.608		0.97 ± 6.43	-2.1 ± 6.09	*0.004	0.388	0.737
	ROM (◦)	23.21 ± 9.16	21.65 ± 7.75	0.500		26.6 ± 8.76	21.77 ± 7.41	*0.007	0.184	0.041

KPPL: knee pain painful limb; **KPNPL:** knee pain non-painful limb; **HDL:** healthy dominant limb; **HNDL**: healthy non-dominant limb; **PKF:** joint angle at peak knee flexion; **ROM**: range of motion during the whole cycle; **VJ:** vertical jump; ***** statistically significant findings (***p*< 0.05** for within-group and ***p*< 0.017** for between-group); **(◦)**: measurement unit in degrees. **Positive values** indicate flexion, abduction or dorsiflexion, whereas **negative values (-)** indicate extension, adduction or plantarflexion.

4.4.11 Stair ascent sagittal plane results

SA waveform graphs (see Appendix K) show that the movement cycle begins when the foot touches the higher step (HS). This is followed by the mid-stance and terminal/late stance phase when the foot pushes off the ground to lift the body to the following stride. Subsequently, the swing phase begins at 64% of the movement cycle. Early swing marks the start of the swing leg's movement; mid-swing is when the leg swings past the body to contact the next step; and late swing is when the leg approaches the next step to prepare for another round of initial contact. **PKF** typically occurs in the **mid-to-late stance phase;** the knee flexes to allow the body to clear the step and maintain stability.

In Table 26, movement is arranged according to its sequence in the movement cycle, starting with movement throughout the cycle, then the stance phase (and subphases) and, finally, the swing phase (and subphases).

4.4.11.1 SA sagittal plane within-subject (KPPL vs KPNPL and HDL vs HNDL) kinematic results

In the **SCI** of the kinematic data, 24 movement alterations were identified in the KPPL compared to the KPNPL and 21 in the HDL compared to the HNDL in the sagittal plane of movement among the three joints. All between-limb alterations are presented in Table 26.

At the hip joint, both the healthy group (HDL versus HNDL) and the CKP group (KPPL versus KPNPL) used either increased or decreased flexion at different phases of the movement cycle. There was no prevalent alteration strategy. At the knee joint, participants in the CKP group (KPPL vs KPNPL) used a combination of increased and decreased flexion at the knee during the stance and swing phases. A similar pattern was identified in the healthy group between the HDL and HNDL. At the ankle joint, both groups demonstrated increased and decreased dorsiflexion and plantarflexion. No prevalent alteration identified.

The results for within-subject **SQA** between the KPPL compared to the KPNPL and the HDL compared to the HNDL indicated no significant findings in any of the outcome variables at the hip, knee or ankle joints ($p > 0.05$) in the SA sagittal plane of movement (Table 27).

4.4.11.2 SA sagittal plane between-group (KPPL vs HDL and KPNPL vs HDL) kinematic results

Joint angle at HS

None of the joints presented statistically significant results between groups at HS in the sagittal plane of movement ($p > 0.017$).

Joint angle at PKF

None of the joints presented statistically significant results between groups at PKF in the sagittal plane of movement ($p > 0.017$).

ROM during the whole cycle

The hip joint demonstrated a statistically significant reduction in hip flexion ROM during the entire cycle which existed between both limbs in the CKP group and the HDL in the healthy group ($p = 0.010$, mean ± SD 50.87 ± 5.09 KPPL vs 54.36 ± 4.12 HDL, d= 0.774; $p < 0.000$, mean ± SD 48.71 ± 5.41 KPNPL vs 54.36 ± 4.12 HDL, d= 1.214, respectively).

In summary, the **sagittal** plane finding of decreased hip flexion ROM during the whole cycle was the only finding identified in the SCI and SQA and was found in the CKP group (both limbs) compared to the healthy group. The SCI demonstrated various altered movement patterns between the limbs of both groups which were primarily identified in the knee joint of the CKP group and in the ankle joint of the healthy group.

Table 26: SA sagittal plane SCI for HDL (n= 31) and KPPL (n= 20)

Joint	*Limb	Altered movement pattern	Number of participants	Percentage of participants
Hip	**HDL**	Increased flexion ROM throughout cycle	1	3%
		Decreased flexion ROM throughout cycle	1	3%
		Increased peak flexion at early stance	3	9%
		Decreased peak flexion at early stance	5	16%
		Increased peak extension at mid-swing	5	16%
		Decreased flexion ROM from mid-stance to mid-swing	1	3%
	KPPL	Increased flexion ROM throughout cycle	1	5%
		Increased flexion ROM during stance phase	3	15%
		Decreased flexion ROM during early stance	4	20%
		Increased peak flexion at early stance	2	10%
		Decreased peak flexion at early stance	1	5%
		Early peak flexion at early stance	1	5%
		Decreased flexion ROM during swing	3	15%
		Increased peak extension at mid-swing	2	10%
Knee	**HDL**	Decreased flexion ROM throughout cycle	3	9%
		Increased flexion ROM during stance phase	3	9%
		Decreased flexion ROM during stance phase	5	16%
		Decreased extension ROM at late stance	1	3%
		Decreased flexion ROM during swing phase	1	3%
		Increased peak extension at mid-swing	4	12%

	KPPL	Increased flexion ROM throughout cycle	1	5%
		Increased flexion ROM during stance phase	1	5%
		Decreased flexion ROM during stance phase	6	30%
		Early peak flexion at late stance	1	5%
		Increased flexion ROM from mid-stance to mid-swing	1	5%
		Increased flexion ROM during early swing	2	10%
		Increased peak extension at early swing	2	10%
		Early peak extension at early swing	2	10%
		Decreased flexion ROM at mid-swing	4	20%
		Increased flexion ROM at late swing phase	1	5%
Ankle	**HDL**	Decreased dorsiflexion ROM throughout cycle	1	3%
		Increased dorsiflexion ROM during early stance	9	29%
		Increased plantarflexion ROM at early stance	2	6%
		Decreased dorsiflexion ROM during mid-stance	1	3%
		Decreased dorsiflexion ROM at late stance	2	6%
		Increased peak plantarflexion at push-off (late stance)	8	25%
		Decreased peak plantarflexion at push-off (late stance)	10	32%
		Early peak plantarflexion at push-off	2	6%
		Increased dorsiflexion ROM at late swing	2	6%
	KPPL	Increased dorsiflexion ROM during stance	3	15%
		Decreased dorsiflexion ROM during stance	3	15%
		Increased dorsiflexion ROM at early stance	1	5%
		Increased peak plantarflexion at push-off (late stance)	6	30%
		Decreased peak plantarflexion at push-off (late stance)	10	50%
		Increased dorsiflexion ROM at late swing phase	1	5%

*** In the limb section, HDL was compared to the HNDL and the KPPL was compared to the KPNPL for each joint, each task and each plane of movement.**

Table 27: Summary statistics for stair ascent sagittal plane within and between group comparisons

Joint	**Time point**	**Within chronic knee pain group (*p*< 0.05)**		**Sig-**		**Within healthy group (*p*< 0.05)**		**Sig-**	**Between-groups Sig (*p*< 0.017)**	
		KPPL Mean ± SD	KPNPL Mean ± SD			HDL Mean ± SD	HNDL Mean ± SD		KPPL vs HDL	KPNPL vs HDL
SA										
Hip	HS (◦)	40.55 ± 7.18	40.43 ± 8.22	0.918		37.96 ± 5.84	37.81 ± 5.48	0.853	0.166	0.217
	PKF (◦)	43.34 ± 7.12	43.04 ± 7.42	0.759		40.910 ± 5.43	41.65 ± 5.69	0.382	0.190	0.263
	ROM (◦)	50.87 ± 5.09	48.71 ± 5.41	0.082		54.36 ± 4.12	53.510 ± 4.710	0.102	*0.010	*0.000
Knee	HS (◦)	82.43 ± 8.29	82.75 ± 8.76	0.851		81.49 ± 6.38	82.76 ± 6.72	0.138	0.651	0.554
	PKF (◦)	85.95 ± 8.34	87.59 ± 8.30	0.270		86.53 ± 6.12	86.97 ± 6.38	0.608	0.773	0.603
	ROM (◦)	76.310 ± 8.92	76.75 ± 8.410	0.843		77.64 ± 5.63	77.40 ± 7.07	0.788	0.581	0.682
Ankle	HS (◦)	6.510 ± 5.85	4.39 ± 5.92	0.060		2.14 ± 7.93	0.23 ± 6.65	0.052	0.235	0.524
	PKF (◦)	7.08 ± 6.31	5.66 ± 6.70	0.212		3.49 ± 8.21	2.13 ± 6.88	0.170	0.235	0.721
	ROM (◦)	38.14 ± 9.77	41.23 ± 10.06	0.126		41.79 ± 9.63	42.11 ± 9.24	0.846	0.195	0.844

KPPL: knee pain painful limb; **KPNPL:** knee pain non-painful limb; **HDL:** healthy dominant limb; **HNDL**: healthy non-dominant limb; **HS:** joint angle at heel-strike; **PKF:** joint angle at peak knee flexion; **ROM**: range of motion during the whole cycle; **SA:** stair ascent; ***** statistically significant findings (***p*< 0.05** for within-group and ***p*< 0.017** for between-group); **(◦)**: measurement unit in degrees. **Positive values** indicate flexion, abduction or dorsiflexion, whereas **negative values (-)** indicate extension, adduction or plantarflexion.

4.4.12 Stair ascent frontal plane results

In Table 28, movement is arranged according to its sequence in the movement cycle, starting with movement throughout the cycle, then the stance phase and, finally, the swing phase.

4.4.12.1 SA frontal plane within-subject (KPPL vs KPNPL and HDL vs HNDL) kinematic results

For the frontal plane **SCI**, there were 23 movement alterations in the KPPL compared to the KPNPL, and 24 in the HDL compared to the HNDL among the three joints for both groups. All between-limb alterations are displayed in Table 28.

At the hip joint, in both groups there is an overall prevalence of increased abduction ROM throughout the cycle and during stance but some evidence that certain people use less abduction. At the knee joint, both the healthy group (HDL versus HNDL) and the CKP group (KPPL versus KPNPL) exhibit increased abduction and adduction ROM throughout the cycle and specific alterations during the stance phase. Among the three joints, the ankle joint presented the most movement alterations in both groups. A trend towards altered ankle adduction ROM throughout the cycle and at different points during the stance phase was identified in both groups. Increased ankle adduction ROM at the late swing was more frequently identified in the KPPL compared to the KPNPL.

Regarding the **SQA** (Table 29), a statistically significant increase in ankle abduction ROM was observed in the KPPL compared to the KPNPL limb within the CKP group (*p*= 0.038, mean ± SD= 22.73 ± 5.65 KPPL vs 19.54 ± 3.82 KPNPL, d= 0.499). Notably, a similar trend was identified in the healthy group, with the HDL demonstrating greater ankle abduction ROM compared to the HNDL (*p*= 0.000, mean ± SD= 20.44 ± 4.96 HDL vs 16.76 ± 4.56 HNDL, d= 0.751).

Statistically significant increases in hip abduction angles at both HS and PKF were also observed in the healthy group in the HDL compared to the HNDL (*p*= 0.046, mean ± SD= 7.31 ± 4.21 HDL vs 4.91 ± 5.09 HNDL, d= 0.374; and *p*= 0.030, mean ± SD= 7.32 ± 4.39 HDL vs 4.40 ± 5.81 HNDL, d= 0.409, respectively).

4.4.12.2 SA frontal plane between-group (KPPL vs HDL and KPNPL vs HDL) kinematic results

Joint angle at HS

No statistically significant differences were found between groups for the hip and knee joints. However, a notable decrease in the ankle adduction angle in the KPPL in the CKP group compared to the HDL in the healthy group was identified (*p*= 0.010, mean ± SD= -5.68 ± 5.19 KPPL vs -10.27 ± 6.43 HDL, d=0.768).

Joint angle at PKF

No statistically significant differences were observed between groups for the hip and knee joint angles at PKF (*p*> 0.017). However, the ankle joint demonstrated a statistically significantly decreased ankle adduction angle in the KPPL compared to the HDL (*p*= 0.012, mean ± SD= -5.83 ± 5.49 KPPL vs -10.58 ± 6.81 HDL, d= 0.361).

ROM during the whole cycle

There was no statistically significant difference found between groups at any of the lower limb joints' ROM (*p*> 0.017).

In summary, the **frontal** plane SCI indicated that most within-subject variations were identified at the ankle joint with more details regarding where these variations existed among the entire movement cycle but this was also confirmed in the within-subjects and between-group SQA because the most significant findings were identified at the ankle joint. Altered (increased or decreased) ankle adduction angles were identified between the limbs of both groups in both the SCI and the SQA. This finding presents statistically significant results at HS and at PKF (during the stance phase) between groups.

Table 28: SA frontal plane SCI for HDL (n= 31) and KPPL (n= 20)

Joint	*Limb	Altered movement pattern	Number of participants	Percentage of participants
Hip	**HDL**	Increased abduction ROM throughout cycle	7	22%
		Decreased abduction ROM throughout cycle	3	9%
		Increased adduction ROM throughout cycle	1	3%
		Increased abduction ROM during stance phase	7	22%
		Increased adduction ROM during early stance	2	6%
		Decreased peak adduction at mid-stance	1	3%
		Decreased abduction ROM from late stance to late swing	1	3%
	KPPL	Increased abduction ROM throughout cycle	3	15%
		Increased adduction ROM throughout cycle	5	25%
		Increased abduction ROM during stance phase	3	15%
		Decreased abduction ROM during stance phase	4	20%
		Increased abduction ROM at late swing	1	5%
		Decreased abduction ROM at mid-stance and mid-swing	1	5%
Knee	**HDL**	Increased abduction ROM throughout cycle	1	3%
		Increased adduction ROM during stance phase	7	22%
		Decreased adduction ROM at early stance	3	9%
		Increased peak adduction at mid-stance	2	6%
		Decreased peak adduction at mid-stance	1	3%
		Increased adduction ROM during late swing	3	9%
		Increased abduction ROM throughout cycle	1	5%

	KPPL	Increased adduction ROM at early stance	7	35%
		Decreased peak adduction at mid-stance	3	15%
		Increased adduction ROM from early to mid-stance	1	5%
		Increased abduction at late swing	1	5%
		Increased adduction at late swing	1	5%
Ankle	**HDL**	Increased adduction ROM throughout cycle	6	19%
		Decreased adduction ROM throughout cycle	4	12%
		Increased abduction during stance phase	1	3%
		Increased adduction at early stance	5	16%
		Increased abduction ROM from mid-to-late stance	1	3%
		Increased peak adduction at mid-stance	8	25%
		Decreased peak adduction at mid-stance	12	38%
		Early peak adduction at mid-stance	2	6%
		Increased adduction ROM during late swing	1	3%
		Increased abduction ROM during late swing	1	3%
		Decreased adduction ROM at late swing	3	9%
	KPPL	Increased adduction ROM throughout cycle	1	5%
		Decreased adduction ROM throughout cycle	4	20%
		Decreased adduction ROM during stance phase	5	25%
		Increased peak adduction at mid-stance	4	20%
		Early peak adduction at early stance	1	5%
		Later peak adduction at late stance	1	5%
		Increased adduction ROM from mid-stance to early swing	2	10%
		Increased abduction from mid-stance to mid-swing	1	5%
		Increased adduction ROM during late swing	7	35%

		Decreased adduction ROM during late swing	4	20%
		Increased adduction ROM during swing phase	1	5%
*** In the limb section, HDL was compared to the HNDL and the KPPL was compared to the KPNPL for each joint, each task and each plane of movement.**				

Table 29: Summary statistics for stair ascent frontal plane within and between group comparisons

Joint	**Time point**	**Within chronic knee pain group ($p < 0.05$)**		**Sig-**		**Within healthy group ($p < 0.05$)**		**Sig-**	**Between-groups ($p < 0.017$)**	
		KPPL Mean ± SD	KPNPL Mean ± SD			HDL Mean ± SD	HNDL Mean ± SD		NPPL vs HDL	KPNPL vs HDL
SA										
Hip	HS (◦)	6.22 ± 4.62	6.32 ± 5.27	0.931		7.31 ± 4.21	4.91 ± 5.09	*0.046	0.390	0.463
	PKF (◦)	5.75 ± 5.49	5.83 ± 5.11	1.000		7.32 ± 4.39	4.40 ± 5.81	*0.030	0.650	0.272
	ROM (◦)	10.90 ± 3.29	11.01 ± 3.910	0.841		10.41 ± 3.52	11.14 ± 3.65	0.360	0.537	0.643
Knee	HS (◦)	-3.11 ± 5.04	-2.33 ± 5.31	0.517		-1.43 ± 6.48	0.65 ± 6.57	0.078	0.333	0.605
	PKF (◦)	-3.44 ± 5.30	-2.03 ± 5.20	0.188		-1.18 ± 6.79	0.10 ± 6.88	0.239	0.214	0.638
	ROM (◦)	12.38 ± 5.24	12.99 ± 4.56	0.652		13.31 ± 5.92	12.28 ± 4.41	0.313	0.728	0.908
Ankle	HS (◦)	-5.68 ± 5.19	-6.65 ± 4.84	0.577		-10.27 ± 6.43	-9.18 ± 5.03	0.390	*0.010	0.036
	PKF (◦)	-5.83 ± 5.49	-6.67 ± 5.40	0.629		-10.58 ± 6.81	-9.56 ± 4.61	0.394	*0.012	0.035
	ROM (◦)	22.73 ± 5.65	19.54 ± 3.82	*0.038		20.44 ± 4.96	16.76 ± 4.56	*0.000	0.133	0.496

KPPL: knee pain painful limb; **KPNPL:** knee pain non-painful limb; **HDL:** healthy dominant limb; **HNDL**: healthy non-dominant limb; **HS:** joint angle at heel-strike; **PKF:** joint angle at peak knee flexion; **ROM**: range of motion during the whole cycle; **SA:** stair ascent; ***** statistically significant findings (**$p < 0.05$** for within-group and **$p < 0.017$** for between-group); **(◦)**: measurement unit in degrees. **Positive values** indicate flexion, abduction or dorsiflexion, whereas **negative values (-)** indicate extension, adduction or plantarflexion.

4.4.13 Stair descent sagittal plane results

According to the SD waveform graphs (see Appendix K), the movement cycle begins with the early stance phase when the foot initially makes contact with the lower step (HS). Next is the mid-stance when the descending limb supports the body. In the late/terminal stance, the descending leg pushes off the step, starting the descent to the following step. After stance, the swing leg's knee flexes to clear the step in the early swing phase. Mid-swing, the leg swings past the body to prepare for the next cycle phase. In the late swing phase, the swing leg approaches the next step and the knee extends to prepare for the next initial contact with the lower step. **PKF** occurs during **the stance phase (early to mid-stance)**.

In Table 30, movement is arranged according to its sequence in the movement cycle, starting with the movement during the whole cycle, then the stance phase and, finally, the swing phase.

4.4.13.1 SD sagittal plane within-subject (KPPL vs KPNPL and HDL vs HNDL) kinematic results

According to the **SCI** of the kinematic data, 20 movement alterations were identified in the KPPL compared to the KPNPL and 18 in the HDL compared to the HNDL among the three joints in the sagittal plane of movement. All between-limb alterations are presented in Table 30.

At the hip joint, the CKP group demonstrated altered (increased or decreased) hip flexion ROM throughout the cycle in the KPPL compared to the KPNPL, particularly during the stance phase. In the healthy group, decreased peak flexion at early swing was the most commonly identified alteration in the HDL compared to the HNDL. In the knee joint, both groups demonstrated altered flexion ROM during the stance phase in the KPPL compared to the KPNPL and in the HDL compared to the HNDL, with notable changes in peak flexion at different points during the stance phase. Reduced knee flexion ROM during the swing phase was also prevalent in both groups. With regards to ankle joint alterations, the CKP group demonstrated decreased peak plantarflexion during the swing phase of SD but this finding was more variable in the healthy group, with most participants demonstrating decreased peak plantarflexion, whereas others presented increased peak plantarflexion in the HDL compared to the HNDL. The CKP group also presented altered (increased or decreased) dorsiflexion ROM during the stance phase in the KPPL compared to the KPNPL.

The results of within-subject **SQA** between the KPPL compared to the KPNPL and the HDL compared to the HNDL demonstrated no significant findings in any of the outcome variables at the hip, knee or ankle joints (*p*> 0.05) in the SD sagittal plane of movement (Table 31).

4.4.13.2 SD sagittal plane between-group (KPPL vs HDL and KPNPL vs HDL) kinematic results

Joint angle at HS

A statistically significant increase in hip flexion angles in both limbs of the CKP group compared to the HDL in the healthy group was observed (*p*= 0.004, mean ± SD= 13.91 ± 6.76 KPPL vs 8.84 ± 5.29 HDL, d= 0.859; and *p*= 0.002, 14.46 ± 6.62 KPNPL vs 8.84 ± 5.29 HDL, d= 0.963).

Joint angle at PKF

No statistically significant differences were observed between groups in either the knee or ankle joint (p> 0.017). However, a significant finding was noted at the hip joint, indicating a greater hip flexion angle at PKF in the KPNPL compared to the HDL (*p*= 0.002, mean ± SD= 32.47 ± 6.11 KPNPL vs 27.48 ± 4.68 HDL, d= 0.263).

ROM during the whole cycle

A statistically significant increase in knee flexion ROM throughout the whole cycle was identified in the KPPL compared to the HDL (*p*= 0.016, 73.78 ± 10.11 KPPL vs

71.05 ±4.95 HDL, d= 0.342). No statistically significant difference between the groups was identified at the hip or ankle joints (*p*> 0.017).

In summary, in the SD analysis of the **sagittal** plane, increased hip flexion was identified between groups in both the SCI and SQA. Most of the alterations identified by the SCI were evident during the stance phase of SD, with fewer alterations occurring in the ROM throughout the whole cycle. However, the SQA only presented a significant increase in flexion ROM between groups at the knee joint and this finding was not clinically significant.

Table 30: SD sagittal plane SCI for HDL (n= 31) and KPPL (n=20)

Joint	*Limb	Altered movement pattern	Number of participants	Percentage of participants
Hip	**HDL**	Decreased flexion ROM throughout cycle	1	3%
		Increased flexion ROM during stance	2	6%
		Increased extension ROM during stance	1	3%
		Decreased flexion ROM during swing	2	6%
		Decreased peak flexion at early swing	7	22%
		Late peak flexion at mid-swing	2	6%
	KPPL	Increased flexion ROM throughout cycle	1	5%
		Decreased flexion ROM throughout cycle	2	10%
		Increased flexion ROM during stance phase	5	25%
		Decreased flexion ROM during stance phase	4	20%
		Decreased flexion ROM at mid-stance	3	15%
		Increased flexion ROM during late stance phase	2	10%
		Increased flexion from early to mid-stance	2	10%
		Decreased flexion ROM during swing phase	2	10%
Knee	**HDL**	Decreased flexion ROM during stance	8	25%
		Increased peak flexion at late stance	8	25%
		Decreased peak flexion at late stance	4	12%
		Early peak flexion at late stance	5	16%
		Late peak flexion at late stance	4	12%
		Decreased flexion ROM at late swing	9	29%
		Increased flexion ROM during swing	3	9%

	KPPL	Decreased flexion ROM during stance phase	6	30%
		Increased peak flexion from mid-to-late stance	6	30%
		Early peak flexion at mid-stance	6	30%
		Late peak flexion at late stance	3	15%
		Decreased peak flexion at late stance	4	20%
		Decreased flexion ROM during swing	4	20%
Ankle	**HDL**	Increased dorsiflexion from early to mid-stance	2	6%
		Decreased plantarflexion ROM from mid-stance to mid-swing	3	9%
		Increased peak plantarflexion at mid-swing	6	19%
		Decreased peak plantarflexion at mid-swing	11	35%
		Early peak plantarflexion at mid-swing	4	12%
	KPPL	Decreased plantarflexion ROM throughout cycle	2	10%
		Increased dorsiflexion ROM during stance	4	20%
		Decreased dorsiflexion ROM during stance	5	25%
		Increased plantarflexion ROM during early and mid-stance phase	1	5%
		Decreased peak plantarflexion at mid-swing	5	25%
		Early peak plantarflexion at mid-swing	1	5%
*** In the limb section, HDL was compared to the HNDL and the KPPL was compared to the KPNPL for each joint, each task and each plane of movement.**				

Table 31: Summary statistics for stair descent sagittal plane within and between group comparisons

Joint	**Time point**	**Within chronic knee pain group (*p*< 0.05)**		**Sig-**		**Within healthy group (*p*< 0.05)**		**Sig-**	**Between-groups (*p*< 0.017)**	
		KPPL Mean ± SD	PNPL Mean ± SD			HDL Mean ± SD	HNDL Mean ± SD		KPPL vs HDL	KPNPL vs HDL
SD										
Hip	HS (◦)	13.91 ± 6.76	14.46 ± 6.62	0.611		8.84 ± 5.29	8.82 ± 6.03	0.980	*0.004	*0.002
	PKF (◦)	31.82 ± 6.89	32.47 ± 6.11	0.513		27.48 ± 4.68	27.85 ± 5.11	0.519	0.019	*0.002
	ROM (◦)	28.04 ± 6.88	28.94 ± 4.46	0.490		26.75 ± 2.89	26.93 ± 3.75	0.764	0.847	0.038
Knee	HS (◦)	20.34 ± 9.29	22.45 ± 10.42	0.208		22.1 ± 7.17	23.4 ± 7.54	0.092	0.449	0.889
	PKF (◦)	80.59 ± 11.47	80.85 ± 9.16	0.940		81.38 ± 6.66	81.01 ± 7.09	0.600	0.985	0.811
	ROM (◦)	73.78 ± 10.11	72.57 ± 7.47	0.173		71.05 ± 4.95	69.99 ± 4.85	0.076	*0.016	0.302
Ankle	HS (◦)	8.87 ± 5.38	10.92 ± 7.08	0.225		10.99 ± 4.66	11.28 ± 4.81	0.645	0.210	0.960
	PKF (◦)	-5.83 ± 9.62	-6.65 ± 8.74	0.503		-9.23 ± 10.44	-9.83 ± 9.73	0.606	0.247	0.364
	ROM (◦)	51.35 ± 10.27	51.72 ± 9.63	0.863		57.64 ± 9.85	58.6 ± 9.9	0.307	0.033	0.039

KPPL: knee pain painful limb; **KPNPL:** knee pain non-painful limb; **HDL:** healthy dominant limb; **HNDL**: healthy non-dominant limb; **HS:** joint angle at heel-strike; **PKF:** joint angle at peak knee flexion; **ROM**: range of motion during the whole cycle; **SD:** stair descent; ***** statistically significant findings (***p*< 0.05** for within-group and ***p*< 0.017** for between-group); **(◦)**: measurement unit in degrees. **Positive values** indicate flexion, abduction or dorsiflexion, whereas **negative values (-)** indicate extension, adduction or plantarflexion.

4.4.14 Stair descent frontal plane results

In Table 32, movement is arranged according to its sequence in the movement cycle, starting with the movement during the whole cycle, then the stance phase and, finally, the swing phase.

4.4.14.1 SD frontal plane within-subject (KPPL vs KPNPL and HDL vs HNDL) kinematic results

According to the **SCI** of kinematic data, 16 movement alterations were identified in the KPPL compared to the KPNPL, and 16 in the HDL compared to the HNDL in stair descent frontal plane of movement across the hip, knee and ankle joints. All between limb alterations are presented in Table 32.

Regarding the hip joint, both groups present similarities in increased abduction and adduction ROM throughout the cycle, as identified in the KPPL compared to the KPNPL and in the HDL compared to the HNDL. However, increased hip adduction ROM during early and mid-stance and a later peak abduction during the late stance phase were also identified in the CKP group (KPPL versus KPNPL). These findings suggest potential alterations in hip joint movement patterns during stair descent among individuals with CKP. Regarding the knee joint, the CKP group displayed an increase in knee adduction during the late stance phase which was the most identified alteration in the KPPL compared to the KPNPL. The healthy group demonstrated altered knee adduction ROM throughout the movement cycle and during stance in the HDL compared to the HNDL. At the ankle joint, both groups (KPPL versus KPNPL and HDL versus HNDL) demonstrated altered (decreased or increased) peak ankle adduction during the swing phase but the CKP group also demonstrated later peak adduction during the swing phase of SD. Other alterations found in both groups were altered abduction/adduction ROM during the stance and/or swing phases.

With regards to the **SQA** (Table 33), both groups exhibited a significant increase in hip abduction ROM during the entire cycle in the KPPL compared to the KPNPL of the CKP group (*p*= 0.036, mean ± SD= 15.05 ± 4.47 KPPL vs 13.72 ± 3.97 KPNPL, d=0.46) and in the HDL compared to the HNDL of the healthy group (*p*= 0.024, mean ± SD= 15.15 ± 2.90 HDL vs 14.18 ± 3.78 HNDL, d= 0.428). Additionally, a significant increase in ankle abduction ROM during the entire cycle was identified in the HDL compared to the HNDL (*p*= 0.001, mean ± SD= 22.17 ± 5.23 HDL vs 18.52 ± 5.32 HNDL, d= 0.643).

4.4.14.2 SD frontal plane between-group (KPPL vs HDL and KPNPL vs HDL) kinematic results

Joint angle at HS

There were no statistically significant findings between groups at the hip, knee or ankle joint angles at HS in the frontal plane of movement (*p*> 0.017).

Joint angle at PKF

There were no statistically significant findings between groups at the hip, knee or ankle joint angles at PKF in the frontal plane of movement (*p*> 0.017).

ROM during the whole cycle

There were no statistically significant differences in the ROM between the groups at the hip, knee or ankle joints during the entire cycle (*p*> 0.017).

In summary, the **frontal** plane SCI of SD presented altered hip and ankle abduction ROM between-limbs in both groups. This finding presented a statistically significant result during the whole movement cycle between limbs in the SQA but the SCI demonstrated more details regarding the timing of these alterations during the movement cycle. A few alterations were also identified in the knee joint but these were only evident in the SCI.

Table 32: SD frontal plane SCI for HDL (n=31) and KPPL (n= 20)

Joint	*Limb	Altered movement pattern	Number of participants	Percentage of participants
Hip	HDL	Increased abduction ROM throughout cycle	3	9%
		Increased adduction ROM throughout cycle	7	22%
		Decreased peak abduction at mid-stance	3	9%
		Increased abduction ROM from mid-stance to mid-swing	4	12%
		Decreased abduction ROM from mid-stance to mid-swing	1	3%
		Increased abduction ROM during swing phase	1	3%
	KPPL	Increased abduction ROM throughout cycle	4	20%
		Increased adduction ROM throughout cycle	4	20%
		Increased adduction ROM during early and mid-stance phase	4	20%
		Decreased peak abduction at mid-stance	2	10%
		Late peak abduction at late stance	2	10%
Knee	HDL	Increased adduction ROM throughout cycle	4	12%
		Increased adduction ROM during stance	5	16%
		Decreased peak abduction at mid-stance	3	9%
		Early peak adduction at mid-stance	3	9%
	KPPL	Decreased adduction ROM throughout cycle	1	5%
		Decreased abduction ROM throughout cycle	1	5%
		Increased adduction ROM during late stance phase	5	25%
		Increased peak abduction at mid-stance	2	10%
		Increased abduction ROM during swing	1	5%

Ankle	**HDL**	Increased adduction ROM throughout cycle	4	12%
		Decreased adduction ROM during stance phase	4	12%
		Increased abduction ROM from early to mid-stance	5	16%
		Increased adduction ROM from mid- stance to mid-swing	5	16%
		Increased peak adduction at mid-swing	9	29%
		Decreased peak adduction at mid-swing	6	19%
	KPPL	Increased abduction ROM throughout cycle	1	5%
		Increased adduction ROM throughout cycle	3	15%
		Decreased abduction ROM during stance phase	3	15%
		Increased adduction ROM during late stance and swing phase	4	20%
		Late and increased peak adduction at late swing	10	50%
		Late and decreased peak adduction at late swing	5	25%

*** In the limb section, HDL was compared to the HNDL and the KPPL was compared to the KPNPL for each joint, each task and each plane of movement.**

Table 33: Summary statistics for stair descent frontal plane within and between group comparisons

Joint	Time point	Within chronic knee pain group (*p*< 0.05)		Sig-		Within healthy group (*p*< 0.05)		Sig-	Between-groups (*p*< 0.017)	
		KPPL Mean ± SD	KPNPL Mean ± SD			HDL Mean ± SD	HNDL Mean ± SD		NPPL vs HDL	KPNPL vs HDL
SD										
Hip	HS (◦)	-2.89 ± 5.49	-1.56 ± 4.34	0.359		-2.96 ± 4.24	-2.38 ± 3.14	0.500	0.957	0.258
	PKF (◦)	7.84 ± 3.53	8.17 ± 5.22	0.789		9.18 ± 3.13	8.66 ± 4.78	0.582	0.160	0.440
	ROM (◦)	15.05 ± 4.47	13.72 ± 3.97	*0.036		15.15 ± 2.9	14.18 ± 3.78	*0.024	0.452	0.145
Knee	HS (◦)	-0.65 ± 1.6	-0.38 ± 0.97	0.313		-0.52 ± 1.89	0.12 ± 1.8	0.061	0.772	0.847
	PKF (◦)	-1.01 ± 5.14	0.83 ± 5.21	0.180		2.13 ± 6.65	3.41 ± 5.62	0.213	0.080	0.465
	ROM (◦)	9.62 ± 2.74	10.68 ± 3.31	0.322		10.45 ± 4.37	10.39 ± 4.03	0.869	0.499	0.487
Ankle	HS (◦)	6.10 ± 4.77	6.43 ± 4.76	0.809		3.75 ± 7.03	1.91 ± 5.62	0.127	0.196	0.141
	PKF (◦)	-2.16 ± 5.82	0.37 ± 5.99	0.122		-4.32 ± 8.42	-4.39 ± 6.04	0.955	0.320	0.036
	ROM (◦)	22.21 ± 5.49	20.71 ± 6.36	0.473		22.17 ± 5.23	18.52 ± 5.32	*0.001	0.981	0.376

KPPL: knee pain painful limb; **KPNPL:** knee pain non-painful limb; **HDL:** healthy dominant limb; **HNDL**: healthy non-dominant limb; **HS:** angle at heel-strike; **PKF:** angle at peak knee flexion; **ROM**: range of motion during the whole cycle; **SD:** stair descent; ***** statistically significant findings (***p*< 0.05** for within-group and ***p*< 0.017** for between-group); **(◦)**: measurement unit in degrees. **Positive values** indicate flexion, abduction or dorsiflexion, whereas **negative values (-)** indicate extension, adduction or plantarflexion.

4.5 Section summary

To summarise, a variety of altered movement patterns were identified in the within and between groups in the sagittal and frontal planes of movement during the execution of various functional tasks using the SCI and SQA of kinematic data. Table 34 presents a summary of the findings from both the SCI and SQA.

During gait, the sagittal plane analysis revealed ankle-related alterations in both the CKP and healthy groups. The CKP participants exhibited reduced knee flexion during stance alongside limited ankle plantarflexion during swing. Many individual variations were emphasised in the CKP group. In the frontal plane, diverse movement alterations were evident among the CKP and the healthy participants, with no significant differences found among the CKP or between the CKP and the healthy participants. The averaged data indicated a significant decrease in knee adduction angle at HS between the painful limb of CKP and the HDL of the healthy group. There was evidence of increased hip abduction between-limbs in the healthy group.

During DLS, neither group demonstrated a consistent pattern of increased or decreased hip, knee or ankle flexion in sagittal plane movements. The averaged data did not reveal any significant group or limb variations and this is likely to be due to diverse kinematic patterns between limbs. In the frontal plane, the participants showed an increased knee adduction angle (dynamic knee valgus) at maximum squat, a recurrent alteration in the CKP group. However, at an individual level there was a prevalence of more alterations in knee abduction/adduction ROM throughout the movement cycle and at maximum squat.

During SLS, lower knee flexion angles and reduced knee flexion ROM across the cycle were identified between the CKP and healthy groups, with further variations on an individual level between limbs with the CKP group exhibiting a trend towards decreased flexion ROM among the three joints. In the frontal plane there was a trend for the HDL and KPPL to demonstrate decreased hip adduction and increased knee adduction compared to their respective limbs. No dominant trend was observed at the ankle. In the CKP group, the hip joint of the KPNPL exhibited a statistically significant increase in adduction at PKF, while the ankle joint showed a statistically significant decrease in abduction throughout the SLS.

During VJ, sagittal plane analysis revealed reduced knee flexion ROM during take-off in the CKP group, identified only at the individual level. Minimal sagittal plane differences were observed in the hip joints between limbs, indicating symmetrical patterns in both groups. SQA averaged data revealed significant alterations at PKF and in ROM throughout the cycle between the CKP and healthy groups, with a small clinically relevant decrease in hip flexion during healthy group landing. Individual-level analysis using SCI revealed detailed waveform alterations not captured by SQA, including joint angles and ROM during take-off and/or landing. In the frontal plane, the SCI of individuals demonstrated greater consistency in the CKP group compared to the healthy group, especially at the knee and ankle joints, as corroborated by SQA. More alterations at the knee and ankle were identified between the limbs of the healthy group, although these were clinically insignificant. Between the two groups, increased knee adduction at the end of the landing phase (at PKF) was found in the KPPL compared to the HDL in both analyses.

During SA, decreased hip flexion ROM during the entire cycle was identified in the CKP group (both limbs) compared to the healthy group which was identified between both groups at the individual level and when averaging the data. Individuals presented various altered movement patterns between limbs, primarily at the knee joint in the CKP group and at the ankle joint in the healthy group. In the frontal plane, altered ankle adduction ROM was identified between limbs in both groups but the averaged data presented statistically significant between-group results at HS and PKF.

During SD, increased hip flexion was identified between groups. Individuals in both groups revealed several alterations during the stance phase of SD across the hip, knee and ankle joints, although these findings did not yield statistically significant results. Minimal alterations were found in the ROM throughout the cycle among individuals, as confirmed by the averaged data. In the frontal plane, altered hip and ankle abduction ROM were identified between limbs in both groups. Individually, additional insights into the timing of these alterations during the movement cycle were identified. Few alterations were identified in the knee joint among the CKP and healthy individuals.

Table 34: Summary of the results of the standard quantitative analysis and structured clinical interpretation of kinematic data in the sagittal and frontal planes

		Sagittal plane findings			**Frontal plane findings**		
		SQA of kinematic data		**SCI of kinematic data (between limbs within groups for CKP & healthy)**	**SQA of kinematic data**		**SCI of kinematic data (between limbs within groups for CKP & healthy)**
		Within-subjects	**Between-groups**		**Within-subjects**	**Between-groups**	
Gait	**ROM**	None.	Statistically significant **decrease in ankle dorsiflexion** between KPPL vs HDL.	Hip: No consistency in the nature of the identified alterations. Knee: Reduced flexion ROM during stance was mostly identified between limbs of CKP group. Most alterations occurred at the **ankle** for both groups. Altered plantarflexion ROM during swing was identified in both groups.	Statistically significant **increase in ankle abduction** ROM in the HDL vs HNDL.	None.	Hip: Increased hip abduction ROM at early-stance in the HDL vs HNDL. Altered abduction and adduction ROM between limbs in both groups. Knee: Altered peak adduction during swing between limbs in both groups. Ankle: Altered adduction ROM during swing in both groups.
	At PKF	Statistically significant **decrease in hip flexion** angle between HDL vs HNDL.	Statistically significant **decrease in ankle plantarflexion** between KPPL vs HDL.		None.	None.	
	At-HS	None	Statistically significant decreased **knee flexion** between KPPL vs HDL.		Statistically significant **increase in hip abduction** in the HDL vs HNDL.	Statistically significant **decrease in knee adductio**n between KPPL & HDL.	

DLS	**ROM**	None.	None.	No consistency of increased or decreased hip and knee flexion and ankle dorsiflexion between limbs in both groups.		None.	Hip: Increased **hip abduction** ROM between limbs in both groups. Knee: **Increased adduction** ROM between limbs in both groups and increased peak adduction at maximum squat in the KPPL vs KPNPL. Ankle: **Altered adduction** ROM in both groups.
	At-PKF	None.	None.		Significant **increase** in **knee adduction** within CKP group. **Decreased knee abduction and ankle adduction** between limbs of the healthy group.	Statistically significant **increase** in **knee adduction** ROM between KPPL vs HDL.	
SLS	**ROM**	Statistically significant decrease in **ankle** dorsiflexion in the HDL vs HNDL.	Statistically significant decrease in peak **knee** flexion between KPPL vs HDL.	Hip and knee: **Decreased hip and knee flexion** angles at maximum squat between limbs in the CKP group. Ankle: **Altered ankle dorsiflexion** ROM throughout the cycle within the CKP group and **increased dorsiflexion at maximum squat** between limbs of healthy group.	None.	Statistically significant **decrease in ankle abduction** in the KPNPL vs HDL.	Hip: Decreased hip adduction ROM between limbs in both groups. Knee: Increased adduction between limbs in both groups. Ankle: No dominant pattern of increased or decreased abduction ROM.
	At-PKF	None.	Statistically significant decrease in **knee** flexion in the CKP (both limbs) vs HDL.		Statistically significant **decrease** in **hip adduction** in the HDL & HNDL.	Statistically significant **increase in hip adduction** between KPNPL & HDL.	

SA	**ROM**	None.	Statistically significant **decrease** in **hip flexion** between both limbs in CKP group vs HDL.	Hip, knee and ankle: there were **no consistent patterns** of increased or decreased hip or knee flexion or ankle dorsiflexion between limbs in both groups.	Statistically significant **increase** in **ankle abduction ROM** within both groups.	None.	Hip: Increased abduction ROM throughout the cycle and during stance between limbs in both groups. Knee: Increased abduction and adduction ROM throughout the cycle. More alterations identified during the stance phase. Ankle: Altered adduction ROM throughout the cycle and during stance between limbs in both groups. Increased ankle adduction ROM at late swing in the CKP group.
	At-PKF	None.	None.		Statistically significant **increase** in **hip abduction** between HDL vs HNDL.	Statistically significant **decrease in ankle adduction** angle between KPPL & HDL.	
	HS	None.	None.		Statistically significant **increase** in **hip abduction** between HDL vs HNDL.	Statistically significant **decrease in ankle adduction** angle between KPPL & HDL.	
SD	**ROM**	None.	Statistically significant **increase** in **knee ROM** between KPPL and HDL.	Hip: **Altered hip flexion** ROM throughout the cycle and during stance between limbs in the CKP group. **Decreased peak hip flexion** at early swing between limbs of the healthy group.	Statistically significant **increase in hip abduction** between limbs of both groups. Statistically significant **increase in**	None.	Hip: Increased abduction & **adduction** ROM between limbs in both groups. Increased adduction ROM during early and mid-stance and later peak abduction during late stance within the CKP group.

				Knee: **Altered flexion ROM** during stance and **decreased knee flexion** ROM during swing between limbs of both groups. Ankle: **Decreased peak plantarflexion** during swing and **altered dorsiflexion** during stance between limbs in the CKP group.	**ankle abduction** in the HDL vs HNDL.		Knee: Increased adduction at late stance between limbs in the CKP group. Ankle: Altered peak ankle adduction during swing in both groups. Late peak adduction during swing between limbs of the CKP group.
	At-PKF	None.	Statistically significant increase in **hip flexion** between KPNPL and HDL.		None.	None.	
	HS	None.	Statistically significant increase in **hip** flexion angle between CKP group and HDL.		None.	None.	
VJ	**ROM**	Significant decrease in hip flexion ROM in the HDL vs HNDL,	Statistically significant increase **in hip flexion** ROM in the KPPL vs HDL.	Hip: Very symmetrical pattern between limbs in both groups. Knee: **Decreased knee flexion** ROM during take-off between limbs of CKP. Ankle: **Decreased dorsiflexion** during landing between limbs of the CKP group. **Decreased**	Statistically significant **increase in ankle abduction** ROM in the HDL vs HNDL.	None.	Hip: No consistent pattern. Increased or decreased abduction and adduction ROM throughout the cycle and at the end of landing in both groups. Knee: Decreased abduction angle at end of landing between-limbs of the CKP group.
	At-PKF	Statistically significant **decrease in hip flexion** angle in HDL vs HNDL.	Statistically significant increase in **hip flexion** angle between CKP group (KPPL,		Statistically significant **decrease in knee abduction** in	Statistically significant **increase in knee adduction** between KPPL & HDL.	

			KPNPL) vs HDL.	**plantarflexion ROM** in the CKP group.	the HDL vs HNDL. Statistically significant **decrease in ankle adduction angle** in the HDL vs HNDL.		Ankle: Altered adduction and abduction ROM at the end of landing and during take-off between-limbs of both groups.

DLS: double leg squat; SLS: single leg squat; VJ: vertical jump; SA: stair ascent; SD: stair descent; CKP: chronic knee pain group; ROM: range of motion; PKF: joint angle at peak knee flexion; HS: joint angle at heel-strike; KPPL: knee pain painful limb; KPNPL: knee pain non-painful limb; HDL: healthy dominant limb; HNDL: healthy non-dominant limb; In within-subjects column, the KPPL was compared to the KPNPL and the HDL was compared to the HNDL. In the between-groups column, both limbs in the CKP group (KPPL and KPNPL) were compared to the HDL.

Chapter 5 Discussion of part 1

This study sought to identify **the between-group and within-subject kinematic differences of people with and without CKP during various functional tasks (gait, DLS, SLS, VJ, SA and SD) in the sagittal and frontal planes for the hip, knee and ankle joints using IMUs**. This was first achieved via a SCI of kinematic waveform data which explored altered movement patterns among people with CKP and healthy individuals using a standardised reporting template. Second, a SQA of kinematic data was conducted to statistically evaluate differences in kinematics at discrete timepoints between CKP and healthy individuals and knee pain for injured and uninjured limbs and healthy dominant and non-dominant limbs. These data were collected outside of the laboratory in a more natural and less controlled setting using IMUs.

5.1 Summary of the overarching findings

A summary of the main kinematic findings is provided in Table 35. Overall, the findings indicate the following:

- The SCI analysis contributed to the results extracted from the SQA analysis in that it enabled analysis of the complexity of the movement cycle in its entirety and provided additional information regarding the variety of movement patterns performed at an individual level in both groups without being limited to averaged data for a group at discrete timepoints.
- The SCI of both planes of movement showed that kinematic differences between the affected and unaffected sides in CKP and the dominant and non-dominant limb of the healthy group are present in the index (knee) joint as well as the adjacent joints.
- Most within-group statistically significant findings demonstrated small effect sizes which indicated limited clinical significance.

- Movement alterations were also presented in the non-painful limb, thereby indicating that the unaffected side should always be included when evaluating patients with unilateral pathology to ensure that secondary alterations are understood in a more comprehensive manner.
- The overall lack of significant differences between-limbs within CKP individuals may correspond to the wide range of alterations identified at the individual level (SCI analysis).
- In clinical practice, integrating individualised kinematic analysis of movement patterns with pain and function assessments is essential to ensure a comprehensive understanding of movement alterations which can offer valuable insights for tailored interventions.

Table 35: Summary of the overarching findings for within and between-group kinematic differences

Activity	Sagittal plane findings	Frontal plane findings
Gait	CKP participants exhibited: - Reduced knee flexion ROM during stance and at HS (between-groups). - Limited ankle plantarflexion during swing. - Both individual and averaged data presented ankle-related alterations observed between limbs and groups.	- No significant differences found within or between CKP and HDL but most were in healthy participants with small-to-moderate effect sizes. - Evidence of increased hip abduction between limbs in the healthy group in averaged and individual data. - Significant reduction in knee adduction angle at HS between painful limb of CKP and HDL (healthy limb) of the healthy group.
DLS	- No consistent pattern of increased or decreased hip, knee or ankle flexion observed in either group.	- Increased knee adduction angle (dynamic knee valgus) at maximum squat observed in both groups. - Alterations in knee abduction/adduction ROM at an individual level throughout the movement cycle and at maximum squat. - Individuals in both groups demonstrated between-limb increase in hip abduction and altered ankle abduction ROM.
SLS	- Lower knee flexion angles and reduced knee flexion ROM identified between groups. - Further variations on an individual level between limbs in the CKP group: Trend towards decreased flexion ROM among the three joints.	- Individually, there was a trend for HDL and KPPL to demonstrate decreased hip adduction and increased knee adduction. However, between-group averaged data demonstrated a statistically significant increase in hip adduction of the KPNPL compared to the HDL exhibited at PKF.

	- Trend towards increased flexion ROM among the three joints in the healthy group.	-Individually, no dominant trend was observed at the ankle but a statistically significant reduction in abduction ROM throughout the SLS was found between-groups (KPNPL and HDL).
VJ	- At the individual level, reduced knee flexion ROM during take-off in the KPPL and during landing in the HDL, in comparison to their respective limbs, were identified. - Minimal sagittal plane differences observed in hip joints between limbs, thereby indicating symmetrical patterns in both groups. - SQA averaged data highlighted significant hip alterations at PKF and in ROM throughout the cycle with increased hip flexion between CKP (both limbs) and HDL.	- SCI of individuals demonstrated greater consistency between limbs in the CKP group, especially at the knee and ankle joints. - More alterations at the knee and ankle identified between the limbs of the healthy group, although these were clinically insignificant. - Between both groups, increased knee adduction at the end of the landing phase was found in the KPPL compared to the HDL in both analyses.

SA	- Individually, no prevalent alteration identified between limbs at the hip joint. - Decreased hip flexion ROM during the entire cycle identified in the CKP group (both limbs) compared to the healthy limb only when data were averaged. - Individuals demonstrated various altered movement patterns between limbs; primarily at the knee joint in the CKP group. - At the ankle joint in the healthy group.	- Altered ankle adduction ROM identified between limbs in both groups. - Averaged data presented statistically significant increase in eversion results between groups (KPPL vs HDL) at HS and PKF. - Between limbs, CKP individuals demonstrated altered hip abduction/adduction but averaged data indicated a significant increase in hip abduction between the limbs of the healthy group.
SD	- Increased hip flexion at HS identified between groups in the CKP group vs HDL but hip movement varied between-groups and limbs across individuals.	- Altered hip (between-limbs in both groups) and ankle abduction ROM (between-limbs in HDL vs HNDL) were identified within both groups. - Absence of significant between-group findings. - Individually, additional insights into the timing of these alterations during the movement cycle were identified.
CKP= chronic knee pain; **KPPL=** knee pain painful limb; **KPNPL=** knee pain non-painful limb; **HDL=** healthy dominant limb; **HNDL=** healthy non-dominant limb; **SQA=** standard quantitative analysis; **SCI=** structured clinical interpretation; **HS=** heel-strike; **ROM=** range of motion; **PKF=** peak knee flexion; **DLS=** double leg squat; **SLS=** single leg squat; **VJ=** vertical jump; **SA=** stair ascent; **SD=** stair descent.		

5.2 Subject demographics

While the participants in the current study were not matched for gender, the percentage of female participants was approximately similar in both groups. Additionally, the percentage of female participants in both groups was slightly higher than that of the male participants. A substantial body of literature indicates that the prevalence of certain CKP conditions (e.g., OA and PFPS) is higher among females in comparison to males. For example, being female is regarded as a risk factor in the development of knee OA (Kellgren and Moore 1952; Pereira et al. 2011; Hunter and Bierma-Zeinstra 2019).

With respect to age, despite considerable efforts to assure age matching among participants, a difference in age was observed between the two groups, with the CKP group being older than the comparator group. This could potentially be attributed to exclusion criteria that limited participation to healthy individuals with specific health conditions (e.g., prior knee joint surgery or injury, or the use of walking assistance). Consequently, the eligibility criteria were satisfied exclusively by younger individuals. Regarding individuals with CKP, prior research suggests that the prevalence of OA escalates from 50 to 75 years of age (Jarvholm et al. 2005; Moghimi et al. 2019). The participants in the current study who had CKP had an average age of 45 years, which does not necessarily correspond to the age range for OA.

5.3 Knee injury and osteoarthritis outcome scores and numeric pain rating scale

The KOOS questionnaire was only used to evaluate the subjective severity of the CKP group. Its results showcased the impact of knee pain across five domains: pain, symptoms, activities of daily living (ADL), sports and recreational activities, and overall knee-related quality of life (QoL). In terms of pain and symptoms domains, the CKP participants in the current study reported higher scores compared to the findings in the previous literature by Ismailidis et al. (2021), van der Straaten et al. (2020), Ismailidis et al. (2020), Crossley et al. (2017), and Grenholm et al. (2009). This was also reflected in the ADL and quality of life domains because the mean scores in the current study were higher than those presented by the aforementioned studies. Therefore, this may suggest that the participants in the current study experienced less pain and better function, which may affect how they moved across the various activities.

With regards to the NPRS, the average pain score for the participants with CKP was 3.33/10. According to the NPRS, pain severity is presented on a scale ranging from 0 (no pain) to 10 (maximum/extreme pain) (McCaffery and Beebe 1989). Based on the cut-off points provided in their study, McCaffery and Beebe (1989) stated that a pain score of 3.33/10 would fall within the ‘mild’ category. This suggests that, on average, the CKP population in the current study reported a relatively low level of pain according to this established scale. Notably, the NPRS results align with the KOOS pain, suggesting a lower pain intensity compared to the other literature concerning movement analysis (Emamvirdi et al. 2023; Beebe et al. 2021; Vårbakken et al. 2019). The relatively lower average NPRS score in the current study relative to the findings in other CKP studies in the previous literature could be attributed in part to the recruitment strategy employed. Most of the participants in the current study were self-referred from the community and were not actively seeking treatment. In addition, relatively few participants were recruited from the NHS and seeking treatment, possibly resulting in a cohort with milder symptoms.

While these self-reported measures of function and pain are significant in terms of providing valid and accurate information about patients' function and pain, a notable limitation is that they do not provide direct information regarding how people move (Brenneman et al. 2016). Accordingly, in clinical practice, movement data need to be considered alongside information about pain and function to identify when and what intervention is needed. Therefore, kinematic analysis of individuals’ movement patterns would provide a comprehensive overview of their movement and provide additional information about an individual’s performance and how this may contribute to the score from the pain and function questionnaires.

5.4 Interpretation and comparison of kinematic findings with previous literature

5.4.1 Gait

The current analysis revealed several between-limb alterations among the CKP group, contrasting with statistically significant differences in the hip and ankle joints between limbs in the healthy group when data were averaged in both planes of movement (see Table 35). Despite the statistical significance, these differences in the healthy group exhibited small-to-moderate effect sizes, thereby suggesting a lack of clinical relevance.

In the sagittal plane analysis, individuals with CKP demonstrated reduced knee flexion ROM during stance. Previous research has similarly reported kinematic differences in CKP individuals during gait, with lower peak knee flexion angles for the affected limb compared to the non-affected limb (Ismailidis et al. 2021; Mills et al. 2013; Creaby et al. 2012; Briem and Snyder-Mackler 2009; Lewek et al. 2006). These studies, however, present conflicting findings at heel strike (HS), possibly due to variations in pain severity, as demonstrated by Ismailidis et al. (2021) who included individuals with severe knee OA, unlike the other studies which focused on mild-to-moderate severity.

Notably, reported sagittal plane kinematic changes across studies were generally less than 3°, raising uncertainty with regards to clinical significance (Ismailidis et al. 2021; Mills et al. 2013; Creaby et al. 2012; Briem and Snyder-Mackler 2009; Lewek et al. 2006). In our CKP population, the between-limb difference was approximately 1.5°, potentially contributing to the lack of statistical significance in the averaged data. The absence of clinically meaningful differences among the individuals in both groups could be attributed to the equal effort exerted by both lower limbs during gait, a primary activity for healthy subjects. Overall, the variations in movement pattern identified between limbs in both groups emphasise the importance of individualised analyses rather than standard group means at discrete time points, necessitating further exploration in larger clinical cohorts to establish clinical significance (Negrini et al. 2022).

The finding of reduced knee flexion at HS was more prevalent in the between- group analysis between the KPPL and healthy group. This finding is corroborated by those of previous studies (Nagano et al. 2012; Duffell et al. 2014; Zeni et al. 2009; Astephen et al. 2008; Mundermann et al. 2005). Duffell et al. (2014) supported the current findings when they examined people with early-stage OA. Their findings showed that gait alterations often linked with OA do not occur in the early stages, whereas neuromuscular adaptations are evident and presented as postural control deficits during one leg standing and altered hip adduction moment (Duffell et al. 2014). It is possible that the avoidance strategy to pain or reduced stability of the knee is induced by reduced knee extension strength, which adversely affects the knee flexion angle (Cabral et al. 2021).

Although many studies in the previous literature have reported findings of decreased knee flexion during the stance and swing phases (Ismailidis et al. 2021; Ismailidis et al. 2020; van der Straaten et al. 2020; Ro et al. 2019; McCarthy et al. 2013; Rahman et al. 2015), these studies only featured severe OA participants who were scheduled for TKA. This could be different from the population in the current study which was not limited to the OA population and their KOOS results indicated that they were not severely affected. To clarify, the KOOS sub-scores presented in Ismailidis et al.’s (2021 and 2020) studies were much lower than the KOOS scores in the current study’s CKP population, thereby suggesting that the knee pain population in the current study was of lower severity. Hence, this may have led to the absence of some movement alterations. Mündermann et al. (2005) found that reduced knee flexion at HS was mostly prominent in people with less severe knee pain. Messier et al. (2005) hypothesised that individuals with knee OA reduce the knee extension moment and, consequently, knee compressive forces by reducing their walking velocity in reaction to pain. Their results supported the discovery of this difference solely in the population with severe knee OA. Astephen et al. (2008) also reported increased gait alterations among people experiencing knee pain which were only apparent among severe OA populations. These investigations supported the current study’s conclusion that individuals with mild-to-moderate disease typically experience less pain and greater joint mobility and, hence, do not exhibit the same deficit in dynamic ROM.

The current study’s sagittal plane findings also demonstrated altered ankle plantarflexion ROM during the swing phase which was identified between individuals and in the averaged data. There is a paucity of previous studies that have evaluated kinematic differences at the ankle between patients with CKP and healthy controls. The results of the current study are consistent with those of Ismailidis et al. (2021) and Ismailidis et al. (2020). While these studies examined people with severe knee OA, Mundermann et al. (2005) reported that ankle angles in the sagittal plane were the same, irrespective of whether patients had less or more severe knee OA. Altered ankle plantarflexion and dorsiflexion during swing is common in CKP conditions and has been found to compensate for knee flexion to avoid heel striking and toe walking on the affected side (Robon et al. 2000). Joint contractures can produce aberrant gait patterns and knee flexion contractures create short leg limps (Ismailidis et al. 2021). The plantarflexion moment at the ankle creates the knee extension moment, while quadricep spasticity reduces knee flexion during the swing phase (Ismailidis et al. 2021).

In the frontal plane, the current study revealed a statistically significant increase in knee abduction angle at HS in the CKP group compared to the healthy group. This finding aligns with Mundermann et al.'s (2005) suggestion that individuals with CKP may employ greater hip adductor muscle forces at HS, potentially aiming to laterally move the trunk, although trunk movement was not assessed in the current study. This lateral trunk motion may be facilitated by a medial force exerted by the foot on the ground, representing a gait alteration often observed in individuals with knee pain to unload the knee joint.

These gait alterations not only affect the knee joint but also extend to adjacent weight-bearing joints including the hip and ankle (Schmitt et al. 2015). The current study’s between-limb analysis of individuals in both groups emphasised the complexity and individual variability of altered movement patterns in the CKP group, affecting not only the knee joint but also the hip and ankle joints. Despite the prevalence of these alterations, individual variability was apparent in the averaged data where no statistically significant differences were found between limbs within the CKP group or between the painful limb of CKP and the HDL in the healthy group.

Only limited research has investigated secondary gait alterations in adjacent joints but Ro et al. (2019) demonstrated that mechanical changes in the knee joint significantly affect the ROM throughout the cycle, coronal motion arc, and joint moment at the hip and ankle. Although the current study's results did not indicate significant differences in knee ROM during the whole cycle, movement alterations were evident in ankle ROM and the increased knee abduction angle at HS, thereby underscoring that the alterations observed in knee movement during gait are not isolated but are part of a complex and interconnected system involving multiple joints.

Some important factors in the methodologies of gait analysis studies may explain the heterogeneity of the findings. To clarify, the gait analysis walkway was only 6m in some studies, which may have caused some participants to walk slower than usual (Duffell et al. 2014). The footwear used by the participants also varied. To remove footwear effects, the participants in the current study walked barefoot (Morio et al. 2009; Zhang et al. 2013b). Some research studies gave the participants standard footwear, others let them walk barefoot, while some wore their own footwear. In some instances, no description of the footwear was offered.

Calibration of motion capture equipment is also important. We employed static and dynamic calibration to accurately extract kinematic data in the current investigation. Most of the empirical research defined the biomechanical model and estimated the joint angles using static calibration. This position may not be neutral for knee pain patients, especially those with significant OA and joint contractures (the knee is severely flexed), which could affect the kinematic results (Favre et al. 2014; Nagano 2012).

5.4.2 Double leg squat

The current findings of between-limb and between-group analysis demonstrated very limited alterations in the sagittal plane (see Table 35), which was reflected in the averaged data by the absence of statistically significant results. Only very few studies have investigated DLS movement for people with CKP. The current study confirms the findings of previous research indicating equivalent flexion angles during DLS in individuals with anterior knee pain (Severin et al. 2017) and others with ACL injury (Roos et al. 2014; Salem et al. 2003). Nevertheless, the authors emphasised that there were kinetic variations between the limbs and cautioned that compensatory movements may not be reflected in the kinematics. Without access to kinetic measures, it is often difficult for practitioners to discover joint substitutions (Severin et al. 2017).

Roos et al. (2014) and Salem et al. (2003) found comparable flexion angles during DLS in persons with a history of ACL injury. Severin et al. (2017) found no significant differences between groups either in the sagittal or frontal plane of movement. The sagittal plane findings could be the result of substituted altered movement patterns by frontal plane movement (Pappas and Carpes 2012). The current findings were more pronounced in the frontal plane and demonstrated altered knee adduction ROM throughout the cycle which was primarily identified between limbs in both groups. The CKP group also demonstrated increased peak knee adduction at maximum squat which was identified between groups (KPPL vs HDL) and limbs (KPPL vs KPNPL).

These inconsistent frontal plane findings between the current study and Severin et al. (2017) could be attributed to the difference in the ages of the study population because the CKP group in the current study were significantly older than those participating in Severin et al.’s (2017) study. Additionally, it could be a result of their inclusion criteria which only included subjects who had experienced lateral knee pain for at least three months, otherwise they were declared healthy (Severin et al. 2017). According to the author's knowledge, these inclusion criteria do not account for individuals with PFPS who should exhibit retro-patellar or anterior knee pain that lasts for more than six weeks and is aggravated by at least two of the following: squatting, prolonged sitting, and/or ascending or descending stairs (Liebbrandt and Louw 2017).

The finding of increased knee adduction could be an avoidance strategy to alleviate pain. Additionally, knee valgus is known to contribute to most of the non-contact ACL injuries and is a result of a lack of femoral control which leads to increased adduction and internal rotation and, consequently, increased stress on the ACL (Bell et al. 2013). Knee valgus can be controlled by the knee's proximal and distal joints, including the trunk, hip and ankle. These findings indicate that some movement alterations could be presented in the other adjacent joints to unload the knee, even though they were not statistically significant and may cause the condition to worsen if not targeted appropriately (Bell et al. 2013). The current study’s between-limb findings for individuals in both groups indicated that multiple alterations appeared in the hip and ankle joints including increased hip abduction and altered ankle abduction ROM. Therefore, physiotherapists should consider the adjacent joints in their rehabilitation for this pain population.

The healthy group recorded significant frontal plane findings of decreased knee abduction and ankle adduction at PKF but the effect sizes were small, thereby indicating no clinical significance. However, this strategy could cause future knee pain and injury if not corrected (Baniasad et al. 2022). Han et al. (2013) recommended that healthy and CKP people perform squats in a neutral position because squeezing and outward squats can cause joint diseases. Clinically, activities which target knee-joint muscles from the top-down or bottom-up reduce knee valgus. These findings may help physiotherapists to develop individual exercise regimens which reduce knee valgus to prevent lower limb injuries.

5.4.3 Single leg squat

Between-limb kinematic analysis of SLS indicated reduced hip and knee flexion and ankle dorsiflexion within the CKP group in the sagittal plane of movement but these observations did not demonstrate any statistically significant results when averaged (see Table 35). In contrast, the healthy group showed increased flexion ROM among the hip and knee joints between healthy limbs. There was an increase in ankle dorsiflexion between-limbs only at maximum squat, however, the averaged data for the healthy group demonstrated decreased ankle dorsiflexion but in the ROM during the whole cycle. This finding demonstrates a small effect size which means that these investigations are not clinically significant (Warner et al. 2019). From a motor control perspective, the healthy group might be exhibiting higher degrees of freedom that they can use and, thus, they often exhibit natural variability in movement patterns (Latash et al. 2002; Davids et al. 2003). This variability can extend to factors including ankle dorsiflexion and hip abduction which are influenced by multiple muscle groups and neural pathways. Also, the variations in the healthy group could result from the lack of standardisation in the depth of squat and the instructions provided to the participants.

Decreased knee flexion ROM during the whole squat cycle (KPPL vs HDL) and at PKF (CKP group both limbs vs HDL) was also identified in the between-group comparisons among individuals and when averaging the data which is consistent with other studies in the literature (Cabral et al. 2021; van der Straaten et al. 2020). The decreased knee flexion angle in SLS was found to be attributable to pain and fear of movement (kinesiophobia) (Cabral et al. 2021) which is accompanied by increased physical disability and results in poor SLS performance (Gunn et al. 2017). Nonetheless, the results of the current study imply that while performing more demanding tasks than walking (e.g., SLS) in which the knee contact force increases, CKP individuals adjust their movement patterns (i.e., knee flexion ROM), most likely as an adaptation approach to reduce knee joint loading or pain (Van Rossom et al. 2018). Both knees in the CKP group recorded a reduction of approximately 10° compared to the healthy group at PKF. This discrepancy may stem from the participants redistributing their body weight to the non-painful limb, possibly due to fear of movement. Prolonged reduction in knee ROM could contribute to structural changes and future knee pathologies in the non-painful limb. Consequently, physiotherapists should address both limbs in individuals with knee pain to promote movement symmetry and alleviate pain. In contrast, Glaviano et al. (2019) reported no significant difference in the knee pain group which consisted of 16 participants and was divided into two groups: the first had seven participants with elevated fear avoidance and the second had nine participants with low fear avoidance. These two knee pain groups were compared against nine healthy controls. While the study presented significant findings in the frontal plane, the subgrouping of participants with a small sample in each group might have led to type II error, resulting in the findings having limited power and precision.

Most of the previous studies that investigated movement alterations in SLS activity focused on the frontal and transverse planes of movement because it was found that movement alterations of SLS primarily appeared in the frontal plane, followed by the transverse and then the sagittal planes (Leibbrandt and Lauw 2017). The results of the current study at the individual level demonstrated a range of individual alterations with a trend for the HDL and KPPL to demonstrate decreased hip adduction and increased knee adduction (dynamic knee valgus) compared to their respective limbs. Previous research has reported a significant correlation between knee valgus alignment and the adjacent joints including the hip (Nakagawa et al. 2012) and ankle (Dill et al. 2014). Most of the previous investigations concerning SLS reported increased hip and knee adduction (increased valgus alignment) (Leibbrandt and Lauw. 2017). This finding of increased valgus was found to be associated with hip weakness. While frontal plane hip or knee alterations were not found to be statistically significant between the KPPL and the healthy limb when averaged, it can be concluded that individuals with CKP appear to utilise distinct kinematics in the affected and unaffected limb.

The finding for the hip was consistent with the conclusions arrived at by Duffell et al. (2014) for SLS which alluded to the fact that the absence of gait adaptations could be more pronounced in SLS activity in the form of postural control deficits and altered hip adduction/abduction (Duffell et al. 2014). It appears that the current study presented inverse frontal plane findings between the painful and non-painful limbs with increased hip adduction in the non-painful limb and increased hip abduction and knee adduction in the painful limb. While the results of increased hip abduction and knee adduction are comparable to the previous literature (Carvalho et al. 2022; Schimidt et al. 2019; Leibbrandt and Lauw 2017), it could be that the CKP group started these movement alterations but they were not sufficiently severe to present statistical significance. On the other hand, these findings in the non-painful limb demonstrated a large affect size which emphasises the importance of assessing both limbs in CKP populations.

While there was no dominant trend at the ankle in both groups when analysing the data individually, a significant reduction in ankle abduction ROM throughout the SLS was found in the non-painful limb of the CKP group compared to the HDL. These findings support our previous sagittal plane conclusions that the CKP group unloaded their knees by altering their movement using the KPNPL, which could have adversely affected the limb and led to the weakness of the limb.

Despite the ankle's significant stabilising role during the closed chain work of the SLS and the fact that it is an essential component in the lower extremity kinematic chain, only a very limited number of studies have included ankle movement in their analysis of SLS. Dill et al. (2014) investigated ankle kinematics during squatting using a sample of people with limited weight-bearing ankle-dorsiflexion ROM. Their results demonstrated that weight-bearing activities such as SLS presented altered ankle kinematic displacement which led to secondary knee-varus displacement. This could explain the current study's findings of altered ankle frontal plane movement in the CKP. Thus, Dill et al. (2014) suggested that increasing ankle ROM during weight-bearing tasks could be an essential intervention to alter high-risk movement patterns which are frequently linked to noncontact sport injuries such as ACL.

5.4.4 Vertical jump

There were few sagittal plane variations in the hip joint between the limbs during VJ, thereby suggesting symmetrical patterns in both groups. Significant differences between the CKP and healthy groups were observed in ROM and at PKF throughout the cycle based on the averaged data (see Table 35). In individuals with CKP, these findings may indicate altered movement patterns and adaptive strategies. Chronic knee pain can lead to changes in hip biomechanics to minimise the stress on the affected knee joint (Dos Reis et al. 2015). Increased hip flexion during a VJ suggests a potential strategy to offload the knee by using the hip joint more actively. Similarly, higher peak hip flexion during landing may be an attempt to absorb the impact with increased hip involvement, possibly to reduce the load on the knee joint and minimise any discomfort or pain during the landing phase (Myer et al. 2009). Previous research found that abnormal hip mechanics can influence knee injury risk (Powers 2010). Powers (2010) demonstrated a link between altered hip kinematics and higher knee valgus angles and moments, a finding observed in female athletes complaining of PFPS. Indeed, this finding was similar to the current study's between-group frontal plane results where increased knee adduction at the end of the landing phase and during the maximum hip and knee flexion was identified in the KPPL of the CKP group compared to the HDL of the healthy group. This may represent an adaptive mechanism aimed at mitigating the impact of CKP on the affected limb.

Analysis of data at the individual level demonstrated reduced knee flexion during take-off in the KPPL and during landing in the HDL, in comparison to their respective limbs. There was also a reduction in ankle dorsiflexion during landing and reduced plantarflexion during take-off between-limbs in both groups. However, these findings did not demonstrate statistically significant results when the data were averaged. Rosen et al. (2015) demonstrated reduced hip and knee flexion in individuals with patellar tendinopathy. Nunes et al. (2019) reported reduced sagittal plane hip, knee and ankle joint angles during the landing phase among people with PFPS. The current study’s finding of increased hip flexion and reduced knee and ankle sagittal plane movement mean that CKP individuals were using a harder landing strategy. These findings stress the importance of individually assessing people with CKP in order to tailor treatment interventions.

The ankle joint generally plays a significant role in jumping movements. The plantarflexion of the ankle joint during the push-off contributes 22-23% of the take-off velocity (Hubley and Wells 1983; Luhtanen and Komi 1978). This ankle joint contribution is characterised by the force applied by the plantar flexors relative to the temporal coincidence of their activation initiation (Bobbert and van Zandwijk 1999) and its ROM (Papaiakovou 2013). Previous research has reported the importance of increased ankle dorsiflexion in the countermovement phase of the jump (the push-off phase) for better jump performance and higher jumps but this should be a coordinated movement with other joints (e.g., the hip and knee) to achieve higher ROM, and lower trunk inclination (Papaiakovou 2013), which was not the case in the current study’s results.

It should be noted that during VJ, large standard deviations were observed in both groups among the three joints in the sagittal plane which reflects the variation in performance of this highly dynamic task. This could be a result of certain factors. First, there were no standardised instructions for jump performance. Thus, it was found that the participants performed the jump using two distinct ways: continuous and discrete jump strategies. When undertaking a continuous jump, the participants flexed their knee on landing and then immediately extended into the next jump, whereas when performing a discrete jump, they flexed the knee on landing and then extended the knee to come to a standstill, before flexing the knee to begin the next jump. Although these different strategies were dealt with cautiously during the data analysis process, they may still have affected the results.

In addition, the arm swing and position of the foot were not controlled. These two factors were extensively investigated in the literature and were known to affect jump performance. The evidence suggested that the arm-swing’s contribution is equally important for improving jump height/performance, as demonstrated by an average 21.1% increase in jumps conducted with an arm-swing over those without (Hara et al. 2008; Akl 2013). In addition, squat depth and knee flexion angles were not controlled. Prior research indicates that individuals who have undergone training to jump from a deep squat position may exhibit greater vertical jumping ability compared to their preferred position, if they have developed the right coordination pattern (Domire and Challis 2007; Hsieh and Cheng 2016). However, in the current study, the idea was to have a system that is useful for clinical settings at the individual level without over-standardising the performance and irradicating these individual variations which is necessary for physiotherapist decision-making and for tailoring the treatment interventions.

5.4.5 Stair ascent

In the sagittal plane, the between-limb analysis in the current study revealed no significant averaged findings in the knee and ankle joints, despite individual kinematic alterations (see Table 35). The CKP population displayed no significant sagittal plane differences at the knee joint, unlike in the prior literature which reported decreased knee flexion ROM and PKF angles in the knee pain groups (van der Straaten et al. 2020; Oliveira Silva et al. 2016; Hicks-Little et al. 2011; de Oliveira Silva et al. 2015). The only significant finding occurred at the hip joint, indicating decreased hip flexion ROM throughout the cycle in the CKP group compared to the healthy participants. Previous studies proposed that reduced hip flexion during SA could be an adaptive strategy for painful knees, potentially compromising effective stair climbing and increasing the risk of hip and knee injuries (Hall et al. 2017). Such limited hip flexion may induce a more upright posture during SA, potentially intensifying load on the patellofemoral joint and exacerbating knee pain, thereby contributing to the progression of knee pathology (de Oliveira Silva et al. 2015).

In the frontal plane, decreased ankle adduction (increased eversion) ROM was observed among individuals within each group but the averaged data revealed statistically significant differences between the KPPL and HDL at HS and PKF. This reduced ankle adduction during SA is consistent with prior research (Oliveira silva et al. 2016; Oliveira silva et al. 2015; Ferrari et al. 2018). The association between excessive rearfoot eversion and knee pain has been interpreted based on the notion that during the stance phase of locomotion, excessive internal rotation of the tibia is induced by an excessively everted rearfoot. Therefore, increased hip internal rotation and subsequent hip adduction may increase PFJ strain (Powers 2010). Abnormal ankle motion will impair knee biomechanics (Rasnick et al. 2016). Extreme pronation will delay the external rotation of the lower leg that occurs concurrently with subtalar joint supination (Standifird 2015). This delay causes a compensatory response at the tibiofemoral joint which may result in patellofemoral discomfort (Rasnick et al. 2016). Unfortunately, the transverse plane was not investigated in this study and, consequently, there could be an increase in hip internal rotation which was not presented to support this finding.

Additionally, the current findings of decreased ankle adduction at HS and PKF in the painful limb suggest that the participants could have used this strategy of moving their ankle towards an abducted position (toe-out movement strategy) as a protective role to avoid knee pain. Previous research used this movement strategy as a modification for gait among those people with knee OA and found that increasing the toe-out angle had the potential to protect the knee against OA progression (Hunt and Takacs 2014; Chang et al. 2007). The explanation for this is that out-toeing has the potential to reduce the knee adduction moment by moving the GRF vector closer to the knee joint centre (Chang et al. 2007). Hunt et al. (2006) suggested the investigation of therapies that minimise the frontal plane moment arm as a viable method for decreasing the knee adduction moment. This idea is further supported by the correlation between a larger toe-out angle (which reduces the moment arm) and a reduced likelihood of OA progression (Hunt et al. 2006).

Individually, the CKP group demonstrated altered hip abduction/adduction but healthy people recorded significantly increased hip abduction between limbs with small effect sizes indicating no clinical relevance. Increased hip abduction in the healthy group during SA is a normal strategy people often use to prevent the contralateral limb from making contact with the intermediate step. This method counteracts the pelvic drop on the contralateral side (Vallabhajosula et al. 2012; Nadeau et al. 2003). The absence of this strategy among the CKP group could be a stiff strategy resulting from knee pain and fear of movement.

5.4.6 Stair descent

In the sagittal plane, both the CKP and healthy groups exhibited changes in hip and knee flexion ROM throughout the movement cycle at the individual level. Despite prevalent alterations, none of the between-limb sagittal plane findings demonstrated statistical significance within each group. Notably, there were some prevalent between-group alterations and the CKP population demonstrated increased hip flexion angles at HS, increased hip flexion at PKF, and increased knee flexion ROM in the painful limb (see Table 35). These observations contradict the existing literature concerning CKP, where studies often report decreased hip and knee flexion angles (Igawa and Katsuhira 2014). The increased sagittal plane movement observed in the current study suggests potential adaptive strategies or protective mechanisms employed by the CKP population. Although increased knee flexion may induce pain, the participants appeared to utilise hip flexion primarily to lower their bodies, resulting in an augmented knee flexion angle. When comparing both CKP limbs with the healthy group, this suggests a consistent strategy employed by the CKP group, potentially indicating a cautious approach during stair descent, guided predominantly by hip movement. Unlike other studies which found increased frontal plane movement at the hip and knee (Ferrari et al. 2018; de Oliveira Silva et al. 2016; Hicks-Little et al. 2011), the absence of significant frontal plane findings between groups further supports this conclusion, suggesting a hip-led protective mechanism among the CKP participants.

On the other hand, some between-limb frontal plane alterations were identified within each group at the individual level and when averaging the data, including increased hip abduction ROM in the KPPL and in the HDL, and increased ankle abduction in the HDL among the healthy group. Excessive pronation, leading to increased ankle abduction, delays lower leg external rotation during subtalar joint supination, potentially causing tibiofemoral joint alteration and patellofemoral pain (Mei et al. 2019). Patients with patellofemoral dysfunction should undergo a subtalar joint examination by a physiotherapist with consideration of altered femur external rotation. Limitations in subtalar joint pronation or supination may result in incorrect external rotation during contact phase knee flexion, potentially affecting patellofemoral compression (Mei et al. 2019; Resende et al. 2019). The severity of aberrant pronation, as indicated by ankle joint angle differences of 3-4° for painful and dominant limbs, can determine symptomatic femur movement alterations. While small and medium effect sizes were observed in the current study’s data, the timing of abnormal pronation is crucial and, if not treated, may exacerbate knee symptoms in CKP or lead to future alterations in healthy individuals. Tiberio (1987) emphasised that more pronounced pronation which exceeds 5°, especially during midstance, is a functional abnormality necessitating femoral adjustments.

The findings of the current study may differ from the previous literature due to methodological variations. Trinler et al. (2016) stressed the need to standardise stair measurements such as the height and breadth of the tread which affect stair walking mechanics. Differences in the stair dimensions in previous studies (16-20cm in height, 22-34cm in width) compared to the current study (17cm height, 27.5cm width) may explain the observed variations. Riener et al. (2002) suggested that stair inclination affects kinematic and kinetic patterns. The current study’s 12-step staircase may represent normal movement patterns and, therefore, discrepancies may potentially be due to the step count. The failure to control the speed introduced variability into the current study, unlike other studies. While the anthropometric data, especially lower limb measurements, were comparable across groups, stair-stepping cadence data may improve outcomes. The current study did not adjust for speed and anthropometric factors but including these as covariates in future research may provide additional insight.

5.5 Strengths and limitations

The novelty of the current study is that it utilised the SCI of kinematic data generated from IMU sensors, thereby providing a detailed interpretation of the entire movement cycle. In addition, it was conducted using a standardised reporting template which was tested for its reliability to help standardise interpretations of waveform data, thereby resulting in a thorough analysis of the results (Zhou et al. 2021). Analysing movement based on discrete variables is important but it does not provide information regarding the entire movement cycle. The integration of the SCI of kinematic data used in the current study provided greater insight into the state of the whole movement cycle and contributed valuable information regarding CKP and the healthy population's movement patterns and variability. Although not all of these investigations were statistically significant when the data were averaged, these subtle changes in movement patterns would not have been apparent if relying on regular analysis and may affect patient treatment by improper management. Thus, the focus of the individuals' analysis was on elucidating the clinical relevance of the observed kinematic alterations for each participant rather than investigating the statistical significance.

Nonetheless, the strength of the current work is that, based on IMUs, multiple clinically relevant activities that were reliable and valid and which could be evaluated outside of the laboratory were identified. IMU technology is often praised for providing accurate and detailed movement data in a more naturalistic setting compared to traditional laboratory-based motion capture systems. Because task complexity and demand may affect coordination patterns and variability (Weir et al. 2019), it is necessary to investigate distinct tasks because they may uncover differing strategies (Briani et al. 2022). Thus, this diversity of tasks can enhance the generalisability of the findings to real-world settings.

Additionally, the importance of the study lies in highlighting differences within and between the two groups at all three lower limb joints in two planes of motion during the performance of various functional tasks. Conducting both within-subject and between-group analyses allows for a comprehensive examination of individual variations and group differences, providing a more nuanced understanding of the data.

There are several limitations with the current study which need to be acknowledged. The main limitation with the current study is the significant difference in age between the two groups because the mean age of the CKP population was 45 ± 16.4 years, whereas it was 30 ± 6.3 years for the healthy group. The effects of aging on muscle mass, strength, and neuromuscular control are well known (Nikolić et al. 2005; Hunter et al. 2016). However, this may have been due to the inclusion criteria which required participants to have healthy, non-arthritic lower limbs with no knee pain; thus, it was difficult to find older adults who did not have lower limb comorbidities. Nonetheless, the CKP group included in the current study could be regarded as a relatively well-functioning CKP cohort because the participants were able to perform the selected activities without assistance. For instance, they negotiated the stairs without requiring a handrail and, furthermore, their body mass and height were not significantly higher than those of the healthy individuals. In addition, these results were confirmed by the subjective patients; self-reported findings of the KOOS and NPRS. For more definite conclusions, the study should be replicated in more severely affected CKP groups and using larger samples in order to be more representative of the wider CKP population. The recruitment strategy may have led to the reduced pain score recorded in our KOOS and NPRS because most of the research participants were self-referred from the community rather than having actively sought therapy. If the CKP participants were recruited from the NHS and actively sought care, they may have had more severe symptoms.

The current study had a mixed knee pain population which made the interpretation of the findings more complex. However, mixed knee disease is often seen in clinics and, therefore, the current study reflects clinical reality. In this study, both males and females participated. Males and females may have distinct kinematic methods for alleviating CKP symptoms. Males and females with CKP cases such as PFPS may position their knees differently during certain activities, such as stair climbing, to alter pressures and alleviate symptoms (Csintalan et al. 2002). Considering the previously documented disparities between the sexes, such as larger impairments in strength (Bolgla et al. 2015) and kinematics (Willy et al. 2012) among participants with CKP conditions, sex differences between cohorts may be especially noteworthy. Further research is required to investigate the possible effect of each of these methodological variations on load absorption during landing tasks among individuals with CKP. Nonetheless, a mixed-gender population in both groups was chosen to increase the generalisability of the results.

While the current study investigated the three lower limb joints (hip, knee and ankle), the trunk was not included in the analysis. By examining the trunk kinematics, it may have been possible to achieve a better understanding of the altered movement patterns employed by the CKP participants. To clarify, in certain cases where there are no abnormalities and a lack of statistically significant findings were found in the hip, knee or ankle kinematics, one possible explanation is that those with CKP increased the angle of trunk forward flexion to compensate for reduced muscle activation around their other joints. A greater angle of forward trunk flexion would shift the centre of mass anteriorly, thereby aiding forward propulsion by increasing forward momentum (Hammond et al. 2017). It has been found that integrating a slightly forward-leaning trunk posture during dynamic exercises increases hip flexion angles and extensor moments (Farrokhi et al. 2008) while reducing knee extensor moments and PFJ loading (Atkins et al. 2019).

Lastly, it should be noted that spatiotemporal parameters, which are well-known to affect the CKP population, were not investigated and were not within the scope of the current study. Furthermore, there may be kinetic variations between the limbs and altered movements may not be reflected in the kinematics. Without access to these measures, it is often difficult for practitioners to discover joint substitutions. Despite appearing symmetrical in the kinematic analyses, it is probable that the CKP group in the current study adopted movement alterations that would have been obvious during kinetic assessments. However, kinetic analysis requires specialist equipment such as force plates or instrumented treadmills which may not be readily accessible in clinical settings. Therefore, focusing on kinematic analysis may be more practical in terms of feasibility and resource availability. Future research which incorporates the assessment of spatiotemporal parameters beside joint kinematics as well as joint moments and muscle activity would provide a more thorough assessment of full-body biomechanics during functional movements in this patient group.

5.6 Methodological considerations

There were some considerable variations between the current study and others in the literature regarding the methods used. For instance, there was heterogeneity between the studies in terms of the events used to determine the joint angles. During gait, for example, whereas some research described loading response angles, others reported peak angles during support, angles at contralateral toe-off, or other events. In the current study, all of the variables were chosen because they are commonly used during movement assessment in human performance labs and in clinical settings (Butler et al. 2014; Paterno et al. 2007; Paterno et al. 2012).

Another important consideration is the different test protocols used for each of the selected tasks. With regards to gait, most studies referred to it as "level ground walking" when performed in a laboratory, long corridor or outdoor setting. A longer pathway is preferable to capture the natural stride of an individual because it allows the subjects sufficient time and space to adapt their walking as necessary (Tura et al. 2012). The current study indicated that a minimum of 25 and 33 strides, respectively, are necessary to accurately compute the step symmetry and stride regularity of healthy control subjects (Tura et al. 2012). Moreover, Belluscio et al. (2020) revealed that curved walking, as opposed to straight walking, is more suitable for assessing individuals with gait abnormalities. Therefore, a treadmill-based investigation may alter the subject's natural gait. Moreover, Sloot et al. (2014) and Chang et al. (2009) argued that self-paced walking, as opposed to walking at a fixed speed, allows for more natural stride variability. In the current study, participants performed 2 gait trials with approximately 40 strides in total. This was performed in a long corridor without providing the participants with any specific instructions regarding their walking speed to ensure normal walking patterns.

In addition, most studies used a staircase ranging from 3-7 steps to analyse SA and SD movements (Sparkes et al. 2019; Ferrari et al. 2018; de Oliveira Silva et al. 2016) which was acknowledged by these studies as a limitation that may have affected their results. The current study is novel regarding CKP and stair negotiation because it used a staircase with 12 steps to simulate natural stair negotiation, unlike the previous studies. As for DLS and SLS, no specific instructions were provided to the participants regarding how to perform the task or how deep to go with the squat. This technique was chosen because this is an exploratory study which sought to identify the altered movement patterns that were performed naturally by the CKP population. Accordingly, standardising instructions with respect to the speed, depth and so on, would prevent the participants from demonstrating their natural behavioural movement.

5.7 Clinical implications

The current study underscores the importance of individualised assessments based on movement analysis. The SCI of kinematic data allows for a nuanced understanding of movement patterns at the individual level. Physiotherapists are able to tailor interventions based on these individualised assessments, addressing specific movement alterations observed during the entire movement cycle. It is of paramount importance for physiotherapists to prioritise the clinical significance of findings at the individual level rather than solely relying on statistical significance. The study also underscores the need for a nuanced interpretation of kinematic data, recognising that subtle alterations in movement patterns, even in the absence of statistical significance, may hold considerable clinical relevance. Physiotherapists should therefore adopt a holistic approach, considering the potential impact of observed kinematic nuances on an individual's functional capacity and pain experience. This perspective aligns with the broader goal of enhancing personalised care and treatment outcomes for individuals with CKP.

It is crucial to appreciate and account for the natural variability in human movement. The emphasis should not be on eliminating these variations but rather identifying the patterns and deviations which are of clinical importance for each person and affect an individual's functional capacity and well-being rather than over-standardising to the point where individualised nuances are lost. The SCI of kinematic waveform data considered the inherent variability in how people move, including how they swing their arms, the size of their steps and other individualised aspects of movement. This approach aligns with the principle of personalised care, recognising that what may be considered a small variation at a group level might be a significant factor for an individual's movement and pain experience.

Therefore, in the context of the current study, striking a balance between standardisation for research purposes and appreciating the inherent variability in human movement is essential. The use of a template for standardising the interpretation of kinematic waveform data was found to improve the robustness and consistency of physiotherapists' clinical decision-making (Button et al. 2022; Zhou et al. 2021). Consequently, inconsistencies in clinical decision-making based on data from movement analysis would be avoided.

The study emphasises the importance of considering both limbs in movement analysis for individuals with CKP. Physiotherapists should conduct a thorough examination of both the painful and non-painful limbs to identify asymmetries and altered movement patterns, thereby contributing to a more comprehensive understanding of the impact that CKP has on movement. The significant number of within-subject alterations or the considerable variability reported in the healthy group requires physiotherapists to evaluate movement analysis data with caution because not all movement deviations in a population with pain will be caused by pathology. The lack of consistency in the movement alterations emphasises the need for tailored movement evaluations of functional tasks and individualised treatment approaches. Also, practitioners should recognise that some asymmetry is normal, even in healthy populations but research has yet to establish the threshold at which asymmetrical motions should be deemed undesirable (Lathrop-Lambach et al. 2014; Paillard 2023). Consequently, the practical consequences of these asymmetric values remain ambiguous.

5.8 Conclusion

The current study sought to identify kinematic differences between individuals with and without CKP across various functional tasks including gait, DLS, SLS, VJ, SA and SD. The SCI of kinematic waveform data provided a nuanced understanding of altered movement patterns in both CKP and healthy individuals utilising IMUs and a standardised reporting template. Additionally, the SQA investigated kinematics at discrete timepoints, offering insight into between-group and within-subject differences. However, a notable limitation with this approach is the grouping of data which results in the presentation of averaged results without providing reporting at an individual level which is not helpful for physiotherapists. On the other hand, by employing the SCI, numerous potential benefits were highlighted which included providing a comprehensive and individualised assessment of kinematic variations that might not otherwise be captured by traditional quantitative analyses alone. Such an approach offers considerable promise for enhancing clinical decision-making and personalised treatment strategies. The findings of the current study, in addition to others conducted by our research team, emphasise the need for the development of a system that is both clinically relevant for physiotherapists and people with CKP at the individual level and scientifically rigorous in capturing meaningful variations in movement patterns to represent these kinematic waveforms in a user-friendly manner. An electronic version of the report has been developed, as recommended by Button et al. (2022), and its usability will be tested in the next part of this PhD thesis.

Chapter 6, Part 2: The usability of an electronic IMU-based movement analysis and reporting tool for physiotherapists treating individuals with CKP

6.1 Introduction

The first study on movement analysis underscored the significance of individualised assessment and reporting of kinematic data in clinical practice. The descriptive analysis of kinematic waveform data reveals individual nuances that are not visible when the data is averaged at discrete time points. This underscores the importance, particularly in a clinical setting, of having an effective method to present these waveform data to physiotherapists in a useful, helpful, and time-saving manner. So, adding an easy-to-use electronic reporting tool was seen as a practical way to make the presentation of kinematic waveforms more efficient, clinically relevant, and easy to understand for physiotherapists. This is what Part 2 of this PhD is about. **The conversion of the toolkit into an interactive digital version that can be used by physiotherapists treating individuals with CKP.** This progression aimed to bridge the gap between research outcomes from Part 1 and practical implementation, enhancing the accessibility and usability of advanced kinematic analyses in everyday clinical practice. It is important to note that, in the current study, the developed tool is undergoing usability testing, representing a critical step towards its potential future integration into clinical practice. Accordingly, the aim and objectives of this part of the thesis are outlined below.

6.2 Aim

The aim of the current study was **to test the usability of an electronic version of an IMU-based movement analysis and reporting tool for physiotherapists treating individuals with CKP**. To address this, the study had two objectives:

- To test the usability of the electronic version of the report in terms of its effectiveness, efficiency, memorability, problems and errors which was achieved using the think-aloud (TA) method.

- To test the overall ease of use of the E-reporting tool using the SUS questionnaire.

The E-reporting tool provided the physiotherapists with better access to the kinematic data and a more user-friendly interface for interpreting kinematic waveforms. The electronic version of the movement analysis report includes the following features:

- Enabling users to mark the amount and nature of the alteration by inserting icons or codes on the graphs.

- Enabling the user to enlarge segments within the waveform or utilise drawing tools to highlight the timing of when the alteration strategy occurs.

- Enabling the user to request numerical data regarding the amount of alteration for key parameters.

- Enabling the user to select which cycles they want to see in the average waveform graphs.

- Use several pictures on each graph to depict the movement cycle for each activity.

In the current study, the physiotherapists evaluated the usability of the E-reporting tool. It is important to note that the tool was tested using data collected in the first part of this thesis, specifically from individuals with CKP (ethics reference number 10/MRE09/28). While the usability study focused on physiotherapists as participants, the data integrated into the E-reporting tool originated from CKP individuals, as investigated in Part 1 of the thesis.

6.3 Methods

The following sections provide an overview of the design applied in the current study, the ethical approval, the setting, the inclusion and exclusion criteria, the interface, and the test procedures.

6.3.1 Design

The current study is a quantitative formative evaluation of usability. Formative evaluation is a type of usability testing which helps to ‘form the design of a product or service. Formative evaluations are used to test a product or service whilst it is being developed, often iteratively, with the purpose of finding and addressing usability issues (Theofanos and Quesenbery 2005). Theofanos and Quesenbery (2005) defined formative usability as “formative testing: testing with representative users and representative tasks on a representative product where the testing is designed to guide the improvement of future iterations” (Theofanos and Quesenbery 2005, p. 29). The use of a quantitative formative approach in the current study is important because it allows for the description of the problems encountered, recording how many and who experienced them, and measuring how long tasks take to complete, what percentage are completed, as well as the number and types of errors resulting from user interface problems.

According to the European standard regulated by the European Committee for Electrotechnical Standardization, the purpose of the usability standard is to identify and minimise user errors and reduce the risks associated with the use of medical devices. It focuses on optimising usability as it relates to safety, as well as how usability relates to task correctness, completeness, efficiency and user satisfaction (International Electrotechnical Commission (IEC) 2015). This standard provides guidelines for user interface design and software development but it also compels manufacturers to undertake usability tests on their products. The standard defines formative evaluation as an assessment of the user interface with the purpose of investigating the strengths, weaknesses, and unforeseen usage errors in its design (IEC 2015).

Sauro (2010) noted that a formative test should be quantitative. Applying a quantitative formative approach entails describing the problems, reporting how many and who encountered them, and measuring how long tasks take to complete, what percentage are completed, as well as the number and types of errors caused by UI problems (Sauro 2010). In other words, quantitative formative usability involves systematically recording events using various metrics and provides numerical descriptions of those events.

Formative evaluation is highly recommended and is a significant step to be conducted prior the final summative usability evaluation. It can be undertaken at the design's ‘summation point’ when the product is complete, ready for manufacturing and the formative usability evaluation has been completed (Barnum 2020). It provides valuable data throughout the product development process (the electronic version of the reporting tool) so that the last evaluation of usability can be conducted successfully (Barnum 2020; Theofanos and Quesenbery 2005). According to the usability evaluation cycle, if the product passes the formative evaluation, the next step will be to conduct a larger summative evaluation which, if conducted successfully, will enable the system’s user interface safety to be validated (Barnum 2020) (see Figure 12).

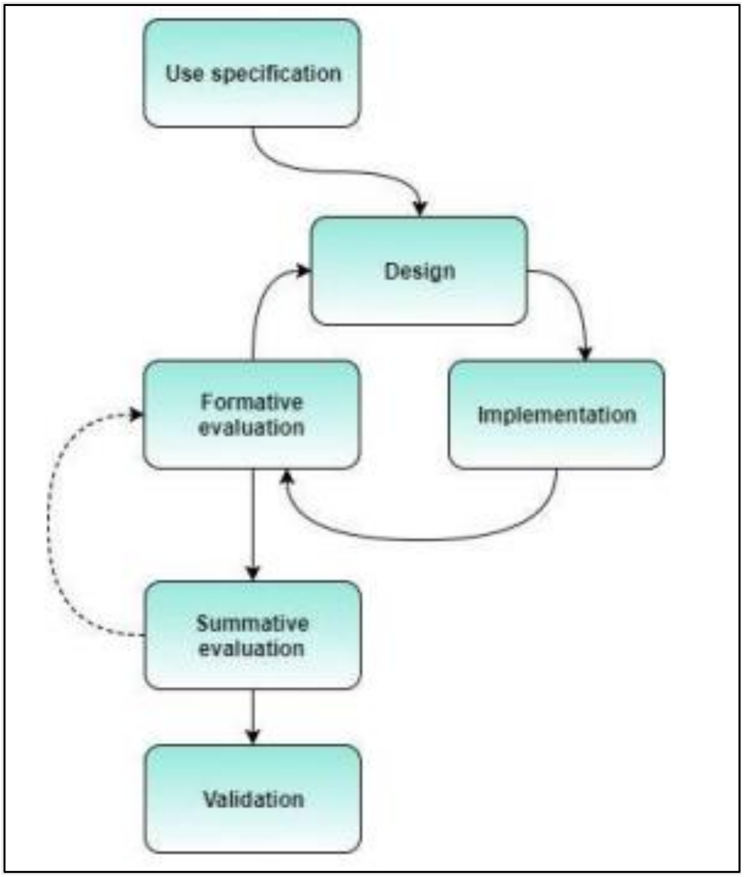


Figure 12: Usability evaluation cycle adapted from Ylikulju (2018)

However, selecting an appropriate technique is very important for formative usability evaluation and, therefore, the TA and SUS questionnaire techniques were chosen in the current study. According to Hartson et al. (2001), who compared various usability evaluation methods, TA is the gold standard for usability evaluation. The TA technique is a form of observational analysis which entails users vocalising their thoughts and actions while performing a set of tasks. Previous studies have shown that this method provides greater accessibility to information about the user's thoughts, interactions and strategies in complex working conditions (Yen and Bakken 2009), thereby indicating the validity and reliability of this method (Yen and Bakken 2009; Guan et al. 2006). Therefore, the aim of TA is usually to collect information about the user's cognitive interaction with the system (Habibi et al. 2018). While performing a task, users are instructed to verbalise what they are thinking and experiencing while the researcher observes any problems that they encounter whilst undertaking various tasks (Barnum 2020). The key benefits of the TA technique are that it allows researchers to witness the task completion process and it is particularly useful for examining prototypes, highlighting any possible problems from a user's point of view (Barnum 2020). Although the method has several limitations including the level of guidance provided to participants, researcher influence and difficulties with data analysis, it was found that the richness of the collected data outweighed these limitations and that the TA method has the potential to advance research in this field (Cotton and Gresty 2006).

TA usability testing is widely acknowledged as the most comprehensive and efficient way to evaluate usability and minimise use-related problems. There are other approaches called usability inspection techniques such as a heuristic evaluation and cognitive walkthrough which can be used but they have certain known weaknesses which limit their suitability for the purpose of the current study. In heuristic evaluation, rather than classifying usability problems, they are only employed to detect them. Therefore, the usefulness of heuristics for problem classification is restricted. Additionally, one of the most notable complaints associated with heuristic evaluation is that it tends to find many minor or non-existent problems (false positives). Multiple usability experts are required which is an additional practical issue. It can be more costly and time-consuming to locate 3-5 usability professionals than it is to test 3-5 people (Faulkner 2003).

Regarding cognitive walkthrough, the objective is to identify users' goals and how they strive to achieve them in the interface, followed by a thorough identification of the problems users may encounter as they learn to use an interface. A reviewer must describe the user's immediate goal and respond to eight questions for each step to complete a task. One of the most common complaints regarding the cognitive walkthrough technique is the length of time required for the evaluators to answer each question (Khajouei et al. 2017).

According to Khajouei (2017), cognitive walkthrough and TA are equally capable of identifying low-priority usability issues, whereas TA detected slightly more serious usability issues than cognitive walkthrough. TA found twice as many high severity problems (major and catastrophic) as cognitive walkthrough (six vs three) and the same number of low severity problems (cosmetic and minor) when only one method was used to identify problems (13 vs 13) (Khajouei 2017). Thus, TA appears to be more beneficial than cognitive walkthrough in terms of identifying different usability problems.

Another usability testing technique which has been presented in the literature is summative evaluation. A summative evaluation of usability is a formal assessment with established acceptance criteria. It can be performed at a ‘summation point’ in the design when the product is deemed complete, production-ready and the formative evaluation of usability has been completed (Barnum 2020). The primary objective of the summative evaluation of usability is to collect objective proof that the interface design is safe to use (Barnum 2020). This reduces the likelihood of committing potentially harmful use errors. This evaluation can be performed for our system in the future stages of usability because this is the system’s first version and formative usability is the appropriate approach at this stage.

The usability questionnaire plays an important role in the system's usability evaluation. According to Preece et al. (2002), a questionnaire is a well-known method for gathering demographic information and user feedback. It also provides surveyors with a better understanding of the topic (Preece et al. 2002). Results would likely be more reliable if one of the currently available standardised questionnaires was used (Sauro and Lewis 2009). Because this is intended to be a usability study, the overall usability was derived from the SUS as a questionnaire that measures the perceived usability of interactive systems (Brooke 1996).

The results of 2,324 SUS surveys on a variety of interfaces (including automated telephone interfaces to websites) were found to be both reliable and useful (Bangor et al. 2008; Mol et al. 2020). The questionnaire was also found to be a valid measure to ordinally compare two or more systems (Peres et al. 2013; Mol et al. 2020). The widespread use of the SUS questionnaire enables the comparability of a system's usability to that of others.

While SUS was not specifically designed to measure satisfaction, it is able to provide insight into users' overall attitudes and opinions about a product, which can be indicative of satisfaction. According to Mol et al. (2020), the SUS was developed to offer a "quick-and-dirty" measure of satisfaction with a system's usability. The high association between usability and satisfaction, as established by previous studies, shows that the SUS offers a relevant measure of satisfaction in many circumstances (Sauro and Lewis 2011; Tullis and Stetson 2004). Accordingly, TA and SUS were augmented to be able to measure all of the characteristics contributing to a usability test, as recommended by Esfahani et al. (2018).

6.3.2 Ethical approval

Ethical approval for the current study was obtained from Cardiff University, School of Healthcare Sciences (21/10/2021) (see Appendix L).

6.3.3 Setting

This usability evaluation was conducted virtually using the ZOOM website. Although conducting usability online could present certain disadvantages such as technical issues or Internet connection issues, it was considered to offer the best way of conducting the test due to the events of the Covid-19 pandemic. The Lead researcher (RA) ensured that there was a good Internet connection and asked all of the participants to make sure of that. On the day before the test, the participants were asked to download the Zoom application or ensure that they had access to it. In addition, they were reminded that they would require the username and password to sign up to the E-reporting tool to check if they could access it and that it was working properly. It was important to ensure that the participants could access the E-reporting tool successfully to avoid any issues that may arise on the day of testing. However, the participants were asked not to try to explore the system until the day of the test.

6.3.4 Participants

A convenient sample of six participants was included in the current study. A common and suggested practice is to begin with approximately six participants and increase the number of participants with each iteration of formative usability testing so that as the design changes, even minor errors are detected (PE et al. 2015). Barnum (2020) advocated the same idea and proposed that during the TA test sessions, a representative sample of five-to-eight end users are requested to interact with the (prototype) system according to a specified set of scenarios while verbalising any thoughts that occur to them whilst undertaking the tasks (Barnum 2020). The most effective usability tests consist of numerous tiny tests rather than a few large ones and the evaluator will acquire more insight by dealing with four-to-five users and asking them to verbalise their thoughts during the test (Sauro 2010). As soon as a user reports a problem, the evaluator must instantly address it (rather than continuing the testing to see how bad it is). The evaluators then retest to determine whether the repair resolved the issue (Sauro 2010).

Earlier investigations undertaken by Nielsen and Landauer (1993) which evaluated 11 usability studies found that, according to a mathematical analysis of the insights (or usability problems) uncovered by the researchers after speaking with the participants, the curve starts to flatten after seven individuals. This suggests that most of the issues were only identified after interviewing five-to-seven people and no ‘new' usability issues or insights were uncovered after that (Nielsen and Landauer 1993). Virzi (1992) also indicated that only six participants are needed to cover 80-85% of the usability issues and that this is sufficient for a testing session (Virzi 1992).

In addition, starting with five-to-seven participants is the norm in a user-experience design for various reasons. First is the budget. Conducting a confined usability test is usually expensive and, therefore, usability researchers are willing to estimate the number of participants required and there is a mathematical method for doing so. Limiting testing to six users will uncover most of the problems that plague the tested tool, while keeping costs low and the process simple. Another factor is the timeframe; because this concerns formative usability, using fewer people as an initial round not only helps to save time and money but also allows the researcher to iterate on ideas, the design and execution throughout the development process.

Finally, the goal of formative usability is usually to have a small sample size that is representative of the target population to be able to provide data in the form of problem description and design recommendations. A small sample size does not mean that there is no opportunity to quantify the data; on the other hand, this could be achieved by quantifying the problems (Sauro and Lewis 2016). For instance, it is possible to track which users experienced which difficulties, how long it took them to accomplish activities, and whether they finished them successfully by quantifying the problems in terms of frequency and severity. The most significant factor to consider in this type of usability is the representative population, not the number of participants included (Sauro and Lewis 2016).

To this end, a decision was taken to include only six users who must be representative of the target population. Further details regarding the inclusion and exclusion criteria are presented below.

6.3.4.1 Inclusion criteria

- Any qualified physiotherapist (no need for postgraduate experience in movement analysis or to be in practice)
- Able to read and understand English.
- Able to give written informed consent.
- Physiotherapists from within or outside the UK because the study was conducted virtually.
- Have Internet access and a computer.

6.3.4.2 Exclusion criteria

- Physiotherapists who are unable to read or understand English.
- Those who refuse to provide consent.

6.3.5 Recruitment procedures

The lead researcher (RA) advertised the research project through an email that was sent to the School of Healthcare Sciences at Cardiff University calling for qualified physiotherapy graduates, postgraduate students or staff. All correspondence was from the lead researcher’s (RA) own email account at Cardiff University. The email included a copy of the participant information sheet (PIS) which provided a detailed explanation of the study and answered questions that the participants may have had about the usability test (see Appendix M). It was stated in the email that only qualified physiotherapists were eligible to participate in the study. In addition, participants were also invited via word of mouth and were recruited if they satisfied the inclusion criteria.

Following this process, interested/eligible participants contacted the lead researcher (RA) to take part. The lead researcher (RA) offered to answer their questions or queries via email or a Zoom meeting. They were then given 48 hours to decide whether or not to take part. Those who wanted to participate received another email including a link to the consent form (see Appendix M) which was sent before the test day to make sure it is signed and returned to the researcher before the test is initiated. Forms application from Microsoft Office was used to create electronic consent forms that enabled participants to sign them electronically. The researcher then signed the consent form and provided a copy for each participant. Besides the consent form, the participants were also provided with information regarding how to access the tool, in addition to the arrangements for the zoom meeting.

6.3.6 The electronic IMU-based movement analysis and reporting tool

An electronic version (E-reporting tool) of the IMU-reports was developed in agreement with the Xsens team using their Xsens MVN Awinda system (see Appendix N). Accordingly, the usability of the E-reporting tool was tested by physiotherapists using previously collected data within the software. This iteration of the E-reporting tool allows the user to interact with an electronic version of the report. The tool provides physiotherapists and patients with real-time access to multi-planar kinematic data and instantly presents complex movement analysis data in an accessible, easy-to-read report. Users of the E-reporting tool gain a thorough understanding of the activity performed by individuals because the system provides detailed and comprehensive movement analysis information, such as general and spatiotemporal parameters, alongside graphs and kinematic waveform data.

The E-reporting tool is unlike the other websites presented in the literature in that it focuses on the kinematic and temporospatial parameters for all lower limb joints and presents them in a highly detailed manner. In addition, it enables patients' waveform movement analysis data to be visualised with their avatar performing the movement which can be minimised, maximised, stopped, and seen from the sagittal, frontal and transverse planes of movement. The E-reporting tool also informs users about the number of successful trials that an individual did and whether there were any outliers. This data can then be used for treatment planning and rehabilitation progress tracking.

The following were also considered in the design of the E-reporting tool:

- Enter a user ID for user filing reasons.

- Select the affected side.

- Select from a list of executed exercises and reports.

- Select the joints of interest.

- Select one or more MVN files to include in the report and compare.

- Synchronised dynamic view of the avatar.

- Plot waveforms windowed per exercise.

- Remove outliers.

- Means of left and right that can be plotted over each other.

- Add comments manually with auto-incremental alpha label at a specific spot in the graph which can be displayed in the report.

- Access to a printable PDF file of the report.

- Allow the user to insert icons or codes to annotate the quantity, timing and nature of the altered movement on the graphs.

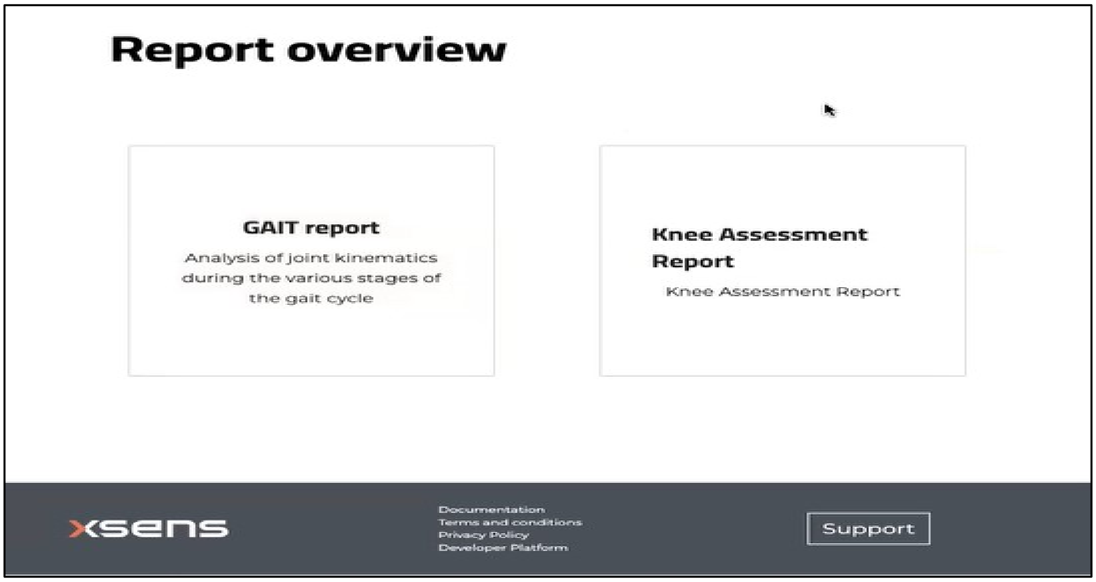
- Allow the user to enlarge portions of the waveform or utilise drawing tools to highlight the timing of when the altered strategy occurred.

- Allow the user to obtain quantitative information regarding the amount of compensation for key parameters.

- Allow the user to choose which cycles to include in the graphs of the average waveform.

- Create a set of images to depict the movement cycle for each activity on each graph.

The E-reporting tool includes two main types of reports: **gait reports** and **knee assessment reports** (see Figure 13). The knee assessment reports enable the analysis of nine different exercises which are available for movement analysis: crossover hop, DLS, drop VJ, VJ, side hop, single drop VJ, single hop for distance, SLS, and triple hop for distance. However, of these nine exercises, only SLS and VJ reports were chosen alongside the gait reports. The reports of these three activities (gait, SLS and VJ) were chosen in preference to the others on the website because these activities were included and analysed in the first part of the current study.



Report overview

GAIT report

Analysis of joint kinematics during the various stages of the gait cycle

Knee Assessment Report

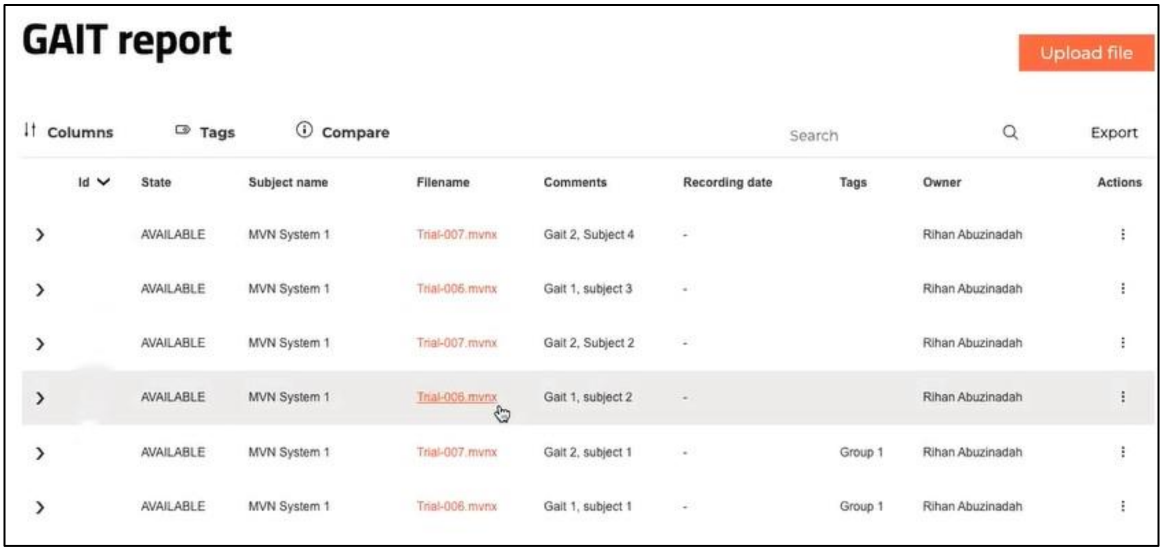
Knee Assessment Report

Figure 13: Overview of the reports included in the E-reporting tool

The following section presents an overview for each type of report included in this usability study.

6.3.6.1 Overview of the gait report

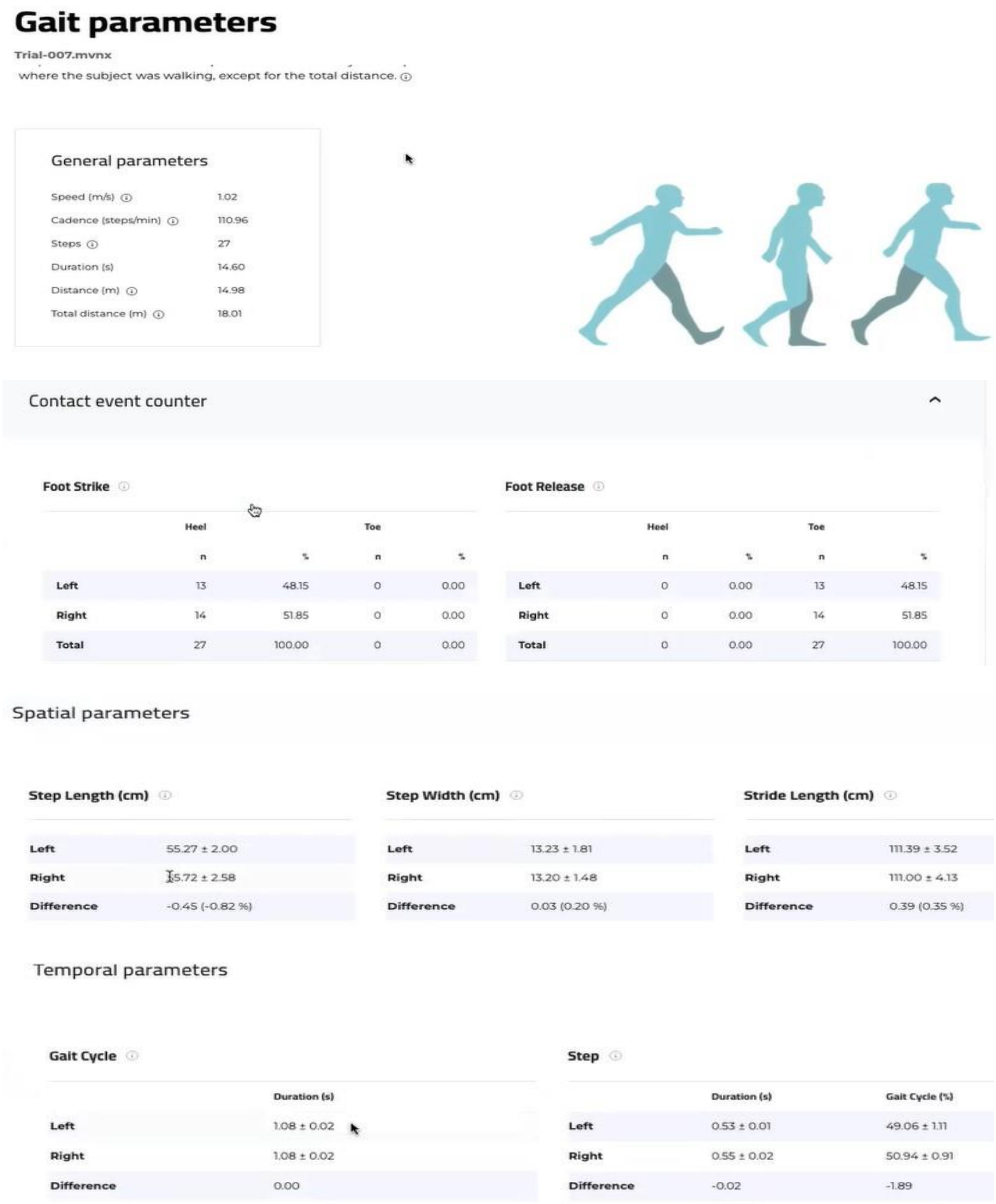
The following image provides a visualisation of the gait report overview page in the E-reporting tool. This overview page in the gait report represents the downloaded subjects' IMU-reports, including their ID, state, subject name and file name, in addition to certain features which enable the user to write comments, the date and add tags. There is also an icon called "compare" which allows the participants to compare some CKP individuals' graphs and another called "export" for exporting subjects' PDF movement analysis reports (see Figure 14).



	Id	State	Subject name	Filename	Comments	Recording date	Tags	Owner	Actions
›		AVAILABLE	MVN System 1	Trial-007.mvnx	Gait 2, Subject 4	-		Rihan Abuzinadah	⋮
›		AVAILABLE	MVN System 1	Trial-006.mvnx	Gait 1, subject 3	-		Rihan Abuzinadah	⋮
›		AVAILABLE	MVN System 1	Trial-007.mvnx	Gait 2, Subject 2	-		Rihan Abuzinadah	⋮
›		AVAILABLE	MVN System 1	Trial-006.mvnx	Gait 1, subject 2	-		Rihan Abuzinadah	⋮
›		AVAILABLE	MVN System 1	Trial-007.mvnx	Gait 2, subject 1	-	Group 1	Rihan Abuzinadah	⋮
›		AVAILABLE	MVN System 1	Trial-006.mvnx	Gait 1, subject 1	-	Group 1	Rihan Abuzinadah	⋮

Figure 14: Gait report overview page

Upon selecting a subject file, the gait parameters page automatically opens, as shown in Figure 15. The gait parameters page presents some general parameters such as the speed, cadence, duration, distance and total distance. The same page also provides the participant with other walking parameters for both sides of the subject. Each of these parameters provides the participant with different information. For example, contact event counter presents the angles at foot strike and foot release, whereas spatial parameters demonstrate the subjects’ step length, width and stride length. With regards to the temporal parameters, detailed information is provided for all phases of the gait cycles for each limb, including the overall gait cycle, the foot trike, the swing phase, the stance phase, the single limb support phase, double limb support phase, midstance, terminal stance and pre-swing (see Figures 15-16).



Gait parameters

Trial-007.mvnx

where the subject was walking, except for the total distance.

General parameters

Speed (m/s)	1.02
Cadence (steps/min)	110.96
Steps	27
Duration (s)	14.60
Distance (m)	14.98
Total distance (m)	18.01

Contact event counter

Foot Strike

	Heel		Toe	
	n	%	n	%
Left	13	48.15	0	0.00
Right	14	51.85	0	0.00
Total	27	100.00	0	0.00

Foot Release

	Heel		Toe	
	n	%	n	%
Left	0	0.00	13	48.15
Right	0	0.00	14	51.85
Total	0	0.00	27	100.00

Spatial parameters

Step Length (cm)

Left	55.27 ± 2.00
Right	5.72 ± 2.58
Difference	-0.45 (-0.82 %)

Step Width (cm)

Left	13.23 ± 1.81
Right	13.20 ± 1.48
Difference	0.03 (0.20 %)

Stride Length (cm)

Left	111.39 ± 3.52
Right	111.00 ± 4.13
Difference	0.39 (0.35 %)

Temporal parameters

Gait Cycle

	Duration (s)
Left	1.08 ± 0.02
Right	1.08 ± 0.02
Difference	0.00

Step

	Duration (s)	Gait Cycle (%)
Left	0.53 ± 0.01	49.06 ± 1.11
Right	0.55 ± 0.02	50.94 ± 0.91
Difference	-0.02	-1.89

Figure 15: Gait parameters page in the gait report

Swing Phase

	Duration (s)	Gait Cycle (%)
Left	0.45 ± 0.01	41.71 ± 1.00
Right	0.44 ± 0.02	40.68 ± 1.89
Difference	0.01	1.03

Stance Phase

	Duration (s)	Gait Cycle (%)
Left	0.63 ± 0.01	58.29 ± 1.00
Right	0.64 ± 0.02	59.34 ± 1.32
Difference	-0.01	-1.05

Loading Response

	Duration (s)	Gait Cycle (%)
Left	0.09 ± 0.01	8.39 ± 1.30
Right	0.10 ± 0.01	9.23 ± 1.16
Difference	-0.01	-0.84

Midstance

	Duration (s)	Gait Cycle (%)
Left	0.17 ± 0.01	16.12 ± 1.37
Right	0.19 ± 0.01	17.17 ± 0.84
Difference	-0.01	-1.05

Single Support Phase

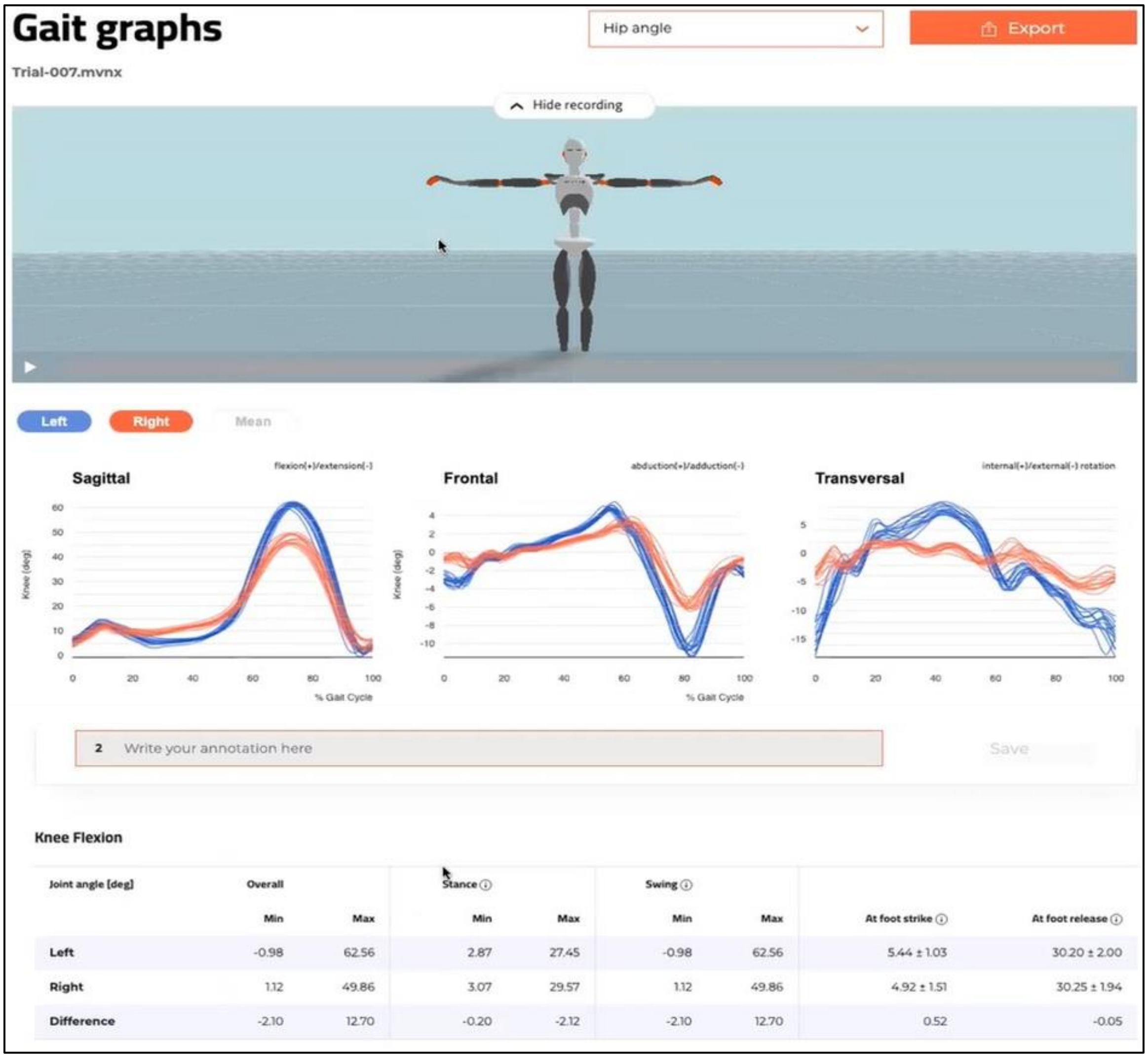
	Duration (s)	Gait Cycle (%)
Left	0.44 ± 0.02	40.67 ± 1.75
Right	0.45 ± 0.01	41.72 ± 1.14

Double Support Phase

	Duration (s)	Gait Cycle (%)
Left	0.09 ± 0.01	8.39 ± 1.30
Right	0.10 ± 0.01	9.23 ± 1.16

Figure 16: Continuation of the gait parameters page in the gait report

The gait graph page enables the participants to watch the subject's video recording during movement. The participants can select various joints to observe waveform data, annotate their waveforms and interpret the subjects' gait data in the tables (see Figure 17). These tables provide information about the subject’s joint angles with minimum and maximum angles at each phase of the gait cycle (stance and swing), in addition to the angles at foot strike and foot release.



Gait graphs

Trial-007.mvnx

Hip angle

2 Write your annotation here

Knee Flexion

Joint angle [deg]	Overall		Stance		Swing			
	Min	Max	Min	Max	Min	Max	At foot strike	At foot release
Left	-0.98	62.56	2.87	27.45	-0.98	62.56	5.44 ± 1.03	30.20 ± 2.00
Right	1.12	49.86	3.07	29.57	1.12	49.86	4.92 ± 1.51	30.25 ± 1.94
Difference	-2.10	12.70	-0.20	-2.12	-2.10	12.70	0.52	-0.05

Figure 17: Gait graph page in the gait report

6.3.6.2 Overview of the single leg squat reports

SLS reports are included in the system's 'Knee Assessment Report' category which comprises numerous other exercises. The system prohibits the generation of any of these reports without first selecting the type of investigated exercise. Thus, once the knee assessment reports category has been selected, the page for selecting the type of exercise opens (see Figure 18). This page allows the user to watch an avatar of the subject performing the activity and select the type of activity from a selection of nine exercises.

Once the participant has chosen the exercise that they want to analyse (SLS in this case), the software automatically generates its report. The SLS report consists of two pages. The first page is a summary page for general movement information showing the depth of the sacrum, maximum knee flexion, maximum/minimum knee abduction for each SLS trial that the subject did, in addition to the mean values of these parameters (see Figure 19). This summary information was presented in traffic light colours (green, yellow and red) with a side bar used to visually represent different levels of ROM or movement quality. For example, green represents a normal or optimal ROM or movement pattern; yellow indicates a cautionary ROM or movement pattern which may require attention or monitoring; whereas red indicates a restricted or problematic ROM or movement pattern which requires attention or intervention. This page also allows the participant to export the report as a PDF file and print it.

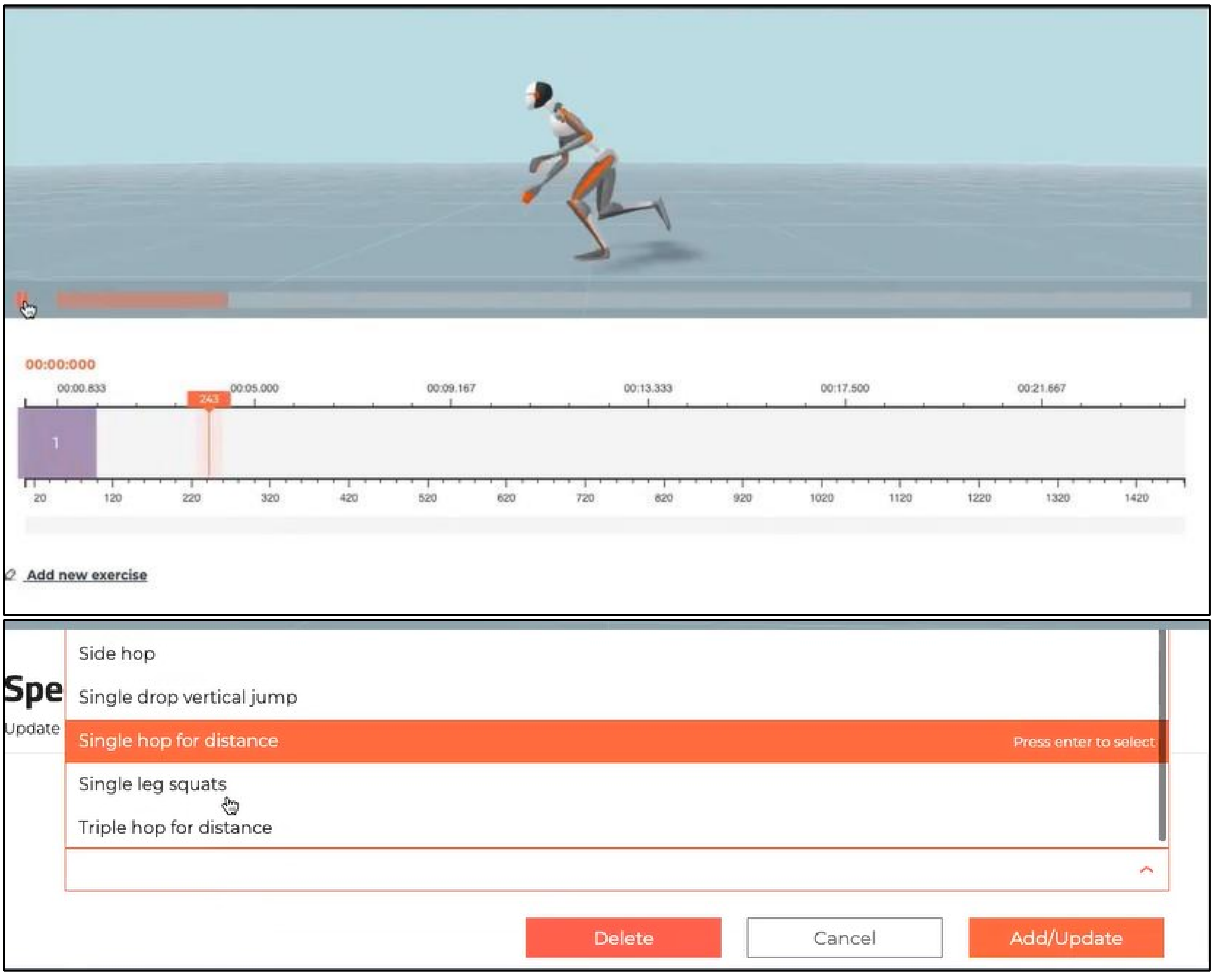
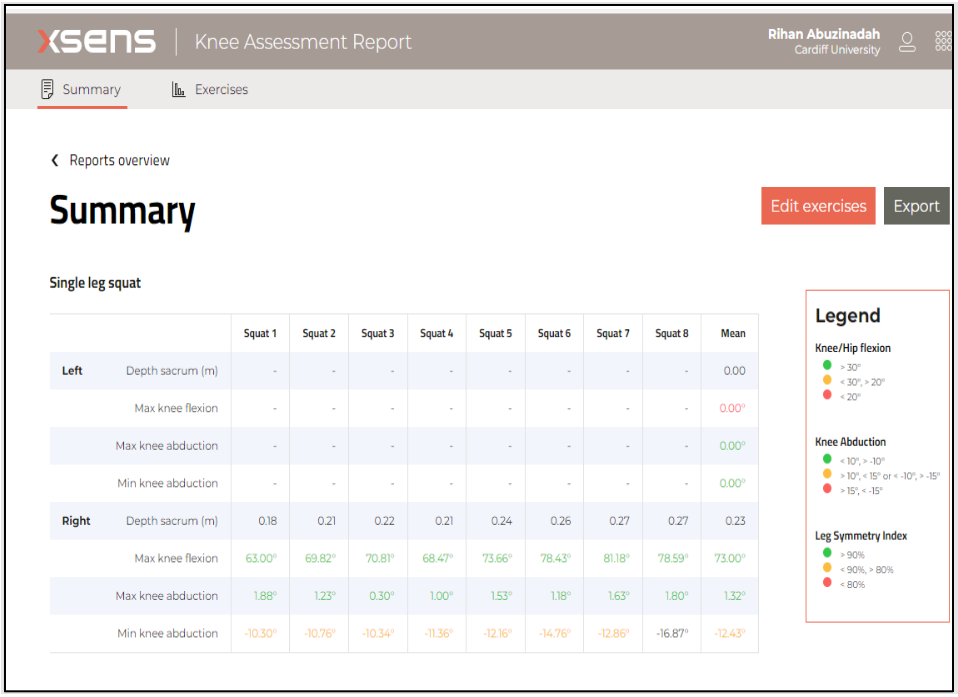


Figure 18: Editing and identifying the type of exercise performed



Summary

Single leg squat

		Squat 1	Squat 2	Squat 3	Squat 4	Squat 5	Squat 6	Squat 7	Squat 8	Mean
Left	Depth sacrum (m)	-	-	-	-	-	-	-	-	0.00
	Max knee flexion	-	-	-	-	-	-	-	-	0.00°
	Max knee abduction	-	-	-	-	-	-	-	-	0.00°
	Min knee abduction	-	-	-	-	-	-	-	-	0.00°
Right	Depth sacrum (m)	0.18	0.21	0.22	0.21	0.24	0.26	0.27	0.27	0.23
	Max knee flexion	63.00°	69.82°	70.81°	68.47°	73.66°	78.43°	81.18°	78.59°	73.00°
	Max knee abduction	1.88°	1.23°	0.30°	1.00°	1.53°	1.18°	1.63°	1.80°	1.32°
	Min knee abduction	-10.30°	-10.76°	-10.34°	-11.36°	-12.16°	-14.76°	-12.86°	-16.87°	-12.43°

Legend

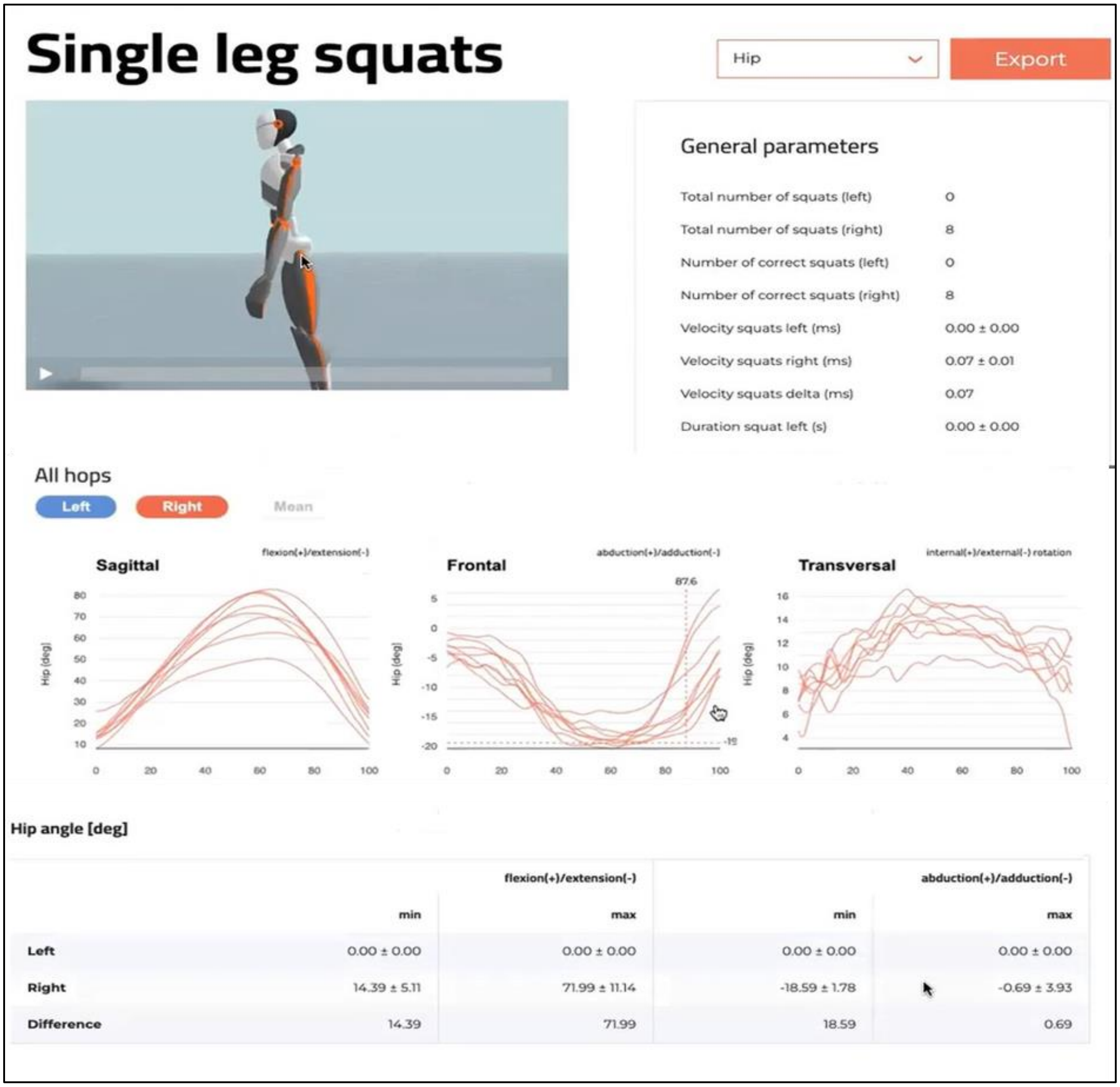
Knee/Hip flexion
● > 30°
● < 30°, > 20°
● < 20°

Knee Abduction
● < 10°, > -10°
● > 10°, < 15° or < -10°, > -15°
● > 15°, < -15°

Leg Symmetry Index
● > 90%
● < 90%, > 80%
● < 80%

Figure 19: Summary page of the SLS report

The second page in the SLS reports is the exercises page (see Figure 20). This page displays the subject's avatar which can be played, minimised and maximised. It also shows other parameters such as the successful trials performed and tables of joint angles including minimum angles, maximum angles and mean angles during the whole movement cycle.



General parameters

Total number of squats (left)	0
Total number of squats (right)	8
Number of correct squats (left)	0
Number of correct squats (right)	8
Velocity squats left (ms)	0.00 ± 0.00
Velocity squats right (ms)	0.07 ± 0.01
Velocity squats delta (ms)	0.07
Duration squat left (s)	0.00 ± 0.00

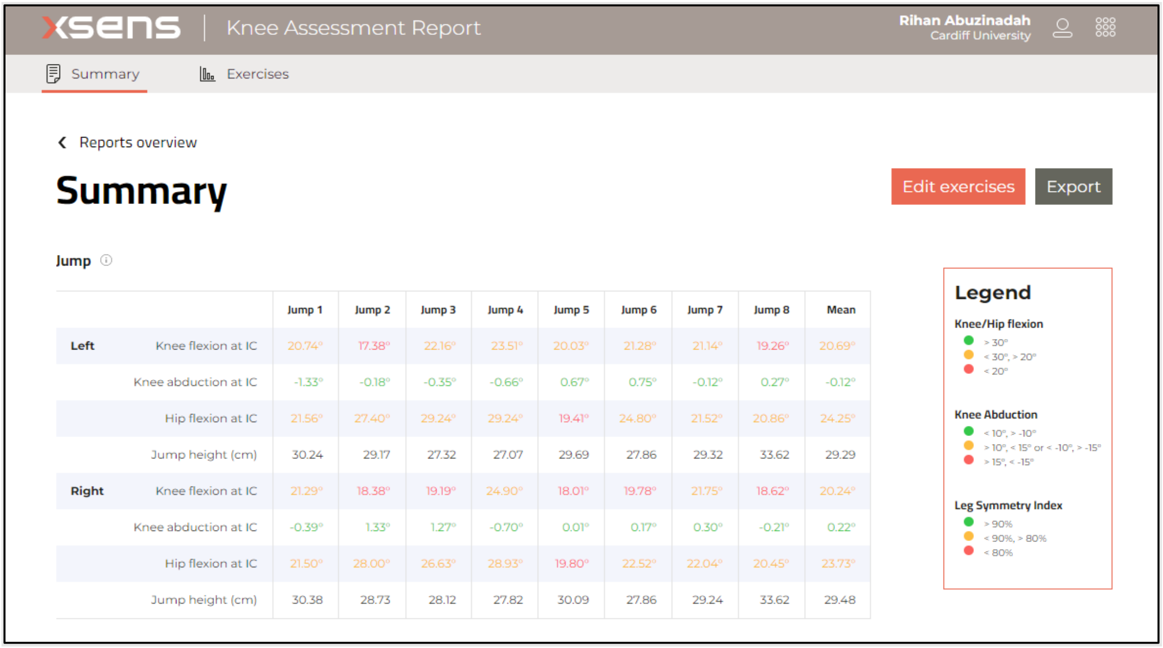
Hip angle [deg]

	flexion(+)/extension(-)		abduction(+)/adduction(-)	
	min	max	min	max
Left	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Right	14.39 ± 5.11	71.99 ± 11.14	-18.59 ± 1.78	-0.69 ± 3.93
Difference	14.39	71.99	18.59	0.69

Figure 20: Exercise page of the SLS report

6.3.6.3 Overview of the vertical jump reports

To generate the report, the VJ exercise needs to be selected from the menu. Vertical jump reports consist of two pages, the first of which is the summary page (see Figure 21). However, it differs from SLS summary page in that it presents information for both legs because the activity is performed using both lower limbs. The information featured in the summary table is also different because it shows the knee flexion angles at initial contact (IC), knee abduction angle at IC, hip abduction angle at IC, hip flexion angle at IC, and the VJ height. All of this information is also presented using the traffic light colours to differentiate between normal, reduced or restricted ROM. These ranges which are visualised using the traffic light colours are automatically generated by the software.



Summary

Jump

		Jump 1	Jump 2	Jump 3	Jump 4	Jump 5	Jump 6	Jump 7	Jump 8	Mean
Left	Knee flexion at IC	20.74°	17.38°	22.16°	23.51°	20.03°	21.28°	21.14°	19.26°	20.69°
	Knee abduction at IC	-1.33°	-0.18°	-0.35°	-0.66°	0.67°	0.75°	-0.12°	0.27°	-0.12°
	Hip flexion at IC	21.56°	27.40°	29.24°	29.24°	19.41°	24.80°	21.52°	20.86°	24.25°
	Jump height (cm)	30.24	29.17	27.32	27.07	29.69	27.86	29.32	33.62	29.29
Right	Knee flexion at IC	21.29°	18.38°	19.19°	24.90°	18.01°	19.78°	21.75°	18.62°	20.24°
	Knee abduction at IC	-0.39°	1.33°	1.27°	-0.70°	0.01°	0.17°	0.30°	-0.21°	0.22°
	Hip flexion at IC	21.50°	28.00°	26.63°	28.93°	19.80°	22.52°	22.04°	20.45°	23.73°
	Jump height (cm)	30.38	28.73	28.12	27.82	30.09	27.86	29.24	33.62	29.48

Legend

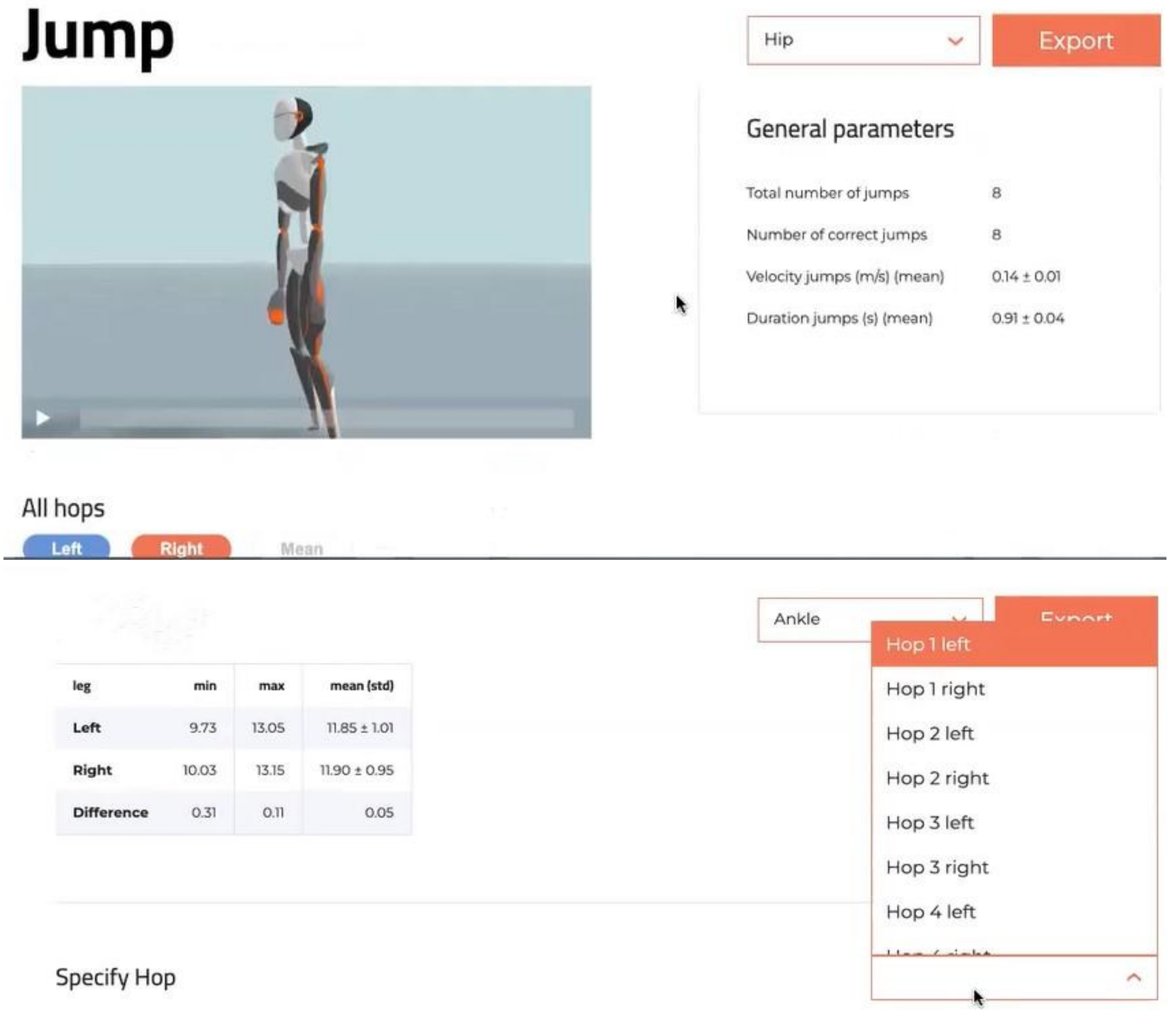
Knee/Hip flexion
🟢 > 30°
🟠 < 30°, > 20°
🔴 < 20°

Knee Abduction
🟢 < 10°, > -10°
🟠 > 10°, < 15° or < -10°, > -15°
🔴 > 15°, < -15°

Leg Symmetry Index
🟢 > 90%
🟠 < 90%, > 80%
🔴 < 80%

Figure 21: VJ report summary page

The second page in the VJ report is the exercise page which includes the avatar video with a summary of the general VJ parameters. On this page (Figure 22), the participants are able to select a specific lower limb joint (hip, knee or ankle) and tables for that joint with minimum, maximum and mean joint angles for the right and left lower limbs are presented. The page also includes information regarding the number of hops for each jump and the joint angles at each hop (see Figure 22).



General parameters

Total number of jumps	8
Number of correct jumps	8
Velocity jumps (m/s) (mean)	0.14 ± 0.01
Duration jumps (s) (mean)	0.91 ± 0.04

leg	min	max	mean (std)
Left	9.73	13.05	11.85 ± 1.01
Right	10.03	13.15	11.90 ± 0.95
Difference	0.31	0.11	0.05

Figure 22: VJ report exercise page

In summary, each report for gait, SLS and VJ is bespoke to that activity, thereby ensuring that the information and parameters key to each exercise are included. This is potentially useful for clinical settings and helpful for physiotherapists treating the CKP population because the kinematic information and waveforms of movement are presented individually for each CKP condition. This allows physiotherapists to utilise individualised assessments and treatment plans, as recommended in part one of the thesis.

6.3.7 Pilot testing

A pilot test was conducted on three participants to confirm the test strategy and estimate how long the test would take. Piloting helped to prepare for the actual testing event by practicing the roles of the lead researcher (RA) who was to conduct the test (Barnum 2020). It is also important to ensure that individuals had no difficulty understanding all of the steps for each task and that these tasks were well defined (Barnum 2020). While the participants were taking the test, the lead researcher (RA) observed and took notes. Based on the feedback obtained, the tasks were adjusted. This pilot test helped the lead researcher to simplify the task description.

Following piloting, it was apparent that certain amendments were needed. For example, the introduction of the tasks was made clearer, as suggested by one of the participants who thought that giving the full task at one time made it more difficult for users to recall what was being asked of them and they suggested introducing the task title in general first, before giving additional steps for that task to be accomplished. The initial pilot test focused solely on the gait report component of the E-reporting tool. The lead researcher (RA) observed that this component was the most straightforward and users completed it quickly. However, it was also noted that the gait report lacked certain features present in knee assessment reports such as the ability to edit and identify the type of exercise performed. Accordingly, it was decided to test another component of the tool which was the knee assessment report to ensure that all of the components of the E-reporting tool and multiple exercises (gait, SLS and VJ) were being tested in this usability evaluation.

Another issue which became apparent during the piloting process was the Internet connection. The E-reporting tool was slow performing certain tasks and the software required extensive system resources (the tool required a significant amount of computational power, memory and other technical capabilities). Therefore, in the real test, a backup plan was developed for how to complete the test in the event that this situation occurred. This backup plan subsequently proved very beneficial in the real test because not all components of the software worked immediately and the issue was not related to the Internet connection but to technical issues within the system.

6.3.8 Usability test procedures

6.3.8.1 Test scenario and researcher's script

The lead researcher (RA) provided each participant with access to the E-reporting tool. The participants received an email from [redacted] explaining how to sign up for the system. The lead researcher (RA) then asked the participants to sign into the system before the test day to ensure that everything was working well and that no problems were identified.

On the day of the test, the participants joined the scheduled Zoom meeting through the link that was sent to them. The lead researcher (RA) welcomed the participants and provided them with a brief explanation of the E-reporting tool, the procedure and what would be required from them before the recording was initiated. This process took approximately seven-to-ten minutes. Once the recording had started, the following steps were applied, as recommended by Barnum (2020):

1) Welcome the participants.

2) Describe the screen-sharing process (including the use of the participant's webcam if required).

3) Verify that audio, video and screen sharing were all functioning properly.

4) Confirm receipt of the signed consent form.

5) Describe the purpose of the study and how the scenarios and questionnaires will be used.

6) Explain the E-reporting tool and what it involves.

7) Describe the TA process.

8) Remind the participants that they are able to withdraw at any time if they feel uncomfortable.

9) Remind the participants that it is the product that is being tested, not them.

10) Remind the participants to ask questions at any time.

11) Start the scenario.

The full test scenario can be seen in Table 36. The test scenario was standardised among all of the participants to ensure the consistency and fluency of the procedure. In steps two and three, the lead researcher (RA) explained how to do screen sharing and take mouse control. The researcher ensured that there were no technical issues that needed to be resolved.

In step four, the participants were reminded about their consent to record the session to ensure that the participants were comfortable with the process. If a participant refused to be recorded, the researcher had the option to terminate the session or continue without recording it.

In step five, the purpose of the study was clarified. Then, because the participants were unfamiliar with the E-reporting tool, the researcher introduced it and this was followed by a quick overview which included training in how to use it. This session lasted no more than approximately ten minutes. The researcher then demonstrated the SUS questionnaire and informed the participants that it should be completed by the end of the test, signed and returned to the researcher.

Table 36: The standardised researcher's script

Researcher's script for a remote usability study

Do you mind if I recorded this session for research purposes? Ok, thank you. I am going to start the recording now.

Welcome

Hi …... This is RA, a PhD candidate at Cardiff University and the lead researcher for this study. First, I would like to thank you so much for agreeing to take part in this research project which aims to test the usability of an electronic version of the kinematic report and reporting template that was used in a previous analysis for the purpose of movement analysis and the identification of movement alteration for people experiencing chronic knee pain compared to healthy individuals. This is the conversion to an electronic format. The usability of this electronic version will be tested by physiotherapists on our previously collected data that will be preloaded to the software. The purpose of this phase is to have a tested electronic movement analysis report that will be ready for feedback in the clinical setting as part of a feedback intervention.

Is it correct that you gave us permission to record the session for internal research purposes? Are you sure you want to do this? Thank you very much. We will now set up screen sharing so we can see your screen and you can operate your mouse and keyboard.

This electronic reporting tool work is still in progress and development, which is why we are asking for your feedback now. Your comments will be used to help improve and develop the tool.

Introduction to scenarios

First, I will ask you to sign into the tool using your registered email and password and I will ask you to perform some common tasks that researchers like you may perform.

We are particularly interested in what works for you and what causes issues.

I am going to invite you to think aloud or share your thoughts as you complete these tasks. (Talk while you are doing the tasks) Tell us what you believe works well and what you think does not. “It is understandable that thinking out loud while working may not be considered ‘normal’ but doing so will provide insight into your experience when you share your thoughts this way.” You can be completely honest about your experiences.

Finally, I will ask you to complete an after-test questionnaire for additional information. All you need to do is to mark one box that best describes your first impression on the electronic reporting tool today without overthinking it. We are very happy to hear from you about how to improve the overall experience with the tool. So, if you have any comments, please write them down in the questionnaire.

Are you ready? Have you understood the plan? Do you have any questions? Have you read the participant information sheet? Do you have any questions before we start? Could you please make sure that you sign into the tool.

OK. Now I’m going to read the first task to you.

Tasks:

------ Tasks go here ------

After the last task, conclude and end the session.

Thanks so much for your participation. We learned a lot from you! I will stop the recording now and could you please start filling in the post-test questionnaire (I will send it to you by email to complete it and send it back to me).

6.3.8.2 The think aloud technique

For step seven in the test scenario, the TA process was described for the users. Prior to initiating the test, each participant was given a brief explanation of the TA technique. The participants were reminded about verbalising their thoughts and actions while performing the tasks and to ensure that the participants understood the plan of the evaluation. The lead researcher (RA) explained that “it is understandable that thinking out loud while working might not be normal but doing so will help the researcher gain insight into your experience when you share your thoughts in this way.” The researcher provided examples of the concept of "expressing their thoughts," including the following: “I appreciate this because… These contents are not what I expected to see when I clicked on that link… This word is completely foreign to me… I wish this item enabled me perform X.”

There were four broad stages in the TA technique:

- State the aim of the evaluation: The main aim of this usability study is to test the usability of an electronic version of the kinematic IMU reports that were used in a previous analysis for movement analysis and the identification of movement alteration for people with CKP compared to healthy individuals.

- Define the tasks: It is important to precisely outline the full task at first (e.g., “this task is about identifying gait parameters”) and then to mention the subtask needed to accomplish the main task. This helps the participants to maintain their concentration on the goal and, as a result, the process required to achieve that goal. Tables 37, 38 and 39 present details of the test tasks for each of the evaluated reports.

- Conduct the evaluation.

- Analyse the data.

6.3.8.3 Usability test tasks

The lead researcher (RA) outlined a task list for the participants to conduct the usability test on the E-reporting tool (see Tables 37, 38 and 39). The tasks were chosen to determine whether the user interface elements are useful or need to be refined. In addition, they were selected in a way that allowed sufficient interaction with the E-reporting tool, utilising most of its features and searching for usability issues but not too much interaction so that the user would forget their work and become fatigued. The tasks should be selected so that the relevant system components are implicitly utilised by the participant (Barnum 2020).

6.3.8.3.1 Justification and explanation for the selected test tasks

6.3.8.3.1.1 Gait report tasks

Task 1: Identifying gait parameters

The first task in the gait reports sought to identify the gait parameters (see Table 37). To achieve this task, users had to perform certain subtasks which allowed them to go through the system and discover its characteristics. They had to select the gait report icon, not the knee assessment report, which took them to the gait report overview page. In the gait report overview page, they had to choose a patient file from several preloaded IMU files with movement data. This page had other features that the participant could choose from, as shown in Figures 15-16. The participants needed to ensure that they selected the icon for a patient filename and not something else. This subtask was important because it provided an impression of the time that a physiotherapist would need in clinics and whether or not this would be manageable and easily accessible.

Upon opening the file, the gait parameter page in the report opened automatically and the participants had to describe what they saw on the page. The task was particularly important to establish whether the participants were able to understand the parameters, if they could access information easily and if they had any comments about it. In the last subtask, the participants had to identify the percentage of swing phase for each limb of the investigated subject's gait. To accomplish this, they had to open the temporal parameters, look at the provided information in the tables and interpret them to provide the answer. By the end of this subtask, the first main task in the gait reports had been completed.

Task 2: Interpreting gait graphs

The second task in the gait report was to interpret the gait graphs. This is accomplished by the first subtask with the participants having to move from the gait parameters page to the gait graphs page and explain what the graph page is about. In this subtask, the lead researcher (RA) investigated whether navigating through the system was easy and if the participants were able to explain the subject's avatar, graphs and tables.

In the second subtask, the participants had to identify the peak knee flexion within the whole gait cycle, select that point and annotate it. This task could not be accomplished instantly because the participants had to change the joint first owing to the fact that the hip joint was chosen by default in the system. They also had to ensure that they were on the right plane of movement because it provided information on the frontal, sagittal and transverse planes for each limb. Once they had changed the joint, the waveforms changed automatically and they could then interpret and annotate them as requested by the researcher. The participants were then asked to find the same variable from the provided tables on the same page. The importance of these two subtasks was to allow the participants to visualise the subjects' movement through the avatar which can be seen from different planes of movement, to interpret a joint angle for a specific joint, and provide an explanation of that movement in terms of the amount, the nature and the timing of that movement. The tables on the graph page provided the joint angle for each limb during the overall cycle, the stance phase and the swing phase with minimum, maximum and the difference in joint angles between the right and left limbs (see Figure 17).

Task 3: Comparing gait graphs

The third task required the participants to compare the gait graphs of two subjects. This task required the participants to perform the first subtask which allowed them to interact with the system, moving from the graph page back to the report page because the comparing option was only available on the gait reports page. In the second subtask, the participants were instructed to click on the 'compare' icon and subsequently select two of the uploaded IMU files. This task involved actively engaging with the system which included processing a file or report, managing a task and navigating through the interface. The participants were also expected to explore the various icons and understand their respective locations within the system. After doing so, a new page opened which included two subjects’ gait graphs with all of the required parameters. The third subtask required the participants to find the right ankle angle at the heel strike for each participant. The reason for choosing this task was to enable the participants to investigate gait graphs and their tables and ensure that they had selected the correct joint and provided an answer. This subtask also enabled the participants to interact with the E-reporting tool and provided the researcher with an overview of this interaction.

Table 37: Usability test tasks for gait reports

Task 1: Identifying gait parameters:

1. Now that you have the gait report overview page open, could you please choose one of the participants and enter his/her profile?

2. First, I would like you to explain to me what you think this page is about.

3. On the same page (gait parameter page), could you identify the percentage of swing phase within the gait cycle for each leg of this participant?

Task 2: Interpreting gait graphs:

1. Could you please now go to the gait graphs page and talk through what you see on that page.

2. Now I would like you to identify where the peak knee flexion is within the whole gait cycle, then select that point and write a note about it or just name that point.

3. Can you identify the same variable in the table below?

Task 3: Comparing gait graphs:

1. Go back to the reports overview page please.

2. Now I would like you to compare the two participants' graphs.

3. Have a look at the page and then tell me what the right foot (ankle) angle at heel strike is for both participants.

6.3.8.3.1.2 SLS report tasks

Table 38 presents the tasks selected to interpret the SLS reports.

Task 1: Editing and identifying the type of the performed exercise

Single leg squat and VJ reports were included in a large category in the system called knee assessment reports which includes nine other exercises with their reports also available. The system does not allow any of these reports to be generated without first choosing the type of exercise being investigated, so this task was required. In the first subtask, the participants had to select a specific file, as requested by the lead researcher (RA). The second subtask required the participants to watch the avatar of a subject performing the activity and then to specify the type of exercise from a list of nine exercises. However, before doing this, the participants were required to select a specific timeframe that allowed for the analysis of the given activity (see Figure 18). To successfully accomplish this task, the participants needed to locate the icon for adding or updating an exercise, constituting the third subtask.

These three subtasks sought to assess the participants' ability to visualise movements through the avatar video, distinguishing the specified exercise from others and determining if they could promptly generate reports for that particular exercise.

Task 2: Identifying SLS parameters

After choosing the type of exercise, the SLS reports generated two pages: a summary page (see Figure 19) and an exercise page (see Figure 20). The initial subtask involved discussing the summary page to assess the participants' comprehension of the parameters. The participants were asked to identify the mean for the maximum knee flexion angle. The participants had to look at the table and interpret the data to respond to the task.

The second subtask involved the participants navigating to the exercise page where they were tasked with determining the number of successful SLS trials performed. For this subtask, the participants had the option to gather this information either by watching the included video featuring the subject's avatar performing the activity or by referring to the table positioned beside the video which presented the required details (see Figure 20)

In the third subtask, the participants remained on the same page and were prompted to identify the minimum hip abduction and adduction angles throughout the entire squat cycle. Beyond navigating the system and observing the participants' interactions, the second and third subtasks provided visualisation, allowed for the interpretation of movement patterns and the description of successful or altered patterns.

Task 3: Exporting a file

The third SLS task involved the participants returning to the summary page where they were instructed to export a subject's file and save it. This task was selected to highlight the functionality that allows the participants to save reports as PDF files and print them. This feature is of significant practical value for physiotherapists and their patients in clinical settings because it facilitates the acquisition of a copy of their movement analysis reports. This, in turn, enables the patients to share their thoughts and decisions with their physiotherapists. Consequently, the researcher sought to observe the participants' attitudes towards this feature through TA and to assess how easily the participants were able to execute it.

Table 38: Usability test tasks for SLS reports

Task 1: Editing and identifying the type of exercise performed
1. First, open the page for the participant’s ID number .... You will need to edit that exercise.

2. Watch the video and then you will need to specify and name that exercise. In other words, from the video you watched, choose which type of exercise that was.

3. Choose add/update exercise.

Task 2: Identifying SLS parameters

1. Have a look at the pages you have for this activity and tell me what you see. Then find the mean for the maximum knee flexion angle.

2. On the same activity, go to the exercise page and tell me the number of successful SLS trials that this subject did.

3. Please identify the minimum hip abduction/adduction angle during the squat cycle.

Task 3: Exporting a file:

Go to the summary page to export and save the file for this participant.

6.3.8.3.1.3 Vertical jump report tasks

Table 39 presents the tasks selected to interpret the VJ reports.

Task 1: Editing and identifying the type of exercise performed

This task was primarily chosen with the aim of assessing the memory of the participants' interaction with the system and to establish how easily they were able to perform a repeated task scenario. Thus, the participants had to perform the same steps that they did to identify the SLS activity but they needed to recognise the difference in the video and the type of exercise performed, which was VJ.

Task 2: Identifying joint angles for a single hop

To complete this task, only one subtask was required: identifying the ankle angle for a single hop. This subtask involved several sequential steps within the report. Initially, the participants needed to transition from the summary page to the exercise page, demonstrating their navigation skills. Subsequently, the participants were required to review the content of the reports, explaining it using TA. Finally, they had to modify the default joint selection in the system and interpret the findings associated with the selected joint.

Table 39: Usability test tasks for jump reports

Task 1: Editing and identifying the type of exercise performed

1. First, open the page for the participant's ID number ….. You will need to edit that exercise.

2. Watch the video and then you will need to specify and name that exercise. In other words, from the video you watched, choose which type of exercise that was.

3. Choose add/update exercise. Look at the pages and tell me what each page is about.

Task 2: Identifying joint angles of a single hop

1. Go to the exercise page and find the ankle angles for a single hop.

The lead researcher (RA) observed the participants' behaviour and attitude towards the system while they were undertaking the usability test and wrote down key elements.

The lead researcher (RA) also noted the start and end times of each participant for completing the tasks through the recorded videos taken from the usability session.

Once the tasks had been completed, the participants were asked to complete the SUS questionnaire. Finally, the session was concluded and the participants were acknowledged for their participation in the study.

6.3.9 Data analysis of part 2

Data acquired from the TA and SUS for this usability study were analysed descriptively using frequencies, means, standard deviations and percentages. The outcome variables of interests are introduced in the following section.

6.3.9.1 Outcome variables

To identify what problems the participants encountered with the system and determine the outcome variables that best answer the research question, the evidence for the key metrics was closely examined. According to the recommendations introduced by the International Organization for Standardization (ISO) regarding what constitutes the key metrics for evaluating the usability of any system, usability refers to how well a product can be utilised by specified users to accomplish specified objectives with effectiveness, efficiency, and satisfaction within a specified usage context (ISO 1998). It is evident from this definition that usability is not a singular, unidimensional characteristic; instead, it is a composite of various elements. This approach is preferred because it introduces the primary usability metrics in an ordered manner, as opposed to a random assortment of disconnected metrics. Nielsen (2012) proposed that usability is a combination of five different attributes, namely: learnability, efficiency, memorability, errors and satisfaction. Nielsen (2012) also indicated the need to assess UI problems because they allow for a better understanding of other metrics (Nielsen 2012). Identifying usability problems is highly recommended by usability experts (Nielsen 2010; Rubin 1994; Dumas and Redish 1999).

For this study, a coding scheme was established based on five usability characteristics derived from combining ISO and Nielsen usability attributes: efficiency, effectiveness, memorability, user interface problems, errors and SUS as a measure for the overall ease of use and predictive measure of satisfaction. Learnability was not included as an outcome in the developed coding scheme for various reasons. Learnability considers how simple it is for users to complete a job the first time they see the interface and how many repetitions it takes for them to become good at that task (Nielsen 2012). Because the participants were new to the E-reporting tool and this was the first time that they had interacted with the system, learnability for tasks that users accomplish infrequently or only once makes little sense and, therefore, it was excluded from the analysis. To make the results of the usability evaluation more meaningful, the lead researcher's (RA) observation was also described. By doing so, a better understanding and justification of the test results was possible. All of the included variables were extracted through the TA approach except for the overall ease of use which was measured using the SUS questionnaire. Table 40 presents the included usability metrics, the approach used for each, and how it was measured.

Table 40: Outcome variables for the usability evaluation

Outcome variables	Approach used	Measurement
Efficiency (m)	TA	Task time
Effectiveness (%)	TA	CR
Memorability (m)	TA	Task time of a repeated task
UI problems	TA	Severity, frequency, probability of problems
UI errors	TA	Frequency/number and average of errors

Overall ease of use (%)	SUS questionnaire	SUS overall score
UI: user interface; **TA:** think-aloud; **SUS:** system usability scale questionnaire; **CR:** completion rate; **m:** minutes; **%:** percentage.		

Data analysis was undertaken after each usability testing session outside the Zoom meeting platform. This approach enabled the researcher to watch the recorded videos and dedicate more time to a thorough analysis of the data. The next section explains how these outcome variables were analysed and measured for the usability evaluation.

6.3.9.1.1 Efficiency

As articulated by Nielsen (2012), efficiency is how quickly participants are able to execute tasks once they have learned the design. Thus, efficiency is measured in terms of the time required to complete a task.

Task time was calculated as the total time taken to finish the usability test, the amount of time it took users to accomplish a specific task scenario for an activity, in addition to the time spent on each task of that activity. Start task time (when the user started reading a task) and finish task time (when the user completed all of the actions) were recorded by the lead researcher (RA).

The time required to perform a task is calculated by subtracting the start time from the end time, as illustrated in the equation below:

Task Time = End Time – Start Time

Task time was measured in minutes. The average task time was only counted for participants who were able to successfully complete all their tasks. However, the time spent on each activity was reported to provide the reader with an insight into the tasks that took longer time to be accomplished and to assist in the analysis of the other usability metrics.

It should be noted that task time can be affected by various factors such as unfamiliarity with the atmosphere, tasks and manual dexterity because some users may be faster than others (Sauro 2010). However, by including other usability metrics, a comprehensive approach to longer task times can be provided. The averages and standard deviations were calculated using the Microsoft Office Excel 2020 software package (Microsoft Corporation, Redmond, Washington, USA).

6.3.9.1.2 Effectiveness

Effectiveness was defined by whether the participant was able to complete the required tasks and achieve the goals and was measured by the **completion rate (CR)** which estimated the task success rate (Sauro and Lewis 2016).

The completion rate provides little insight into why participants fail or the quality of the tasks they complete but it is simple to obtain and a very informative statistic. Ultimately, if the participants cannot complete their intended task, all else is meaningless (Nielsen 2012). The CR is the bottom line of usability.

The CR was calculated using Excel 2020 software package from Microsoft Office and was reported as an average score among the participants by dividing the number of participants who successfully finished a task by the total number of participants that attempted it. Thus, **effectiveness was represented as a percentage using the following equation:**

$$Effectiveness = \frac{\text{Number of tasks completed successfully}}{\text{Total number of tasks undertaken}} \times 100\%$$

There were eight tasks in total (three for gait, three for SLS and two for jump). Therefore, for each participant and each task, C indicated a full CR score out of 100%, whereas NC indicated an incomplete task status and meant 0%. However, some tasks presented partial completion (PC) if the participants tried to do the task and went through all of the appropriate steps needed for its completion but could not reach the last step due to technical issues. In such cases, the task was given the symbol PC to provide better clarification of the longer task time or certain problems and errors encountered. However, the score was also 0%. This method of analysing CR has been recommended by several usability experts (Sauro and Lewis 2016; Sauro 2010).

6.3.9.1.3 Memorability

Memorability was measured by any repeated task scenario a participant had to perform to accomplish a new task. In other words, memorability was measured by the difference in time between the task performed in one report and a repeated task required in another report. For example, task one in the VJ activity of the knee assessment report was a repetition of task one in the SLS activity. However, the difference was the type of exercise which should be recognised by the participant.

6.3.9.1.4 Usability problems

It is critical in a usability evaluation to improve a software system by identifying its usability problems and prioritising them based on their impact on the users. If the participant experienced a problem associated with the interface while attempting a task then it was a user interface problem. The user interface problems were categorised into lists with titles and descriptions. In addition, the frequency and probability of each problem was calculated.

The impact of a problem was calculated as suggested by Rubin (1994) and Dumas and Redish (1999) by assigning impact scores based on whether the difficulty: (1) hinders task completion; (2) causes a major delay or frustration; (3) has a minor influence on task performance; or (4) is a suggestion or comment (Rubin 1994; Dumas and Redish 1999). Nielsen (2010) also suggested categorising the problems according to their severity.

The frequency of occurrence of a problem ***(F)*** was measured by the sum of the number of problems encountered by each participant.

$$\boldsymbol{F\ of\ a\ problem} = number\ of\ problems\ by\ user\ A + number\ of\ problems\ by\ user\ B + \cdots$$

The probability of a participant encountering a problem with the system was also measured by dividing the total (T) number of participants who encountered a problem by the total number of participants. Understanding the probability that users will encounter a problem at each level of development can be a crucial indicator for analysing the impact and return on investment of usability activities (Sauro and Lewis 2016).

$$p\ of\ problem = \frac{T\ No.of\ participants\ who\ encountered\ a\ problem}{T\ No.of\ participants\ in\ the\ usability\ evaluation}$$

6.3.9.1.5 Errors

Errors are different from the problems encountered. Errors are any unintentional action, slip, mistake or omission made by a participant while performing a task. Errors provide important diagnostic information and should, whenever possible, be mapped to user interface problems. Even basic recordings of errors could provide an insight into the effects of user interface problems, so they are relevant to each other. They also account for a significant portion of the reasons for prolonged task times and lower completion rates (Sauro 2010; Hantunen 2022). Without an error log, it is only possible to see a longer task duration and wonder why a participant may have taken longer. In fact, errors have a strong correlation with task completion time and account for approximately 25% of the variance in participant timings (Sauro and Lewis 2009). Errors can enable the identification of omissions and commissions that nearly result in task failure and can occur several times per task.

Error data were analysed by the lead researcher (RA) who recorded and noted any unintended actions. Schäfer et al. (2021) and Kastner et al. (2010) advocated the categorisation of types of errors depending on the researcher's observation of the errors during the test and how frequently they occurred. Accordingly, errors were classified into seven categories and each category was given a number to facilitate its analysis (see Table 41).

Table 41: Types of errors

* **Types of errors**	**Definition/examples**
(1) Navigation	An inability to move from one page to another without assistance; errors due to categorisation.
(2) Layout	Errors due to design, arrangement, organisation or structure.
(3) Handling	Errors in the processing of a file or report; dealing with a task.
(4) Misclassification	Errors due to unclear wording, content and information.
(5) Technical	Errors in the system (such as the system's inability to open a page) that prevent participants from completing a task.
(6) Interface design	Errors caused by font, tab size or colour.
(7) Input device	Mis-tapping; clicking on another icon on the screen.
*Each type of error is given a number (1, 2, 3, 4, 5, 6 or 7) which represents its category (i.e., number 1 is navigation error, etc).	

A detailed description of the executed errors can be seen in Appendix (O).

The **frequency of occurrence** of errors was reported for each participant on each task. The **total number of each type of error** was also computed. Finally, the **average**

number of errors was calculated using the method suggested by Sauro (2010) through the calculation of three different measures of errors.

First, the **error opportunity** was calculated by the number of tasks in each report multiplied by the total number of users who attempted the tasks:

$$\boldsymbol{Error\ opportunity} = No.of\ tasks\ for\ the\ report\ x\ Total\ No.of\ users\ attempted\ the\ tasks$$

Second, the **error rate** was calculated by the total number of errors in that report divided by the error opportunity:

$$\boldsymbol{Error\ rate} = \frac{No.of\ total\ errors\ in\ a\ report}{error's\ opportunity}$$

Third, the **average number of errors** was measured by dividing the error rate by the number of tasks in the report. The same method was used to calculate the total average number of errors that occurred during the whole test procedure. This method was chosen for the analysis of errors because it provides the researcher with an average score that can be compared to a benchmark of the average number of acceptable errors provided by Sauro (2010) and Sauro and Lewis (2016).

$$\boldsymbol{Average\ No.of\ errors} = \frac{error\ rate}{Number\ of\ tasks\ for\ each\ report}$$

6.3.9.1.6 System Usability Scale questionnaire

The SUS is a ten-item Likert scale questionnaire which has been used to quickly and reliably (Mol et al. 2020) assess the usability of a system across several sectors. It consists of questions which ask the participants to rate the usability of the system on a five-point scale ranging from “strongly agree” to “strongly disagree.” Unlike other usability metrics, the SUS is not diagnostic and is used to provide an overall measurement of ease of use.

After completing the questionnaire, the responses are converted into a score from 0 to 100, with higher scores indicating better usability. The SUS score can be used to make comparisons to a growing body of literature to establish percentile rankings for a system’s usability performance (Brooke 1996).

To calculate the SUS score, the score contributions from each item are added together. The score contribution of each item will vary from zero to four. The score contribution for items 1, 3, 5, 7 and 9 is the scale position minus 1. The contribution for items 2, 4, 6, 8 and 10 is 5 minus the scale position. To calculate the total value of SU, the sum of the scores is multiplied by 2.5 (Barnum 2020; Brooke 1996).

According to Brooke (1996), the percentage of each question against the participant's response was determined and interpreted as follows:

- 100% corresponds to a perfect system without usability problems.
- Values above 80% indicate good-to-excellent usability.
- Values between 60% and 80% are interpreted as borderline-to-good usability.
- Values below 60% are indications of significant usability problems.

These benchmark criteria were used for the analysis and interpretation of the SUS questionnaire. The SUS questionnaire can be seen in Appendix (P).

6.3.9.1.7 Researcher’s observations

The researcher observed participants while performing the tasks and took notes about their behaviours. Observation involves carefully looking, listening and thinking about what the participants were seeing and hearing which allows the researcher to pick out significant details. Based on the researcher’s plan, the following elements should be addressed: the tasks and individual steps involved; interruptions; the problems that the participants encounter; and environments (personal or shared workspaces or communal areas). The researcher’s overall observations of participants were then written down for each of the previously selected tasks.

Because the TA interviews were video/audio-recorded, the researcher had the opportunity to review the recordings following the tests for further analysis and write down key observations. These observations, in addition to the users’ comments, were later chosen to provide the developers with recommendations for future iterations of the E-reporting tool.

6.3.10 Ethical considerations

All of the information regarding the participants that was gathered was kept strictly confidential and any personal information provided was managed in accordance with data protection legislation. As per the General Data Protection Regulation (GDPR), personal data comprises any information that pertains to a living individual who is identifiable, either directly or indirectly. This may consist of personal information such as the name, address, email address, or date of birth of the individual. The only personally identifiable data that were collected in the current study were the users’ names (on the consent form) and their email addresses so that the researcher could contact them. These data were stored on servers at Cardiff University. An anonymous research project number was used on all of the research documents.

The consent forms will be stored for five years on secure servers at Cardiff University. Email addresses were destroyed after the data collection process was completed. All of the research data collected about the usability of the E-reporting tool and the tasks completed were anonymous and were saved directly onto Cardiff University’s servers and will be destroyed after five years, in accordance with the University Records Retention Schedules. These documents may be accessed by members of the research team and, where necessary, by members of the University’s governance and audit teams or by regulatory authorities. Anonymised information may be published in support of the research project and/or retained indefinitely if it is considered likely to have continuing value for research purposes.

If participants withdraw from the study, all personally identifiable data will be destroyed. It was made clear to the participants that their data could be used in future development studies of the E-reporting tool. There will be no mention of the participants in any report, publication or presentation. It was also explained to the participants that they could contact the lead researcher to acquire a copy of the publication if they wished.

Chapter 7 Results of Part 2

7.1 Overview

The study aim was to test the usability of an electronic version of an IMU-based movement analysis and reporting tool for physiotherapists treating individuals with CKP. This was achieved using the TA technique and SUS questionnaire to measure all of the metrics contributing to a usability test of the E-reporting tool which were efficiency, effectiveness, memorability, problems, errors and the SUS score. The researcher’s observations were also presented to enable a better understanding of the findings.

This chapter presents the results derived from the analysis of the collected data from the participants with usability evaluation methods. The results of the TA technique are presented first, followed by the data derived from the SUS questionnaire. Three reports were tested in the E-reporting tool, namely the SLS and VJ reports in addition to gait reports because these three activities were also included in part one of this PhD thesis. There were three tasks for the gait reports, three tasks for the SLS reports and two tasks for the jump reports. Each task consisted of some subtasks which needed to be accomplished.

7.2 Participants

The participants comprised five females and one male with a mean age of 33. 66 ± 0.94 years. All of the participants were physiotherapists and had at least two years’ experience of treating people with knee pain. They were also experienced in the usual movement analysis methods through visual observation. However, they had no experience of movement analysis using motion capture technologies and/or with online reporting websites.

7.3 Efficiency

Efficiency was measured in terms of task time. Task time was measured in minutes and was reported as the average time spent on the evaluation process, average time spent to successfully accomplish a task, and the average time spent for each of the selected reports. Table 42 provides a summary of the overall test results with the minimum, maximum and mean time spent during the overall evaluation.

Table 42: Summary of the overall test results

Participants	Full test time (M)
User A	00:30:34
User B	00:30:20
User C	00:35:16
User D	00:40:41
User E	00:37:06
User F	00:27:07
Mean	00: 33:31
SD	00:13:34
Maximum time (M)	00:40:41
Minimum time (M)	00:27:07
SD= standard deviation; **M**= minutes	

Table 43 provides details of the total duration spent on each report (gait reports, SLS reports and jump reports), the duration for each task and the status of each task: completed (C), partially completed (PC) or not completed (NC).

Table 43: Summary of task duration and status for gait, single leg squat and vertical jump reports

Subjects	*Total time (M)	Task 1 (M)	Task 2 (M)	Task 3 (M)	CR (%)
		Status	Status	Status	
Gait					
User A	00:11:00	00:01:52	00:04:40	00:04:28	
		C	C	C	100%
User B	00:11:29	00:02:52	00:04:15	00:03:42	
		C	C	C	100%
User C	00:10:18	00:03:57	00:03:06	00:03:15	
		C	C	NC	67%
User D	00:11:55	00:02:20	00:05:37	00:03:36	
		C	C	C	100%
User E	00:08:13	00:02:43	00:03:16	00:02:14	
		C	C	C	100%
User F	00:08:41	00:02:45	00:03:52	00:02:04	
		C	C	C	100%
Average time	00:10:27	00:03:15	00:04:13	00:03:22	
CR		100%	100%	83.33%	95%
SLS					
User A	00:08:14	00:04:57	00:02:54	00:00:23	
		PC	C	C	67%
User B	00:06:33	00:04:08	00:00:57	00:00:48	
		PC	C	C	67%
User C	00:07:51	00:04:41	00:02:58	00:00:12	
		PC	C	C	67%
User D	00:09:20	00:04:41	00:02:28	00:01:31	
		PC	C	C	67%
User E	00:09:42	00:03:28	00:05:54	00:00:20	
		PC	C	C	67%
User F	00:02:29	00:02:29	00:00:00	00:00:00	
		PC	NC	NC	0%
Average time	00:08:20	00:04:04	00:03:02	00:00:39	
CR		0%	83.33%	83.33%	56%
VJ					
User A	NC	00:01:13	00:02:25		
		PC	NC		0%
User B	00:05:28	00:03:20	00:02:08		
		PC	C		50%

User C	00:04:05	00:01:20	00:02:45		
		PC	C		50%
User D	NC	00:02:14	00:04:43		
		PC	NC		0%
User E	00:02:42	00:01:19	00:01:23		
		PC	C		50%
User F	NC	00:00:00	00:00:00		
		NC	NC		0%
Average time	00:04:05	00:01:53	00:02:05		
CR		0%	50%		25%
***=** total time spent on each report; **CR**= completion rate; **C=** completed status of task; **PC=** partially completed status of tasks; **NC=** not completed status of tasks; **m=** minutes; **SLS=** single leg squat; **VJ=** vertical jump.					

For gait reports, the average time spent on all of the tasks was 10:27 minutes. Among the three predetermined activities, the participants spent the most time on the second task which consisted of detecting gait variables in the gait waveform graphs, with an average duration of 4:13 minutes.

For the SLS reports, the average time spent on the tasks was 08:20 minutes and only five of the participants were able to complete all of the tasks successfully. The first task which addressed editing and identifying the type of exercise performed was the task on which the participants spent the most time, with an average duration of 04:04 minutes. For the jump reports, only three of the participants were able to complete the tasks successfully, with the average time spent on all tasks being 04:05 minutes.

7.4 Effectiveness

Effectiveness was measured by the CR. Table 43 provides details of the participants who successfully completed the tasks and those who failed. The average completion rate among the three reports was 95% for gait reports, 56% for the SLS reports and 25% for the jump reports (see Figure 23). To clarify, for the gait reports, all six participants completed tasks one and two successfully (100%), whereas five of the six participants completed task three successfully, which involved comparing gait graphs.

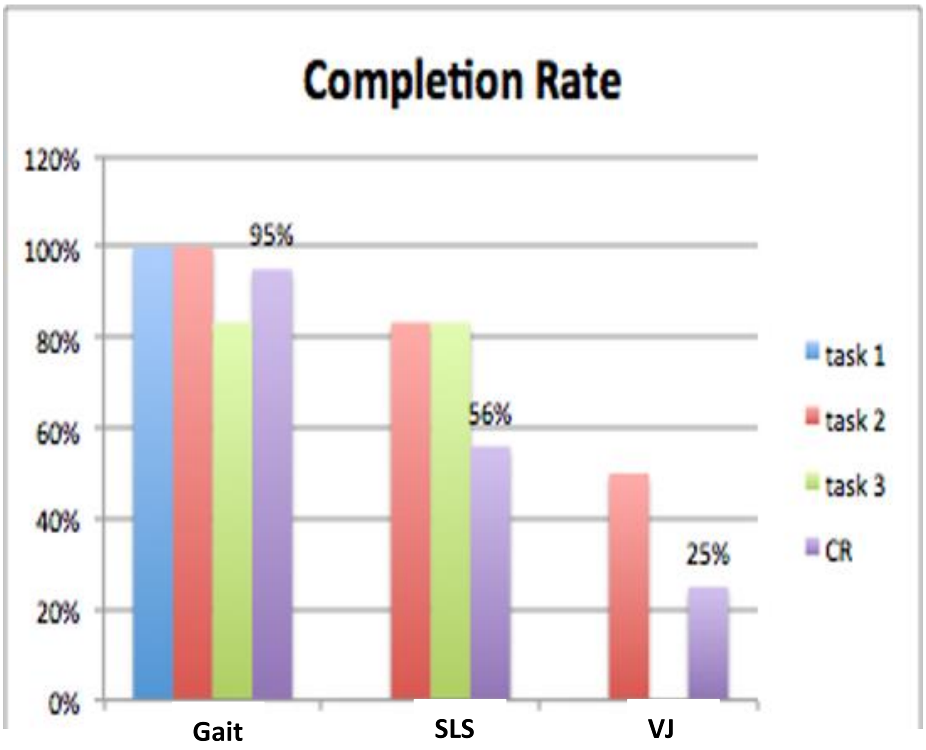


Figure 23: Activity and task completion rate for gait, single leg squat and vertical jump reports

For the SLS reports, all six of the participants only partially completed task one which involved editing and identifying the type of the selected exercise due to some technical issues in the system. Five of the six participants were able to complete tasks two and three successfully. The remaining participant failed to complete tasks two and three due to some technical issues which prevented the participant from completing the task.

For the VJ reports, the total CR for task one was 0% because none of the participants completed this task successfully due to technical issues. To clarify, five participants partially completed the task and one participant failed to complete this task. Regarding task two, three out of the six participants failed to complete the task.

Of those, two participants failed to complete the task due to technical issues and one participant did not know how to deal with the system.

7.5 Memorability

Memorability was investigated by a repetition of task one in the SLS reports. As such, task one in the VJ reports was a repetition for task one in SLS reports; hence, the difference was in terms of the type of exercise that should be recognised by the participant. It can be seen in Table 43 that there was a noticeable difference in task one's average time between the SLS and VJ reports (04:04 minutes vs. 01:53 minutes, respectively) and the participants spent less time on the repeated task. This difference in time indicated that the participants had gained good memorability of the way this task should have been accomplished because they were able to go through all of the subtasks required to accomplish the main task with less time being spent on the task.

7.6 Usability problems

Table 44 presents details of the total number of users encountering each type of problem, the frequency and the probability of each problem identified while the users attempted to accomplish tasks in the gait, SLS and VJ reports.

Table 44: User interface problems for the gait, single leg squat and vertical jump reports

	User A	User B	User C	User D	User E	User F	*Frequency	*Total	*Probability
UI problems for **Gait** reports									
Problem 1	×						1	1	0.17
Problem 2		×	××	×			4	3	0.5
Problem 3	×××	×		×××	××	×	10	5	0.83

Problem 4					× ×××	××× ××	9	2	0.33
Total	4	2	2	4	6	6	**F= 24**		**P= 0.46**
UI problems for **SLS** reports									
Problem 1	×		×	×	×	××	6	5	0.83
Problem 2	×	×	×	×	×	×	6	6	1
Problem 3		×	×	×	×××	×	7	5	0.83
Problem 4			×		×	×	3	3	0.5
Total	2	2	4	3	6	5	**F= 22**		**P= 0.79**
UI problems for **Jump** reports									
Problem 1	××	×	×	×	×	××	8	6	1
Problem 2	×	×		×			3	3	0.5
Problem 3		×	×	×	×		4	4	0.67
Problem 4			××				2	1	0.17
Total	3	3	4	3	2	2	**F= 17**		**P= 0.59**
Total problems							**63**		

Note: Xs represents the times that a problem occurred. For example, in the gait reports, user D encountered problem 2 one time and problem 3 three times. ***F=** frequency of occurrence of each UI problem; **Total=** total number of users who encountered a problem; **P=** probability a user will encounter a problem; **Problem 1**= problem hinders task completion; **problem 2**= causes major delay or frustration; **problem 3**= has a minor influence on task performance; **problem 4**= a suggestion or comment; **UI=** user interface; **SLS=** single leg squat; **VJ=** vertical jump.

In total, 63 problems were identified. There was a total of 24 problems presented in the gait reports and problem number 3, which was defined as the one that had a minor influence on task performance, had the highest frequency of occurrence because it occurred ten times for five participants. This was followed by problem four which presented a suggestion or comment made by the users which occurred nine times. With regards to the probability that a user will face a problem in the gait reports, this figure was 46%.

Regarding the SLS reports, the total number of problems identified was 22 problems (see Table 44) and problem three was the most frequent problem a user encountered (seven times), followed by problem 1 and 2, which were confronted by 5 and 6 participants, respectively. It was found that the probability that a user will encounter a problem with the SLS reports was 79%.

With regards to the VJ reports, the total number of problems identified was 17 problems. Problem one, which was categorised as a problem that hinders task completion, was the most frequently occurring problem because it was registered eight times by the six users. The probability that user would encounter a problem in the jump reports was 59%.

7.7 Errors

Table 45 provides information regarding the frequency of errors executed by the participants, how many users made each error and the average number of errors.

Table 45: User interface types and number of errors

Types of errors	User A	User B	User C	User D	User E	User F	Frequency	Total
UI errors in **Gait** reports								
Error 1	××			×		××	5	3
Error 2	×	×		×	×	×	5	5
Error 3		×		××		×	4	3
Error 4	×	× ×	×		×	×	6	5
Error 5			×	×	×		3	3
Error 6		×	×× ×		×	××	7	4
Error 7	×			×			2	2
Total	**5**	**5**	**5**	**6**	**4**	**7**	**F= 32**	
***Average N of errors**							**0.6**	
UI errors in **SLS** reports								
Error 1		×	×	×	×	×	5	5
Error 2							0	
Error 3	×	×	×	××	××	×	8	6
Error 4			××		×		3	2
Error 5	×	×		×	×××	××	8	5
Error 6							0	
Error 7						×	1	1
Total	**2**	**3**	**4**	**4**	**7**	**5**	**F= 25**	
Average N of errors							**0.43**	
UI errors in **VJ** reports								
Error 1		××		×			3	2
Error 2			××				2	1

Error 3		××		××	×		5	3
Error 4	×	×					2	2
Error 5	××		×	×	×	××	7	5
Error 6							0	0
Error 7							0	0
Total	**3**	**5**	**3**	**4**	**2**	**2**	**F= 19**	
Average N of errors							**0.8**	
Total N of UI errors							**76**	
Total average N of UI errors							**0.2**	

Note: Xs represents the number of times an error occurred by the user. For example, in the Gait reports, user A encountered error one twice and errors two, four and seven once. **UI=** user interface; **F=** frequency of occurrence of errors; **Total=** total number of users who executed an error; ***Average N of errors=** error rate/number of tasks; **Error 1=** navigation (i.e., moving from one page to the next without assistance, categorisation); **Error 2=** layout (design, arrangement, organisation, structure); **Error 3=** handling (processing, dealing with); **Error 4=** wording, content and information; **Error 5=** technical; **Error 6=** interface design (e.g., font, tab size and colour); **Error 7=** input device (i.e., mis-tapping, clicking on another icon on the screen); **SLS=** single leg squat; **VJ=** vertical jump.

From Table 45, it can be concluded that a total of 76 errors were executed during the usability of the E-reporting tool with a total average number of errors being 0.2 errors per tasks. While attempting to complete the three assigned tasks in the gait reports, users executed a total of 32 errors, and error six, which concerned the interface design, was the most encountered error, recurring seven times by four participants. The average number of errors that could be performed by users when using the gait reports was calculated and resulted in a total of 0.6 errors per task.

For the SLS reports, the participants were trying to complete three tasks and 25 errors were encountered by the users. Errors three and five, which concerned handling and dealing with the system and technical errors, respectively, were the most executed ones. Error number three was made by all six users and the technical error was made by five of the participants. Regarding the average number of errors while using the SLS reports, this totalled 0.43 errors per task.

For the VJ reports, two tasks were assigned to the participants and the number of errors encountered by the users was 19. The most frequently occurring error was number five, which is the technical system issue and it occurred seven times for five of the participants. With regards to the average number of errors, the total was 0.8 errors per task.

7.8 SUS questionnaire

All six users completed the SUS questionnaire and Table 46 presents the SUS results for each of the questionnaire items, in addition to the overall SUS score. It can be deduced from Table 46 that the overall SUS score was 63.33 ± 13.61. According to Brooke (1996), values between 60% and 80% are interpreted as borderline-to-good.

Table 46: SUS questionnaire results

Users	**Questionnaire statements**											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Sum of scores**	**SUS scores**
User A	3	3	3	3	3	3	3	4	3	3	31	77.5
User B	2	4	4	4	3	4	1	4	4	4	34	85
User C	2	3	3	3	2	3	3	1	3	3	26	65
User D	2	0	0	0	3	2	0	1	1	0	9	22.5
User E	1	3	3	3	3	3	1	3	3	3	26	65
User F	1	3	3	3	3	3	1	3	3	3	26	65
Mean	1.83	2.66	2.66	2.66	2.83	3	1.5	2.66	2.83	2.66	**152**	**63.33**
For the overall mean SUS score, the sum of the scores from each participant were added and the result was multiplied by 2.5, before being divided by 6 to give the mean SUS scores for all of the participants.												

7.9 Participants’ feedback and author’s observations

While participants were interacting with the E-reporting tool, they were instructed to verbalise their thoughts and actions to enable the researcher to collect the data by observing their interactions using the TA approach. Table 47 provides an example of the participants’ feedback and the suggestions they provided while using the E-reporting tool. This feedback was arranged into positive and negative themes for each of the reports used to make it easier to understand the data and get a sense of the users’ impressions about the E-reporting tool during the usability evaluation.

Table 47: Participants’ positive and negative feedback regarding the usability of each of the selected gait, single leg squat and vertical jump reports

Positive comments	Negative comments
Gait reports	
“It is quite clear on the page (referring to the parameters).” “They are very obvious” (meaning the parameters).	“How can I find or write a note?” “I got confused.” “How can I write a note?” “Where can I write a note?”
“It's really nice to have the video.” “I actually liked the video more than the graphs.” “Seems very good” (the video).	“I am not quite familiar with some of the naming or labelling like right and left.” “Oh, where is the knee, I did not see this one.” “Contact event counter, I didn’t really understand this.”
“Ok that makes it easy to understand” (the comment beside parameters).	“Ok, it takes a while opening a graph page.” “It takes really long time.” “Sorry, I think also the website taking a lot of energy because there is sound in my laptop now.”
“The colours make it easier to compare the participants.”	“Am lost here. How did they make it? These colours are?” “I don’t know, am lost here.” “This is too small to detect actually.”
“Well, I am not an expert in gait cycle analysis but this information seems very useful for movement analysis and it’s very clear it is showing all the graphs and everything you might need.”	“I don’t understand this data is for which participant. I can understand that each colour is for one participant but I don’t know which one belongs to who.”
“Here I can see the difference between left only or right only or both together and compare between them, very useful, and that’s the mean; the mean is obviously important.”	“I can't detect their numbers here. It says 007 and 006 which is not the same numbers.” “It would be clearer if the ID number showed here” (meaning at the top of page instead of the trial number).
“I like writing a note on this specific part of the analysis.”	“Is very small the writing here.”
SLS reports	

“I was thinking about this one 1, 2, 3 and it seems in the video that they were squats.”	“It is slow.” “It takes ages.”
“Yeah, it's clear here how to export a file.”	“Am not sure if my Internet is slow or this is from the software itself.”
“It's interesting it makes biomechanics easy to understand and to document as well.”	“Sometimes it is quite annoying while waiting and there is something but this is technology and this happens.”
“So, this will show how many times the participants do the squats within the specified timeframe? That seems very useful.”	“It's complicated for this one. I mean it's not complicated maybe the instructions are not really clear or they are clear but not straightforward maybe.”
“So far it’s easy to use and easy to understand”	“I don’t know if this is overload for the laptop from Zoom sharing or from the website. It’s a little bit slow; takes time to do every step which needs to be improved.”
	“I think the website takes some time to upload the files.”
	“Am not sure about the unit.”
VJ reports	
	“This part (detect exercise) is annoying and takes ages. It seems like an issue with the network.” “So, what to do now? It’s not working.”
	“You know what I think? I think this one (meaning adding a new ex button) should be here” (above the bar, not below). “It will make it easier because when you say add new exercise, I mix up with the bar first and did not notice this one.”
	“Why it is all the way down? It should be up, I think” (means the ankle graphs for a single hop). “It should be somewhere here beside the joint, not to scroll down.”
	“I think there is a problem here with saving exercises. When I open this, immediately this message (the one about energy) appears.”
	“I don’t know.” “How can I select single hop?”

Regarding the gait reports, the participants commented on some naming and labelling features during the performance of the first task which was about identifying gait parameters. The cause of this was due to the image presented at the top of the page being highlighted at the left foot which made the participants think that all of the parameters were only on the left side. For example, one of the participants commented: ***"because left leg is the one that is highlighted".***

Therefore, they suggested making the difference between the right and left foot clearer. The participants also commented on the size of the text in the tables, saying that ***"It is very small the writing here."***

With regards to task two, while the participants liked the presence of a video showing the patient's avatar moving saying that ***"It is really nice to have the video." "I actually liked the video more than the graphs." "Seems very good" (the video),*** they again had some comments about the naming and size of the texts and the option of choosing the joint to be analysed.

The participants also commented on the notation icon. Some participants found it very easy and useful, such as one of the participants stating that ***"I like writing a note on this specific part of the analysis",*** others thought there should be some instructions regarding how to use this. The participants reported experiencing difficulty navigating between the pages, including moving from the gait parameters page to the gait graphs page.

For task three, the participants liked the different colouring of the columns. For example, one of the participants commented ***"The colours make it easier to compare the participants",*** but another was confused about how the columns aligned to the participants, saying that ***"I don't understand this data is for which participant. I can understand that each colour is for one participant but I don't know which one belongs to who"***. This occurred because the labelling of each participant was not consistent between the pages of the report.

For the SLS reports, all of the participants experienced difficulty in task one, identifying the type of exercise performed. Their feedback highlighted the need for instructions on using the timeframe presented on this page. For example, one participant commented: ***"It's complicated for this one. I mean it's not complicated maybe the instructions are not really clear or they are clear but not straightforward maybe"***.

The participants accidently overlooked this component by choosing the video first and then swiftly moving to select the type of exercise. However, completing the task required them to select a portion of the timeframe before adding the exercise from the options available. This task had a technical issue that is a major issue encountered by all of the participants and prevented them from completing the task. Almost all participants had this issue. Example for their feedback on this: ***"I think the website takes some time to upload the files"***, ***"Sometimes it is quite annoying while waiting and there is something, but this is technology and this happens"***, ***"I don't know if this is overload for the laptop from Zoom sharing or from the website"***.

Task two involved finding some SLS parameters. The participants were happy and found this task easy to perform, such as one of the participants who said that ***"It's interesting it makes biomechanics easy to understand and to document as well"*** but some of the participants felt confused about how to move from one page to another. Task three, which required the participants to export a file, was very easily accomplished by most of the participants except for two; one was unsure what exporting a file entailed and the other could not complete the task due to technical issues.

For the VJ reports, the first task was a repetition of task one from the SLS reports to enable the researcher to measure memorability. The participants were able to understand what was required and they accomplished the task faster, although they still faced the same handling and technical issues. For task two which required the participants to identify the ankle angle for a single hop, the participants complained about the place of ankle hop graphs which were all the way down the page. Example of one of the participant's feedback was: ***"Why it is all the way down? It should be up, I think"*** (means the ankle graphs for a single hop), ***"It should be somewhere here beside the joint, not to scroll down".*** Participants found it difficult to recognise where this should be done and how.

Chapter 8 Discussion of part 2

8.1 Overview

The aim of this study was to test the usability of an electronic version of an IMU-based movement analysis and reporting tool for physiotherapists treating individuals with CKP. The main objectives of this study were to explore the system's usability regarding its effectiveness, efficiency, memorability, problems and errors encountered, as well as to test the system's overall ease of use. Accordingly, this was achieved by conducting quantitative formative usability testing using the TA method and SUS questionnaire. Several commonly used metrics for measuring usability were selected: task time; completion rate; repetition of previous tasks; number and probability of problems; number and average of errors; and the SUS score for overall ease of use.

8.2 Summary of the main findings

The findings showed that applying the approach described was able to reveal a substantial number of usability issues. The technique enabled problems to be uncovered and recommendations to be provided to satisfy the actual needs of the users.

- Gait reports had the highest CR (95%) and were the most effective and efficient reports. Single leg squat reports were the second most effective in terms of their efficiency and effectiveness, whereas the VJ reports were the least effective.

- Various problems were identified among the three reports but the VJ reports had the most severe types of problems which hindered the completion of certain tasks and these were encountered by all of the participants.

- Many errors were made by the participants when interpreting the reports which were substantially connected to participant problems and explained the longer task time and poorer CR. Technical errors were the most type of errors that affected the CR of the tasks and led to a longer task time and were most frequently identified whilst interpreting the VJ reports.

- The system demonstrated good memorability between the SLS and jump reports, with less time being spent on the repeated task.
- The overall SUS score for ease of use indicated borderline-to-good usability.

8.3 Interpretation and explanation of the findings

This section interprets the current study's findings in terms of the different usability metrics and outcome variables.

8.3.1 Efficiency

Sauro (2010) stated that efficient tasks take between 30 seconds and seven minutes because the user requires sufficient interaction to discover usability faults but not so much that they lose interest and become exhausted. While the whole testing session had an average time of approximately 35 minutes, this could be affected by factors including the time participants spent receiving the task demand from the researcher. However, the results showed that none of the tasks took more than seven minutes when interpreted individually, thereby demonstrating their efficiency.

Esfahani (2018) conducted a usability study using the same approaches applied to the current study, a combination of the TA method and a usability questionnaire to compare the usability of three picture archiving and communication systems. The author suggested considering all usability characteristics when testing a reporting system (radiology and picture reporting in their study), namely those proposed by ISO and Nielsen; efficiency, effectiveness, learnability, and satisfaction, problems and errors (Esfahani 2018). The study demonstrated tasks time around 10 minutes per task, which was longer than the time spent on tasks of our study. This could indicate that our tasks were more efficient than their proposed ones, however, the author alluded to the fact that there is a good chance that an increase in task time may occasionally be attributable to user-specific characteristics rather than usability issues with the system. Therefore, other factors should be considered.

Sauro (2010) indicated that the number of tasks, their difficulty and their CR may change this time restriction (30 seconds to seven minutes). The current study showed that gait reports, which had three tasks and took the longest time to achieve, had the highest CR and the least severe problems. Jump reports had only two tasks and took less time to complete but they had the lowest CR and the most severe problems. Hence, longer task time does not necessarily indicate task failure or execution issues. In other words, a longer task time to complete the gait report tasks does not mean that the gait reports were less efficient. However, this should be linked with the CR and the severity of the problems encountered.

8.3.2 Effectiveness

Regarding the task CR as an indicator of effectiveness, the results indicated that effectiveness was highest for the gait reports, followed by the SLS reports and, lastly, the VJ reports. The probable explanation for this result is the participants' familiarity with the activity. Physiotherapists may be more familiar with assessing gait patterns because this is a frequently used clinical measurement (McAuley et al. 2014; McGinleyet al. 2003). Due to their professional training and experience, physiotherapists are likely to possess a higher level of knowledge and expertise in assessing gait patterns. Gait analysis is a fundamental aspect of their clinical practice and they may encounter it more frequently in their professional work. Conversely, SLS and VJ movements may be analysed less frequently, resulting in lower effectiveness scores. Because physiotherapists are familiar with gait analysis, the tasks related to the gait reports in the usability study may align more closely with their routine work. This familiarity is likely to make it easier for them to understand and complete the tasks efficiently, resulting in a higher CR. Additionally, physiotherapists, accustomed to interpreting gait, may navigate through the gait reports more quickly and accurately. Their familiarity with the terminology, data presentation and expected outcomes may result in the smoother and more efficient completion of tasks, thereby positively impacting the CR, unlike SLS and VJ.

The design of the user interface also varied between the gait, SLS and jump reports, resulting in variations in user engagement and effectiveness. For instance, the SLS and VJ reports were all grouped with seven other activities in a large category called knee assessment reports. Thus, to be able to work and interpret the report, the user should go through the task of identifying the type of exercise performed. This task was one which particularly hindered the task completion rate and caused significant problems. Therefore, gait reports appear to be created in a more user-friendly fashion. Jorritsma et al. (2014) conducted a usability study to compare different Picture Archiving and Communication System workstations and determine if a usability test adds value to comparing the systems based on functional requirements and assess the suitability of a task-based methodology. The authors did not consider the task CR in their study; however, they did recognise that incorporating a measure of effectiveness could enhance the accuracy of the usability assessment, particularly when more complex tasks are incorporated into the test (Jorritsma et al. 2014). Therefore, the inclusion of more complex activities, such as SLS and VJ, and tasks besides gait reports was important for the study and allowed for more interaction with the different aspect of the E-reporting tool and uncover more usability issues.

According to a benchmark published by Sauro (2010) which was based on 1,200 task completions from over 120 usability tests, a task with a 90% completion rate is at the 70th percentile, indicating that it has a higher completion rate than 70% of the tasks in the dataset. Additionally, a task with a completion percentage below 56% would be below the 30th percentile and have one of the lowest CRs (Sauro 2010). In the current study, the completion rate for gait reports was 95%, for SLS reports it was 56% and for VJ reports it was 25%. This would place the VJ reports in the bottom quartile of usability datasets. The lower CR observed in the VJ and SLS reports was attributed to the appearance of several usability issues and faults that the participants encountered while using the E-reporting tool, which are elaborated upon in the following sections.

8.3.3 Memorability

Because the users could only accomplish each task once, memorability was measured for only one repeated task scenario and the results indicated good memorability of the users. In the current study, the participants performed the first task of the VJ after three SLS tasks and other subtasks. This VJ task was a duplicate of the first SLS task. The findings of less time being required to execute the repeated task indicated that users gained good memorability using the reports. Nielsen (2010) and Huantunen (2022) indicated that memorability denotes that a user can use a product following a long pause and still remember the product easily. Unfortunately, this metric was measured after the participants' first use of the first iteration of the product and all measurements were made in one sitting, thereby making it difficult to establish user memorability after a lengthy period or over different days and weeks. Therefore, it would be good to retest memorability in the next iteration of the E-reporting tool.

8.3.4 Usability problems

By integrating the findings for the user interface problems with the efficiency and effectiveness results, it was found that the increased frequency of a problem does not necessarily mean that the report was the most difficult. The type and severity of the problems should be approached with care. For instance, in the VJ reports there were fewer problems overall compared to the SLS and gait reports and the probability rate was lower than that of SLS reports. Despite this, the majority of the problems encountered by all six participants were in the VJ reports. These were classified as type one problems (significant problems which impede task completion). Conversely, problem three is considered to have only a minor impact on task performance and was the most common in both the gait and SLS reports. This was evident in the CR section where the VJ reports had the lowest CR among all three reports analysed.

Sauro and Lewis (2016) alluded to the fact that knowledge of the probability that users will encounter a problem at each phase of development can be a crucial metric for measuring the impact and return on investment of usability activities. Thus, fixing the issues raised by participants regarding the VJ and SLS reports would be of great importance because the persistence of problems that cause frustration could lead to a lack of adherence to the system. According to Sauro (2010), if standard guidelines for user interface design are adhered to, numerous usability problems can be avoided. Moreover, usability problems, particularly severe ones, can be avoided if usability evaluations are conducted early in the system development process (Sauro 2010). This was the purpose of the usability evaluation because this is the first version of the E-reporting tool. Accordingly, these problems will be raised with the developers.

The classification and reporting of usability problems must also be accurate and efficient to effectively communicate and address the most pertinent usability issues (Neilsen 2010). The techniques for usability problem classification used in the current study provided the necessary information regarding the frequency, significance and severity of the problems, as advocated by usability experts (Rubin 1994; Dumas and Redish 1999; Neilsen 2010).

8.3.5 Errors

Sauro (2010) and Sauro and Lewis (2009) stated that errors offer valuable diagnostic information to clarify lower CR; they are closely correlated with task completion time and account for approximately 25% of the variance in user timings. Errors also map to user’s interface problems (Sauro 2010). In the current study, the errors that occurred in each report were compared with the CR; the lowest CR was presented in the VJ reports, followed by the SLS reports and, lastly, the gait reports.

Combining this with the problems encountered by the users, it can be concluded that the most frequently reported problem in the VJ reports (identified by all six participants) was problem 1 (classified as a major barrier to task completion). This was reflected in the technical error that the participants faced while using the VJ report which prevented them from completing the task, thereby explaining the lowest CR in this activity. In contrast, interface design errors in gait and handling errors in

SLS were reflected by problem 3 (classified as having a minor impact on task performance), a problem which did not affect the completion of tasks extensively.

Sauro (2010) presented a benchmark for the accepted average number of errors in a usability evaluation that was extracted from a large dataset of usability data from in excess of 120 usability tests which contained error data for 719 tasks. The author indicated that a usable interface should be within the provided range of at least 50% fewer errors than other systems in the benchmark table (i.e., less than .66 errors per task) (Sauro 2010). The results of the current study confirmed that the gait and SLS reports had a lower average error result (0.6 and 0.43 errors per task, respectively) than the VJ reports which presented an average of 0.8 errors per task, thereby placing the VJ reports within the 40th and 45th percentiles. This means that 40-45% of the benchmark tasks have more errors than the VJ reports.

The usability test results indicated a total average of 0.2 errors per task for the three reports used in the E-reporting tool. This average would give the E-reporting tool a percentile score of approximately 80% which means that 80% of the tasks presented in the benchmark table have more errors than the tasks presented in the current study. According to the author, anything more than 2.4 errors per task means that the system is unusable and unusual, which did not apply to the current findings (Sauro 2010; Sauro and Lewis 2016). Indeed, these results are promising and it is important to ensure that the issues raised by the users are considered in the next iteration for a user-friendly E-reporting tool.

8.3.6 System usability scale questionnaire

According to previous research, a strong correlation exists between SUS and satisfaction. For instance, Sauro and Lewis (2011) found a significant correlation between the SUS score and consumer satisfaction ratings for a variety of software programs. Meanwhile, Tullis and Stetson (2004) discovered that the SUS score offers a more accurate predictor of users' overall satisfaction with a website than more conventional measures of satisfaction such as a Likert-scale rating. Sauro (2010) performed thorough benchmarking of SUS scores on numerous systems and determined that the average SUS score across 500 studies is 68. Based on the mean SUS score, any score above 68 is deemed to be above average (Sauro 2010). According to Brooke (1996), values between 60% and 80% are interpreted as borderline-to-good (Brooke 1996). While looking at each user's response, the SUS scores in the current study ranged from 65 to 85, except for one participant. However, the mean SUS score calculated from all user responses was 63.33, corresponding to respective percentile ranges of 60% to 80%. This rank corresponds to grade 'C' on a scale ranging from A to F (Sauro and Lewis 2012). This borderline score means that our E-reporting tool still requires some improvements (Sauro 2010). Some participants provided some of their thoughts about the system in the comment section provided within the questionnaire (see Appendix Q for more details). Participants' comments are critical and would enable developers to improve the system in future iterations.

Numerous studies have tested the usability of a newly developed sensor-based movement biofeedback system using the SUS questionnaire in addition to other metrics (Argent et al. 2019; O'Reilly et al. 2018b; Chughtai et al. 2019). Their results demonstrated a higher SUS score more than 79% compared to the SUS score of our E-reporting tool. The lower score presented in the current study could be attributable to several factors. Participants in Argent et al.'s (2019) study were undergoing knee replacement surgery. They were provided with the system at home for two weeks and instructed by a physiotherapist regarding how to use it. Therefore, it is more likely that they would become accustomed to using the system, unlike the physiotherapists in the current study who were using the system for the first time.

In O'Reilly et al.'s (2018b) study, the usability of their system was assessed with three types of participants: novice gym-goers, experienced gym-goers, and qualified strength and conditioning coaches. They engaged with a sensor-based system, conducting tasks under the guidance of a physiotherapist. The system had notable features: it determined whether each repetition adhered to an 'acceptable' or 'aberrant' technique and accurately identified and quantified the repetitions of the exercises under investigation (O'Reilly et al. 2018b). However, their system lacked certain features. It did not offer users kinematic information, access to waveforms or a kinematic report. Consequently, the features were presented in a binary manner (acceptable or not; detectable or not) without the capability to interpret a detailed kinematic report. In contrast, the current report sought a more comprehensive approach, offering detailed information that could be utilised by physiotherapists. This difference in features may have contributed to the lower usability score observed in the current study.

8.4 Strengths and limitations

A major strength associated with the current study is that the usability evaluation test examined end users' actual interactions with the system and helped to evaluate objective metrics such as the efficiency, effectiveness, memorability, problems and errors of user interactions with greater precision using the TA technique which is regarded as the gold standard in terms of usability evaluation (Hartson et al. 2001). The TA method was augmented with the SUS questionnaire which is a valid and reliable tool for measuring the overall usability of the system and a good predictor of user satisfaction. These two methods were augmented to be able to measure all usability characteristics contributing to the test and to improve the validity and accuracy of the results.

In addition, the measurement criteria were chosen based on a designed framework by combining certain usability characteristics based on the ISO (Abran et al. 2003) and Nielsen’s definitions (Nielsen 2012). Standardising the usability problem descriptions ensured the following benefits: (1) minimal subjectivity in the analysis of the problem descriptions; (2) effective reporting and comprehension of the problem descriptions by (re)designers to enhance the design of the current system; and (3) identification and comparison of trends across usability studies of comparable applications, including alternative systems. The standardised method was based on several suggestions provided by quantitative usability experts who indicated the importance of finding the frequency of problems, knowing which users encounter which problems, and establishing the impact of that problem (Rubin 1994; Dumas and Redish 1999; Nielsen 2010), all of which were accomplished in the current study. Additionally, errors were calculated based on the suggestions made by Sauro (2010), a quantitative usability expert who indicated that errors offer valuable diagnostic information and explain longer task times and reduced completion rates, which were also reflected in the current study's results.

However, the current study contains several limitations. The results suggest that the usability findings pertain to the initial usage of the tested E-reporting tool. Therefore, it is important to note that usability experiences may differ when utilising the E-reporting tool on subsequent occasions. Indeed, the current study was conducted as the very first formative stage for the first iteration of the system which is very important for the aim of the study in revealing usability problems and providing future recommendations. According to Karapanos et al. (2009) and Sonderegger et al. (2012), the valued aspects of product usability change as the product is used. For instance, during initial use, aesthetics and learnability are the most valued features, whereas during long-term use, utility is the most valued feature.

This was a remote usability study that conducted using the Zoom application and the participants were engaged in a variety of places such as in an office or at home, which could be different from real clinical settings where the E-reporting tool will be used when integrated into practice. However, Sauro (2010) found that valid results can still be obtained if the proper approach to unattended testing is applied, which likely refers to situations where participants are not directly supervised during the testing process. Sauro (2010) compared the CR, task times and SUS scores that were obtained from 12 users to those obtained by another team which remotely tested in excess of 300 users. The substantial overlap between the confidence intervals for each task indicated a surprising degree of agreement (Sauro 2010). These results indicate that small sample sizes for tests with participant attendance yield comparable results to those for tests with remote participation. Therefore, despite the current study having been conducted in a remote and potentially different environment from the intended real-world 'clinical setting' it can still provide valid results.

It has been suggested by some usability experts that altering the tasks between participants improves the validity of usability results and reduces the learning effect (Esfahani et al. 2018; Sauro 2010). However, this was not possible in the current study because it was the first usability study for the first iteration of the E-reporting tool, unlike other studies which had more than one iteration to compare between. Besides, this usability study was conducted using a tool which had three different reports with different tasks for each and, consequently, there was no possibility of a learning effect between reports.

8.5 Clinical implications

The E-reporting tool has significant clinical implications for physiotherapy practice. Its integration into clinical workflows could enhance the efficiency and precision of movement assessments. Physiotherapists would benefit from comprehensive and real-time kinematic analyses, enabling more informed decision-making when designing tailored interventions. The tool's capacity to generate detailed reports, including kinematic waveforms and avatars, not only facilitates objective documentation but also fosters improved communication between PTs and patients. Furthermore, the tool's user-friendly interface and detailed insights could help to advance clinical education and promote more engaged patient-therapist collaboration. Ultimately, the electronic reporting tool has the potential to elevate the standard of care in physiotherapy by providing a sophisticated platform for nuanced movement analysis and informed therapeutic strategies.

The E-reporting tool's features, particularly the ability to individualise movement assessments and treatments, make a substantial contribution to enhancing the clinical practice of physiotherapy. This capability allows for a personalised approach to patient care, tailoring assessments and interventions based on individual needs and characteristics.

Additionally, features such as selecting the icon for a patient filename play a crucial role by providing insights into the time management aspect for physiotherapists in clinical settings. This feature facilitates the assessment of the tool's usability and accessibility, thereby ensuring physiotherapists a workflow that is both practical and efficient. Other features that were very simply accomplished by the participants during the task performance, such as exporting a file, offer considerable practical value for both physiotherapists and their patients. In clinical settings, this function simplifies the process of acquiring a copy of the movement analysis reports. Such accessibility empowers patients to actively engage in their care by obtaining detailed insights into their movement patterns. Consequently, this feature facilitates a more collaborative dynamic between patients and physiotherapists, enabling them to share perspectives, discuss treatment decisions and contribute to an informed and cooperative therapeutic relationship.

8.6 Future research and development

The results of the current study will inform subsequent improvements of the E-reporting tool by considering all aspects that have affected the user experience. The need for these improvements was confirmed by the lead researcher's (RA) observations in addition to the participants comments provided in the SUS (see Appendix Q). For instance, it is critically important that the technical issue which emerged when using the VJ and SLS reports is fixed by the Xsens developers because it was one of the main reasons why the participants could not complete some of the tasks and this led to frustration. It is unlikely that this issue was caused by the Internet connection. Although the study was conducted remotely via Zoom, the author ensured that the participants had a good Internet connection before initiating the test. In addition, this issue was identified in the pilot study which was conducted prior to the real test, which led the researcher to set up a backup plan in case the reports did not work appropriately. The real usability test was then conducted using six participants and all of them experienced the same issue, thereby reducing the likelihood that this could have happened due to a problem with the Internet connection. Rather, it appears that it occurred due to unknown technical issues within the software.

Other areas for possible improvements include minor modifications such as renaming and reorganising the interface content to improve the navigation, content and facilities presented to improve the users' experience. These include the font size which was very small and the organisation and labelling of the main features which should be bigger and bolder. In addition, further instructions are needed regarding how to use certain icons or how to perform specific tasks such as how to identify the type of exercise performed, how to select a specific point on a graph and write a note about it, how to change from one joint to another, and how to compare between the participants’ graphs. These features would improve the user experience and enhance its efficiency and effectiveness, thereby facilitating the interpretation of the reports and making it more practical.

The placing of pictures, videos and certain icons should also be reviewed so that they do not cause confusion for the user. For example, the placing of the timeframe and the selection of the exercise option caused some confusion and the participants suggested that these be replaced by putting the select exercise icon prior to the timeframe. The image on the gait parameters’ page also caused some confusion due to the left leg in the image being highlighted which made the participants think that the parameters were only on left leg.

In future, it would be good to extend the functionality of the E-reporting tool by allowing physiotherapists to prescribe exercises based on their interpretation of the kinematic data. Thus, future developments should support the professional demands of physiotherapists by enabling them to define exercise prescriptions within the tool as part of individualising the exercise regimen to the unique conditions. Such data would enable physiotherapists to monitor patients' recovery and support treatment through exercise prescription and progression.

8.7 Conclusion

The aim of the current study was to test the usability of an electronic version of an IMU-based movement analysis and reporting tool for physiotherapists treating individuals with CKP. The E-reporting tool was designed to help physiotherapists with their individualised interpretation, visualisation and rehabilitation of CKP conditions by uncovering usability problems and errors executed by participants in addition to other usability metrics utilising two approaches: the TA technique and SUS questionnaire. Thus, a user-friendly tool can be facilitated by these two approaches which focused on real users’ interaction with the tool. This approach identified several problems with the E-reporting tool and provided recommendations for refining the next iterations. The findings confirm the importance of usability testing for all end users in the development of new tools to reduce problems and errors, especially if the goal is to implement such systems in a clinical setting.

Chapter 9: Thesis conclusion

9.1 Introduction

This final chapter provides a summary of the primary outcomes of the two studies carried out as part of this PhD thesis. Subsequently, the contribution of new knowledge acquired from this thesis is explained. Then the strengths and limitations of the entire PhD thesis are elucidated. Finally, the fundamental implications and recommendations for education, clinical practice and future research that arose from the PhD thesis are delineated. While each study of this PhD thesis has its own individual strengths, limitations and implications, this chapter deliberates upon the overall strengths, limitations and implications of this project.

9.2 Thesis summary

The overall aim of this PhD thesis was to explore the utility of individualised IMU-based clinical movement analysis for people with CKP. The studies of the current PhD thesis were guided by the theoretical framework set forth in the MRC guidelines for the development and evaluation of complex interventions, as proposed by Skivington et al. (2021). It is essential to clarify that this research did not entail the direct development of an intervention. Instead, it represents a pivotal phase within the broader framework of intervention development, guided by the principles outlined in the MRC guidelines, as proposed by Skivington et al. (2021). The systematic approach of the MRC framework, encompassing elements such as considering context, building program theory, involving stakeholders, identifying uncertainties, refining intervention, and economic considerations, has been integral to shaping the findings of this PhD thesis. This developmental phase lays a robust foundation for subsequent stages in the intervention development process, aligning seamlessly with the comprehensive approach advocated by the MRC framework (Skivington et al. 2021).

First, a comprehensive review of the literature was carried out to explore the gaps in the current evidence concerning movement analysis of altered movement patterns for individuals with CKP using motion capture systems and how these alterations were reported. This stage was necessary to identify key uncertainties and revise theories related to pain and movement alterations, as recommended by the MRC framework (Skivington et al. 2021). Accordingly, this thesis has sought to address the following gaps:

1. While investigating altered movement patterns in diverse functional tasks using various motion capture systems, it became evident that there is a pressing need for individualised assessment and reporting of kinematic data using a clinically available tool such as IMUs. Relying solely on group averages is insufficient, emphasising the significance of capturing individual nuances in movement patterns. There is an unmet need to explore how descriptive analysis of waveform data, focusing on individual variations, aligns with or deviates from averaged data, potentially refining movement analysis methodologies.

2. During the assessment of methods for reporting and interpreting kinematic data obtained from a clinical motion capture system, it became apparent that physiotherapists in clinical settings require a user-friendly kinematic reporting tool. Such a tool should facilitate individualised movement analysis and treatment, addressing the current lack of accessible resources for PTs in this domain.

Thus, this PhD thesis included two parts to fill these gaps, both of which addressed part of the developmental phase of the MRC framework. Part one consisted of one study which was conducted considering one of the six core elements of the MRC framework: **the context**. This was achieved by obtaining a better understanding of altered movement patterns and identifying kinematic movement alterations among people with and without CKP while performing various functional tasks including gait, DLS, SLS, VJ, SA and SD for the hip, knee and ankle joints in the sagittal and frontal planes using IMUs. Altered movement patterns were investigated using two approaches which were combined. Firstly, the SCI of kinematic waveforms were analysed using a standardised reporting template to enhance the accuracy and consistency of reporting kinematic data. Secondly, there was a SQA of the kinematic data in which altered movement patterns at discrete time points were investigated and compared between and within groups using statistical tests. Combining both approaches, several altered movement patterns were identified in both groups and both planes of movement. The SCI's ability to analyse the entire movement cycle at an individual level provided essential information beyond the limitations of averaged data, emphasising the need for considering individual data in clinical practice. Healthy individuals demonstrated various between-limb alterations and, therefore, in clinical practice, integrating kinematic analysis findings of CKP individuals with pain and function assessments proves crucial for tailoring interventions effectively. Looking for standard alterations that usually apply to CKP individuals is not applicable for clinical practice. The findings of this study in addition to gaps identified in the literature review emphasise the need for a user-friendly electronic reporting tool that is available in clinical settings for physiotherapists treating individuals with CKP. This led to the second part of this PhD thesis, the usability of the electronic version of kinematic IMU-reports.

Part two was a usability study of an electronic IMU-based movement analysis and reporting tool. Physiotherapists participated in a study using an electronic version of the IMU kinematic reports to interpret gait, SLS and VJ. This study is considered a step in the intervention development and could be aligned with **engaging stakeholders** (physiotherapists) as one of the core elements of the MRC framework (Skivington et al. 2021). The system's usability was measured using six usability metrics: efficiency, effectiveness, memorability, problems, errors, and overall ease of use. In the evaluation of the three reports, the gait report achieved the highest completion rate and proved to be the most effective and efficient. A total of 63 problems were identified across the reports. Errors were predominantly linked to participant problems, thereby contributing to extended task time and reduced completion rates. The system demonstrated good memorability. Overall, the system usability indicated borderline-to-good usability. The E-reporting tool allows for individualised movement assessments of people with CKP but the next step should include refining the tool according to the recommendations made in part two.

9.3 Contribution to knowledge

The principal contribution of the current research lies in the development of an approach to individualised movement analysis in clinical settings for people with CKP, which was achieved using IMU sensors to identify alterations in movement patterns among those with CKP during various functional tasks. This approach to individualised assessment provides invaluable insights into the specific movement impairments and kinematic anomalies associated with CKP, enabling targeted and individualised treatment interventions.

Other contributions to the existing body of knowledge resulting from this PhD thesis can be summarised as follows:

Inclusion of general CKP conditions: By focusing on the CKP population, this research can address diverse issues and help to improve the management and treatment of many individuals by exploring commonalities and differences in movement patterns and identify broader strategies for assessment and intervention. This can also contribute to the development of effective strategies for long-term management including monitoring movement patterns, identifying compensatory mechanisms and designing individualised interventions. The investigation of the CKP conditions is of significant translational relevance. The outcomes of the current research are directly applicable to clinical practice because physiotherapists and healthcare professionals frequently encounter individuals who are afflicted with CKP.

Utilisation of IMUs in non-laboratory settings: The incorporation of IMU sensors in non-laboratory settings constitutes a noteworthy contribution of the current study, offering objective and quantitative insights into the movement patterns of individuals with CKP. Employing IMUs to measure 3D movement across various tasks in non-laboratory settings enhances the practicality and clinical relevance of movement analysis. This data can be systematically analysed to identify kinematic alterations between CKP and healthy individuals. The use of IMUs facilitates the standardisation of movement analysis, currently a subjective practice, thereby influencing the potential development of interventions for knee pain in the future.

Demonstrating the utility of a standardised clinic reporting template for sensor-based movement analysis for physiotherapists treating CKP patients: This template has the potential to standardise and improve the accuracy of movement data reporting, leading to improved knee pain diagnoses and treatments. **Testing the usability of an electronic version of the kinematic report (E-reporting tool):** This electronic version will make it simpler for physiotherapists to utilise and interpret movement data, resulting in enhanced treatment decisions and patient outcomes.

Overall, the current PhD thesis has the potential to considerably advance physiotherapists' understanding of the kinematics of CKP patients and lead to the development of new and improved knee pain treatment strategies. In addition, the use of a clinic reporting template and an electronic version of the kinematic report has the potential to revolutionise how physiotherapists interpret and apply movement data in clinical practise.

9.4 Strengths and limitations

9.4.1 Strengths

The use of the MRC framework (Skivington et al. 2021) for the development of complex interventions as a guidance for this research was a significant asset of the current PhD thesis. Applying the MRC recommendations will result in a systematic establishment of the E-reporting tool in four progressive stages. Because the current PhD thesis comprises part of the development phase of the MRC framework, the recommended elements within this development phase were considered (identifying key uncertainties, considering context, engaging stakeholders, developing programme theory, and refining intervention) (Skivington et al. 2021). Adherence to these recommendations ensured that the thesis was developed, and future iterations of the tools will be refined, using robust evidence.

Moreover, movement analysis of six distinct functional activities using IMUs in non-laboratory settings has not previously been undertaken. This selection of various tasks was dependent on the recommendations from OARSI guidelines (Dobson et al. 2013). This analysis provided a comprehensive understanding of altered movement patterns that are usually associated with patients with CKP. Also, the inclusion of various CKP conditions improved the generalisability of the results because most of the research conducted in this area to date has focused on OA and PFPS conditions.

Additionally, the current research made use of a standardised reporting template for the waveform data which had not previously been done. Standardising the interpretation of waveform data has the potential to enhance the consistency and reproducibility of the analysis. The research developed a clinic reporting tool for sensor-based movement analysis for physiotherapists treating patients with CKP, thus addressing an important issue in clinical practice.

9.4.2 Limitations

The comparison of angular waveforms between the affected and non-affected limbs in the kinematic reports of the current PhD thesis facilitated the interpretation of altered movement patterns and, subsequently, individualised treatment plans. Additionally, incorporating an averaged kinematic waveform from a biomechanical database representing the normal and abnormal movement patterns of healthy individuals and those with knee pain during various functional tasks would have enhanced the analysis for both studies in this PhD thesis. Unfortunately, this was unfeasible given the constraints of the PhD timeline and funding. Nevertheless, future studies should consider including this information in the kinematic waveform graphs presented in the reports.

Additionally, the design of the studies included in this PhD thesis made it difficult to establish causality or evaluate changes in movement patterns over time. Therefore, future longitudinal studies are recommended. While the benefits of including general CKP conditions and how this decision contributes to knowledge has been discussed in Section 9.3, the investigation is still limited to a specific population and the findings may not be applicable to other populations.

9.5 Implications and recommendations

9.5.1 Further research

In accordance with the MRC guideline recommendations (Skivington et al. 2021), the initial developmental phase was partly informed by the findings of the two studies presented in this PhD thesis, as well as the literature review. Some of the fundamental components of the developmental phase, as proposed by the framework, were found to have been fulfilled. Nevertheless, one aspect pertaining to the economic considerations of the E-reports necessitates further evaluation before proceeding to the subsequent stage of feasibility. This can be accomplished by assessing the costs and benefits associated with the utilisation of E-reporting tool in clinical practice. There are various frameworks which can be utilised to direct economic evaluations such as cost-benefit analysis (Drèze Stern 1987) and cost-sequence analysis.

Upon completion of the development stage and satisfaction of all core elements, an assessment of the feasibility of the E-reporting tool in clinical settings is advised. While this topic lies beyond the scope of the present PhD thesis, the objective is to ascertain the feasibility of utilising E-reporting tools alongside usual physiotherapy treatment for individuals suffering from CKP within clinical settings. As part of this feasibility analysis, an evaluation of the acceptability of the refined iteration of the E-reporting tool must be conducted through the utilisation of the theoretical framework of acceptability to ensure inclusivity by incorporating diverse acceptability constructs (Sekhon et al. 2017). Various aspects of feasibility, such as recruitment and retention rates, user engagement, adherence to the study protocol, the incidence of adverse effects, and intervention fidelity, should also be scrutinized.

There are several recommendations for future research to emerge from this PhD thesis. For instance, the research findings could motivate additional research to investigate particular movement patterns and their correlation with CKP. Researchers should investigate the biomechanical aspects, neuromuscular controls and motor adaptations linked with diverse CKP conditions. Longitudinal studies investigating the long-term effects of altered movement patterns on people with CKP are necessary. Further research on electronic platforms for reporting and interpreting kinematic data is also needed.

9.5.2 Education

The results obtained from this research can be used to inform curriculum development in healthcare and rehabilitation education programmes by emphasising the significance of alterations in movement in cases of CKP. Furthermore, they can facilitate the inclusion of evidence-based techniques in the evaluation and treatment of these alterations, thereby enhancing the quality of patient care. Furthermore, there is growing evidence supporting the use of IMUs in clinical practice as a less-costly alternative to motion-capture systems. However, it has been suggested by Demain et al. (2013) and Hughes et al. (2014) that the implementation of technologies in clinical practice may be limited by inadequate knowledge and confidence regarding their usage. This implies a need to enhance awareness of these technologies through education. Incorporating diverse technologies in the undergraduate and postgraduate curriculum could potentially expand knowledge and awareness, leading to their future use in clinical settings.

9.5.3 Clinical implications

The research may have clinical implications because the change in understanding highlights the need for individualised and patient-centred approaches which consider the individual's pain experience. Additionally, the findings can be used to guide physiotherapist training, establish interventions to improve movement patterns and enhance the effectiveness of exercise at an individual level. Because many common altered movement patterns were identified, this could be used as preliminary data to help physiotherapists with their clinical decision-making.

The development of electronic reporting tools enhances the potential to incorporate advanced kinematic analyses into everyday clinical practice, emphasising the need for future research to assess the usability of such tools in clinical settings. The implementation of the E-reporting tool revealed certain shortcomings, indicating the need for further improvements. Hence, in accordance with the MRC framework, this implementation is contingent upon additional development and the completion of iterative stages to further enhance and refine the tool.

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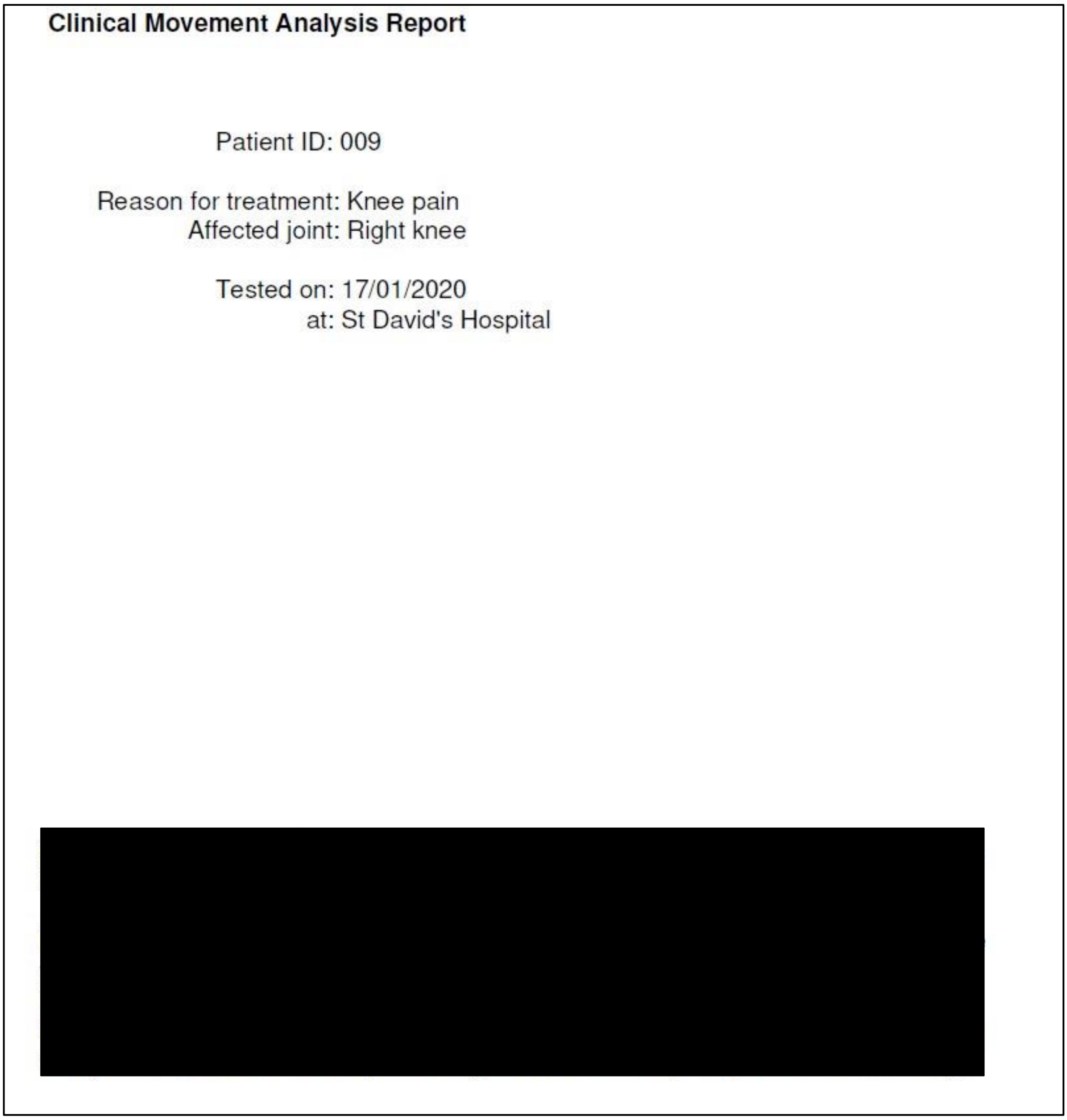
Appendices

Appendix A: IMUs movement analysis kinematic report

1) **Page one** is participant’s information and the affected joint



Clinical Movement Analysis Report

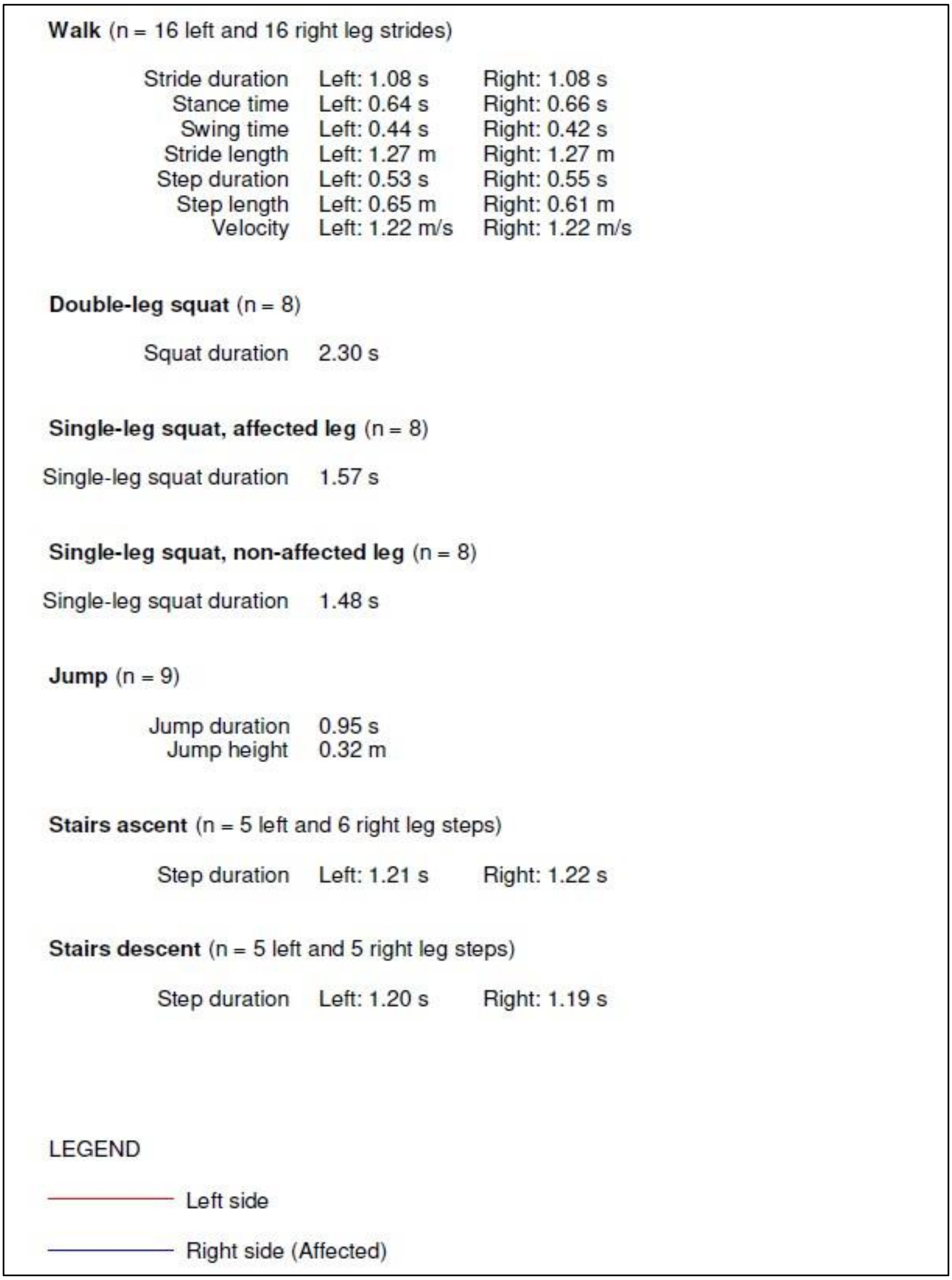
Patient ID: 009

Reason for treatment: Knee pain
Affected joint: Right knee

Tested on: 17/01/2020
at: St David's Hospital

[redacted]

2) **Page two** is participant’s spatiotemporal parameters for each of the performed activities



Walk (n = 16 left and 16 right leg strides)

Stride duration	Left: 1.08 s	Right: 1.08 s
Stance time	Left: 0.64 s	Right: 0.66 s
Swing time	Left: 0.44 s	Right: 0.42 s
Stride length	Left: 1.27 m	Right: 1.27 m
Step duration	Left: 0.53 s	Right: 0.55 s
Step length	Left: 0.65 m	Right: 0.61 m
Velocity	Left: 1.22 m/s	Right: 1.22 m/s

Double-leg squat (n = 8)

Squat duration	2.30 s

Single-leg squat, affected leg (n = 8)

Single-leg squat duration	1.57 s

Single-leg squat, non-affected leg (n = 8)

Single-leg squat duration	1.48 s

Jump (n = 9)

Jump duration	0.95 s
Jump height	0.32 m

Stairs ascent (n = 5 left and 6 right leg steps)

Step duration	Left: 1.21 s	Right: 1.22 s

Stairs descent (n = 5 left and 5 right leg steps)

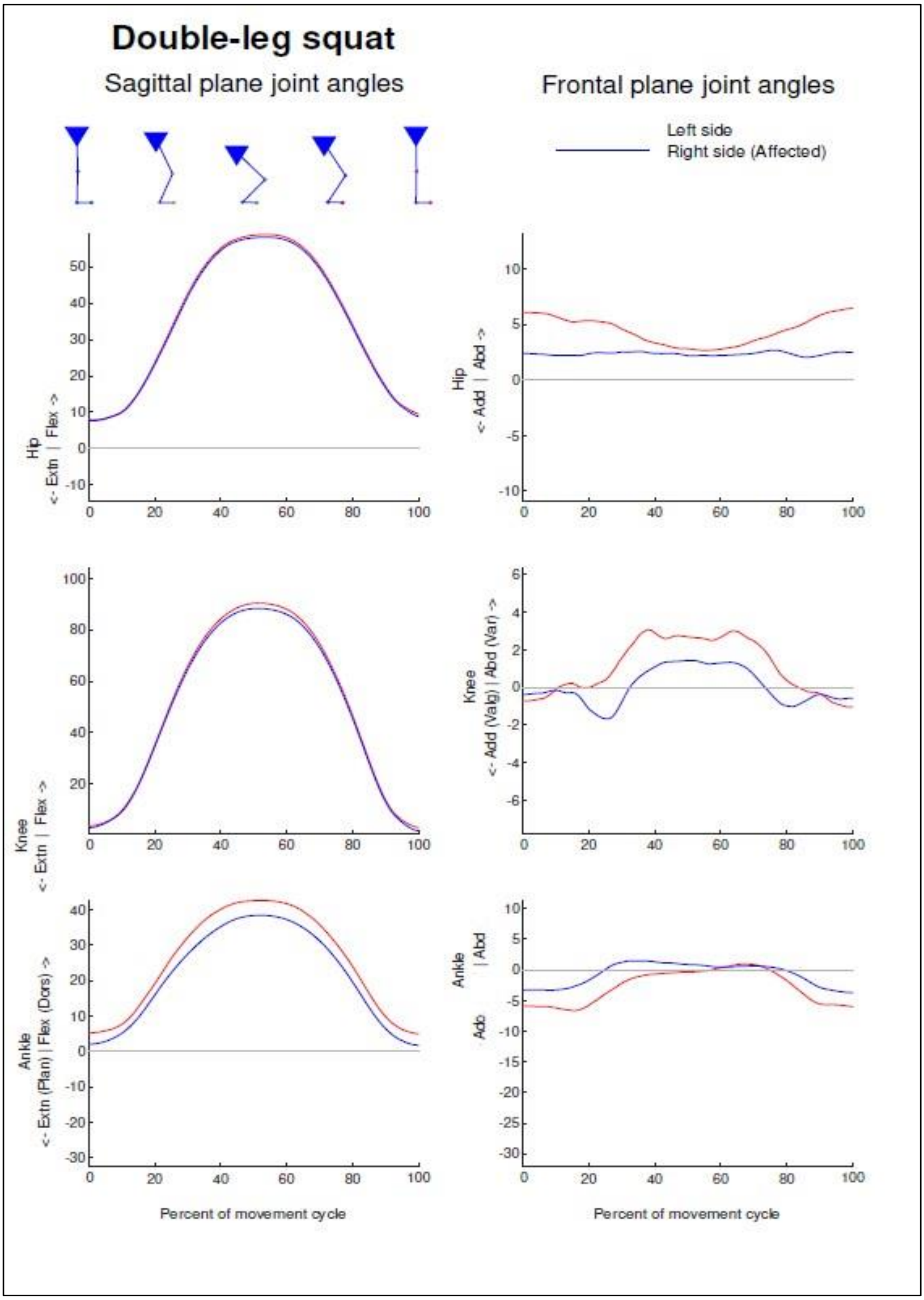
Step duration	Left: 1.20 s	Right: 1.19 s

LEGEND

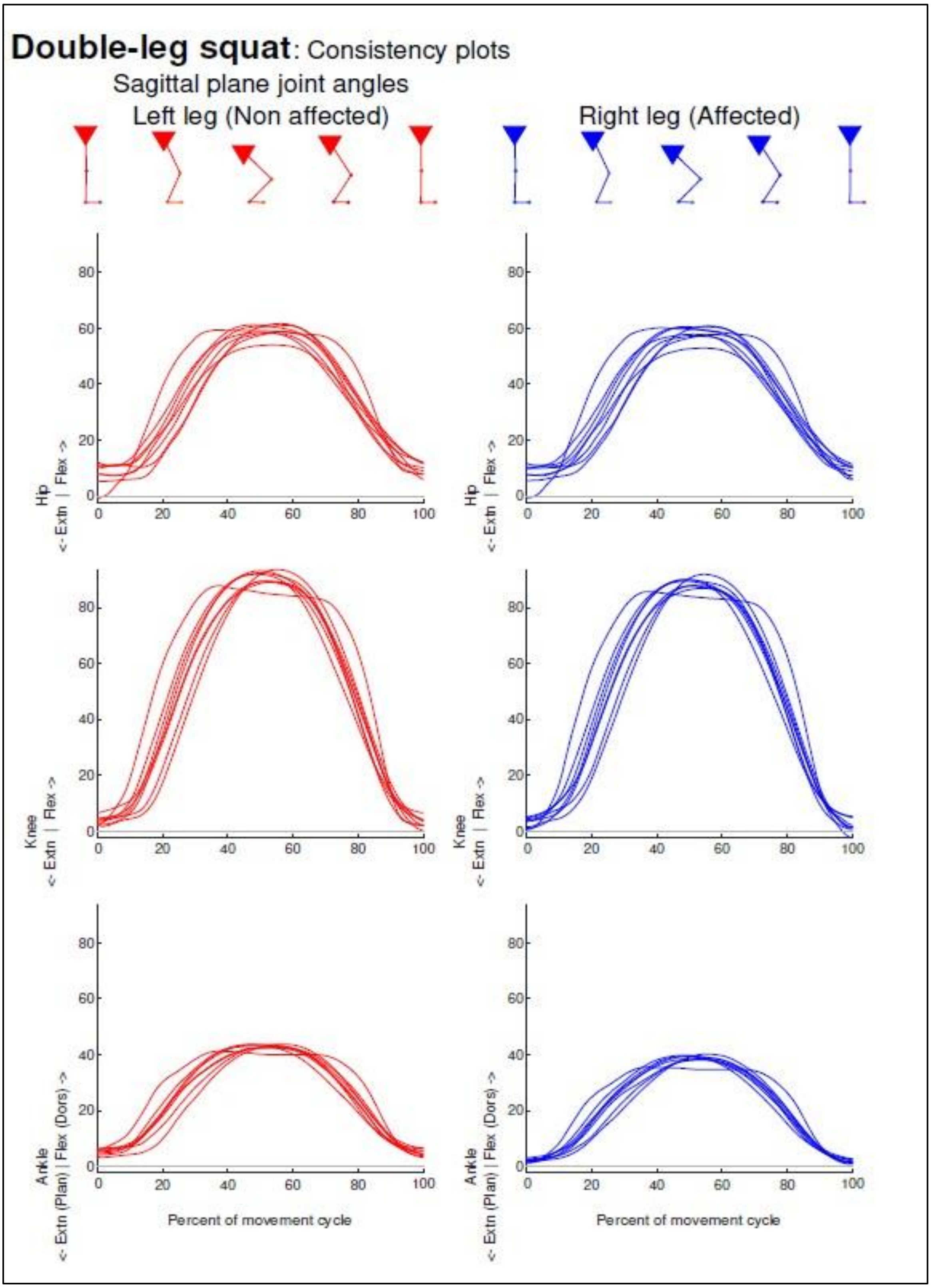
—— Left side

—— Right side (Affected)

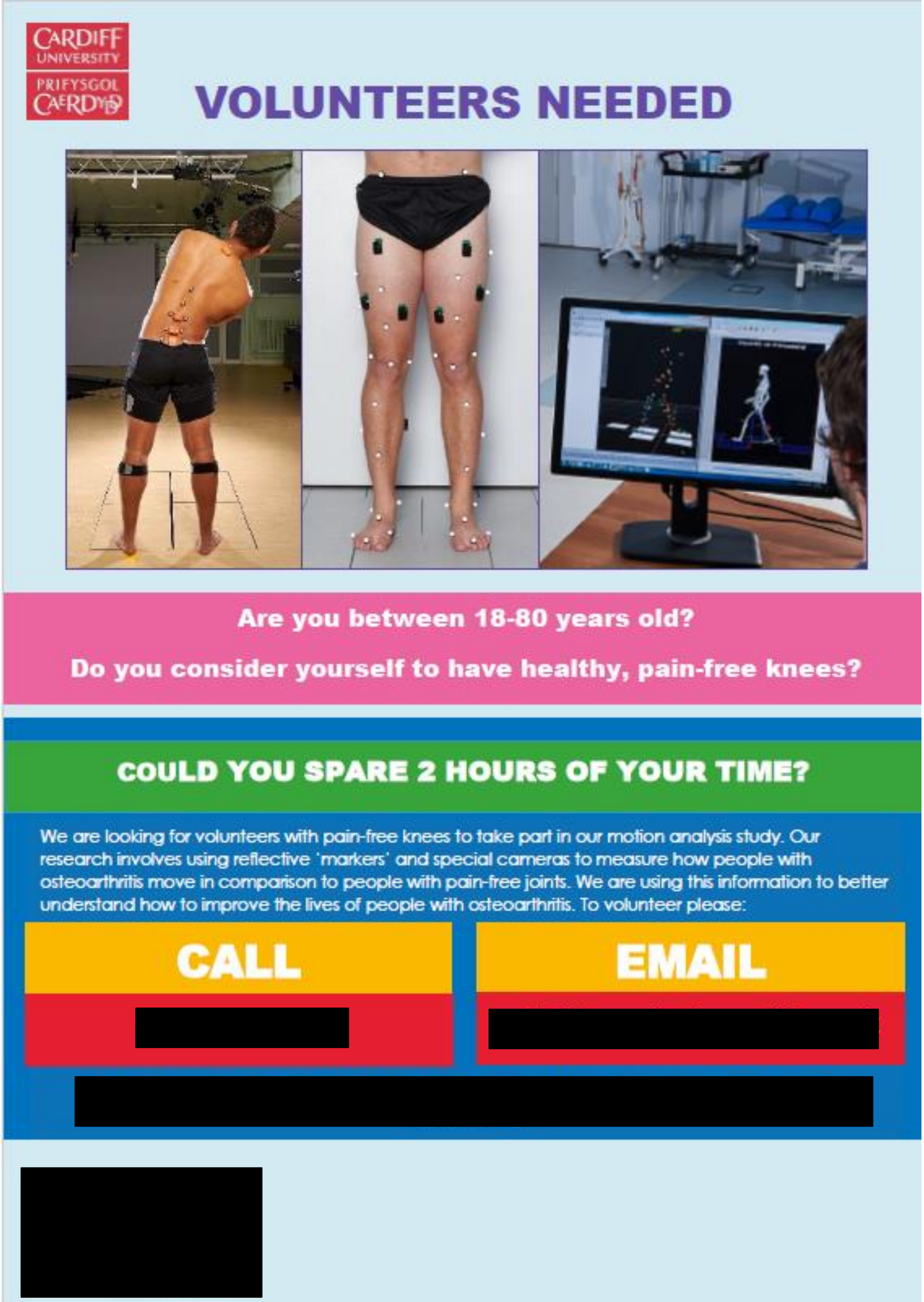
3) **Page three** is movement waveforms in the sagittal and frontal plane for the hip, knee and ankle joints along with a stick figure for the performed activity



4) **Page four** is the consistency plots demonstrating all the performed trials for an activity for each joint, limb and plane of movement



Appendix B: Study poster (Part 1)



CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

VOLUNTEERS NEEDED

Are you between 18-80 years old?

Do you consider yourself to have healthy, pain-free knees?

COULD YOU SPARE 2 HOURS OF YOUR TIME?

We are looking for volunteers with pain-free knees to take part in our motion analysis study. Our research involves using reflective 'markers' and special cameras to measure how people with osteoarthritis move in comparison to people with pain-free joints. We are using this information to better understand how to improve the lives of people with osteoarthritis. To volunteer please:

CALL

[redacted]

EMAIL

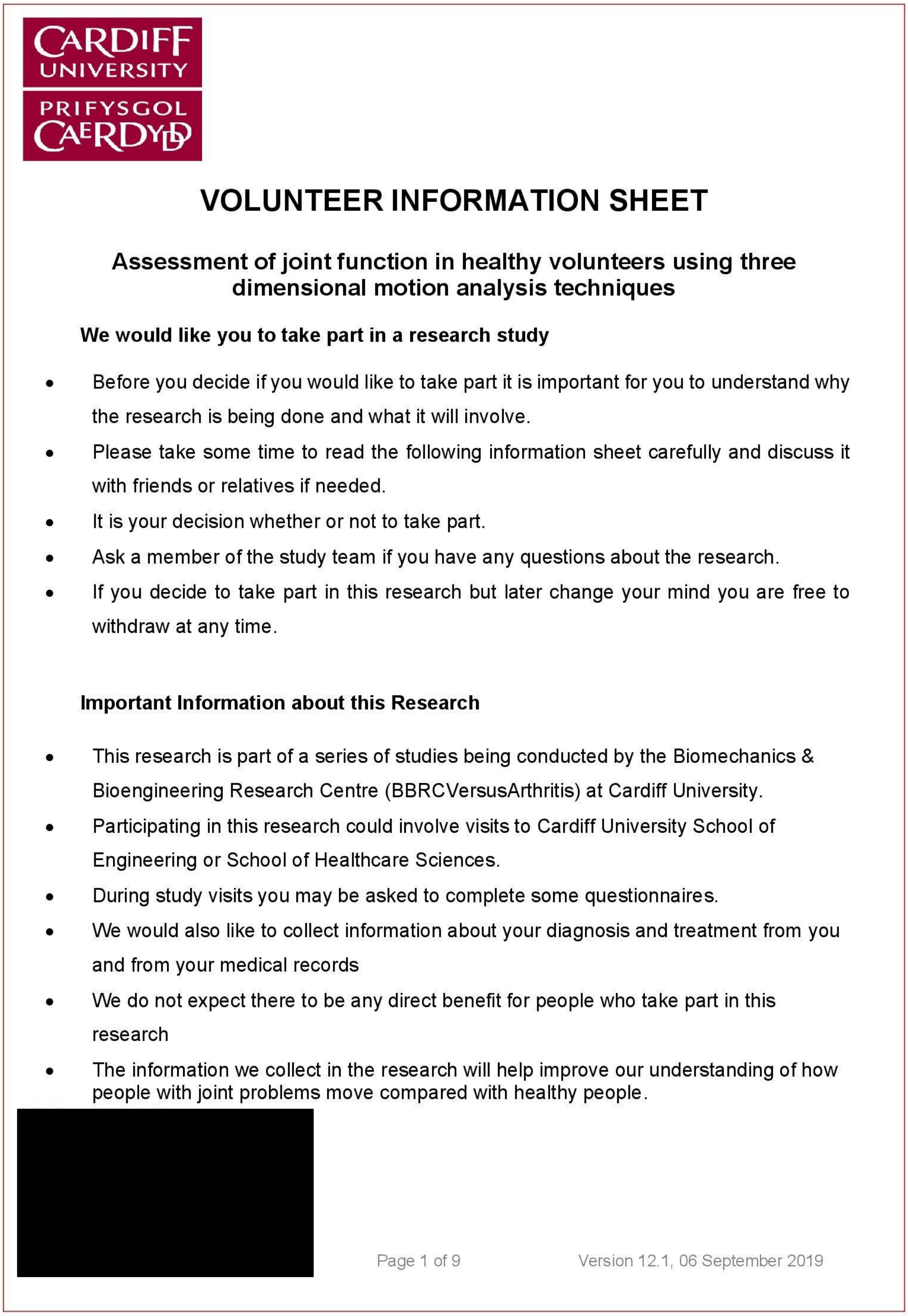
[redacted]

[redacted]

[redacted]

Appendix C: Information sheet and consent form for healthy and patient participants (Part 1)

1) Healthy



VOLUNTEER INFORMATION SHEET

Assessment of joint function in healthy volunteers using three dimensional motion analysis techniques

We would like 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.

Important Information about this Research

- This research is part of a series of studies being conducted by the Biomechanics & Bioengineering Research Centre (BBRCVersusArthritis) at Cardiff University.
- Participating in this research could involve visits to Cardiff University School of Engineering or School of Healthcare Sciences.
- 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 compared with healthy people.

[redacted]

Why have I been asked to 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.

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.

Do I have to take part?

It is up to you to whether or not to take part. 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 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 setting such as an NHS clinic or room in a University Building**

The number of times we would ask you to attend will be discussed with you when going through this information sheet – in most cases you will be asked to attend a single session, but you may be asked to attend a maximum of 6 times.

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 under investigation.

If you are happy to take part in the study we will ask you to sign a consent form

What will I have to do?

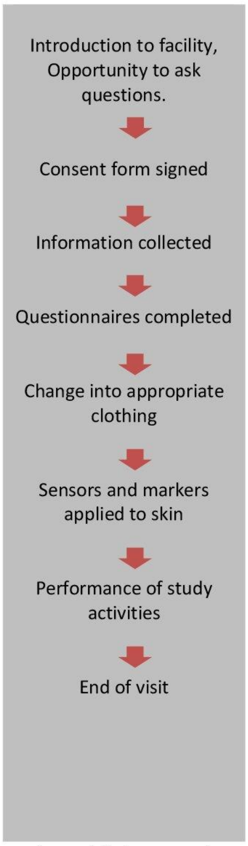
After you have signed a consent form we will ask you some questions relating to your health, and take some measurements (e.g. height, weight, limb circumference)

You may also be asked to complete some questionnaires and be asked to answer some questions about your daily life (activities).

To prepare for the movements you will be asked to change into **appropriate clothing**. For lower limb studies this is usually loose fitting shorts and t-shirt. For spinal studies you 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 the joint/area under study.



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:

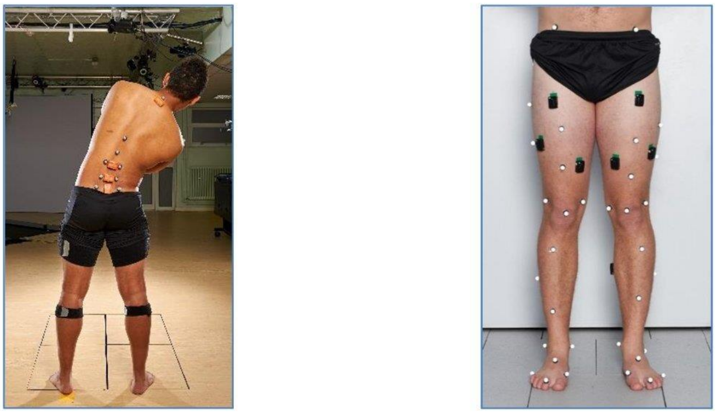
Back	**Hip, Knee and Ankle**	**Shoulder and Elbow**	**Wrist**
Bending	*Walking*	*Lifting light objects*	*Grip*
Stretching	*Up and down stairs*	*Range of motion*	*Range of motion*
Sit to stand	*Sit to stand*	*Reaching for objects*	
	Standing on one leg		
	Up and walk from a chair		

Depending on the joint / area being studied, 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. 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 (removal of features) when needed.

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)

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

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.

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.

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 University computers. Access to this information will be restricted to members of the research team.

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.

You can find out more about how we use your information at: [redacted] or by contacting the University's Data Protection Officer: [redacted]

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 the course of a research project, 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 how it may affect your participation in the research.

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.

If something goes wrong and you are harmed by taking part in this research project, you may have grounds for a legal action but you may have to pay for it. If you wish to make a complaint about the way you were approached or the treatment you have received within the study please contact Cheryl Cleary: Centre Manager [redacted] [redacted] If you feel your complaint is not adequately addressed, you may escalate your complaint by writing to: The School Manager, School of Bioscience, Cardiff University, Museum Avenue, Cardiff, CF10 3AX

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.

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.

VOLUNTEER CONSENT FORM

Assessment of joint function in healthy volunteers 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 initial the box and amend as necessary:

1. I confirm that I have read and understand the information sheet dated 06 September 2019 (Version 12.1) 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. 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. ☐

5. I agree to take part in the above study. ☐

[redacted]

Optional

6. You may contact me in the future to ask if I would be interested in participating in a future research project/survey ☐

7. I agree for you to share anonymised data with external collaborators in the UK and aboard, including commercial companies.. ☐

Name of Participant	Date (dd/mmm/yyyy)	Signature
Name of person obtaining Consent	Date (dd/mmm/yyyy)	Signature

[redacted]

Original Centre Trial Master file, 1 copy for the volunteer, 1 copy for the researcher

2) Patient

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

[redacted]

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.

Introduction to facility, Opportunity to ask questions.
↓
Consent form signed
↓
Information collected
↓
Questionnaires completed
↓
Change into appropriate clothing
↓
Sensors and markers applied to skin
↓
Performance of study activities
↓
End of visit

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)

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 Cheryl Cleary: Centre Manager [redacted] If you feel your complaint is not adequately addressed, you may escalate your complaint by writing to: The School Manager, School of Bioscience, Cardiff University, Museum Avenue, Cardiff, CF10 3AX

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:

[redacted]

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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 initial 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.. ☐

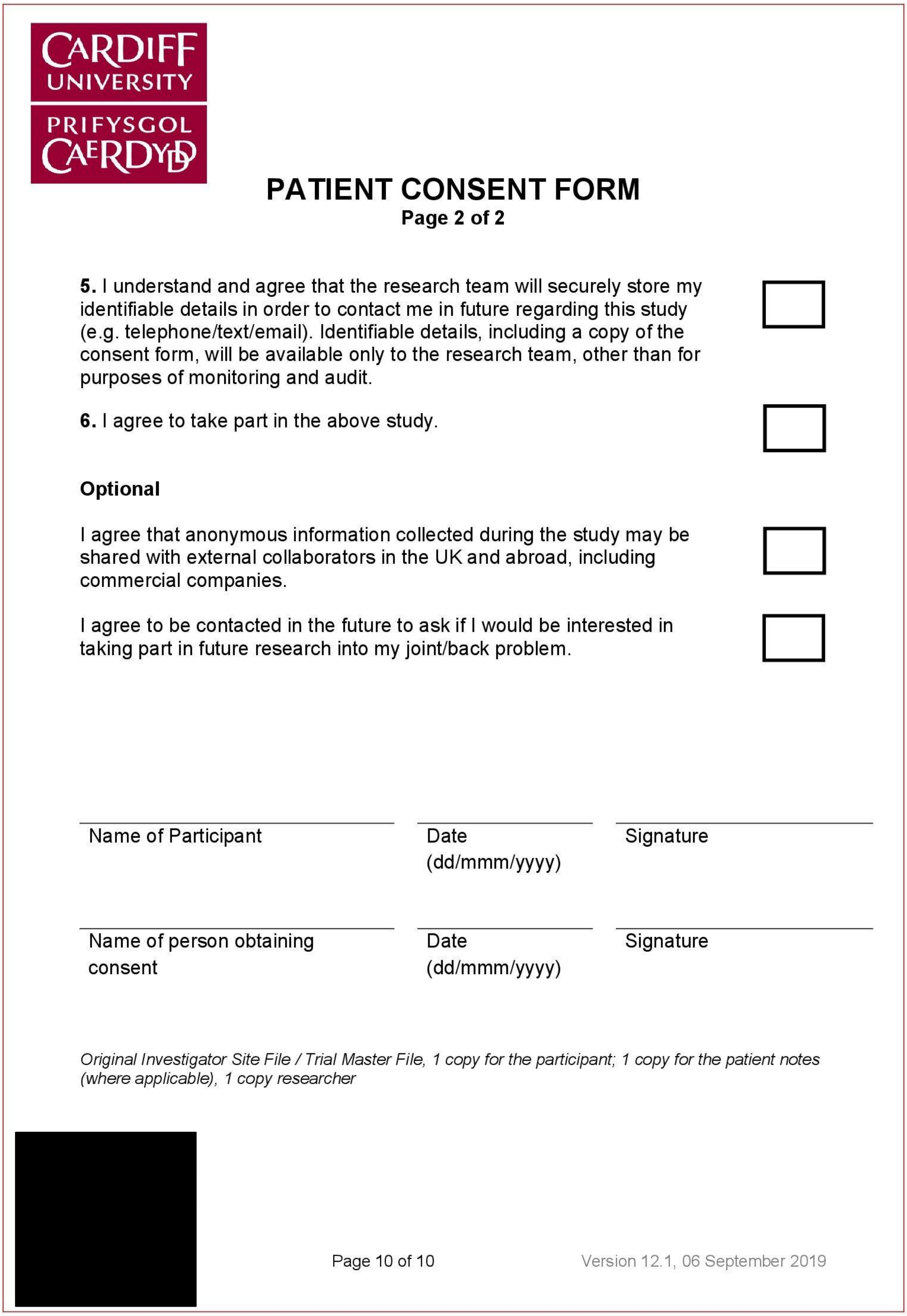
2. I understand that my participation in the study is voluntary and that I am free to withdraw at any time, without giving any reason, and without my medical care or legal rights being affected but any data collected up to the point of my withdrawal will be kept. ☐

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. ☐

[redacted]

Page 9 of 10 Version 12.1, 06 September 2019



CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

PATIENT CONSENT FORM

Page 2 of 2

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. ☐

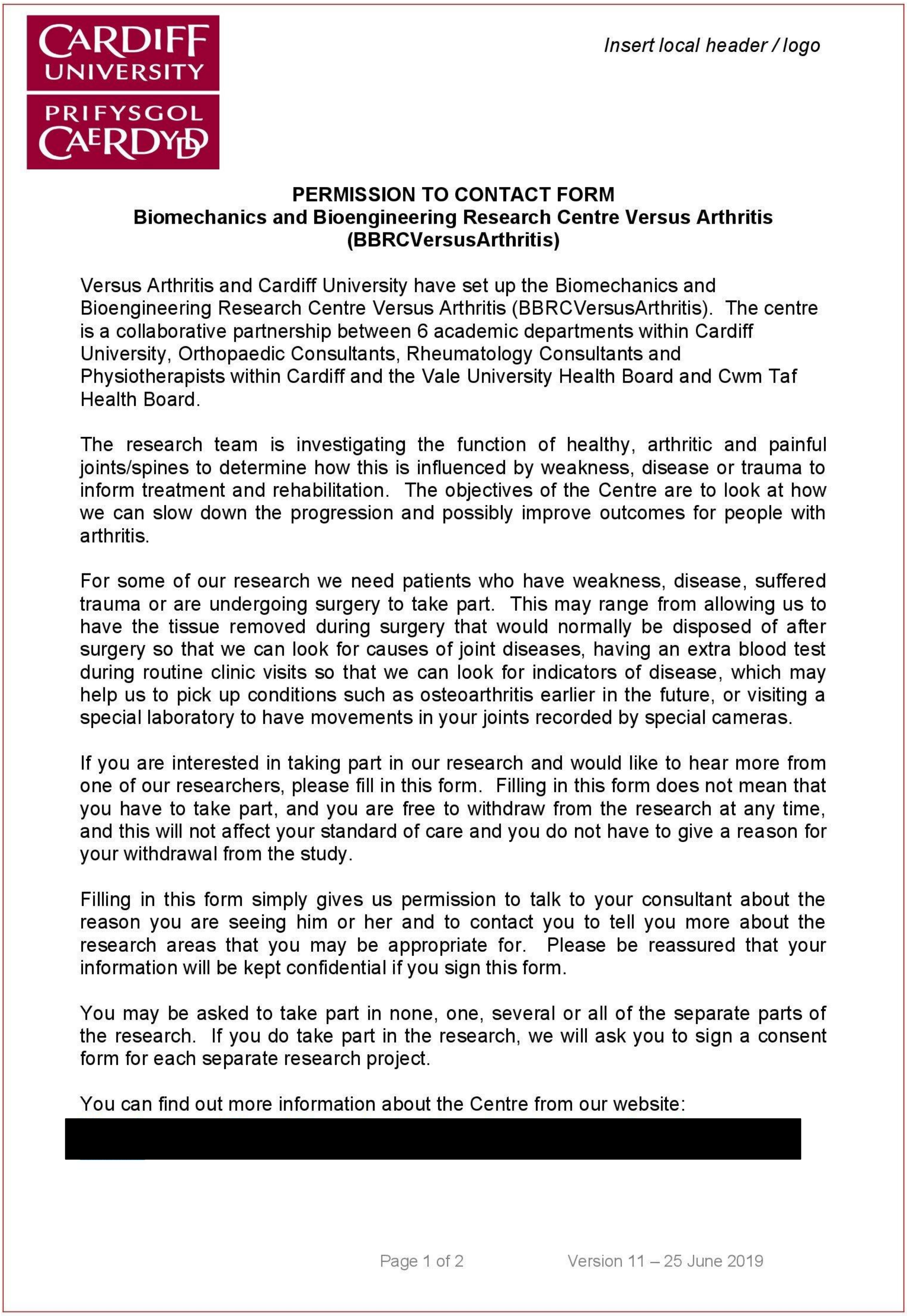
I agree to be contacted in the future to ask if I would be interested in taking part in future research into my joint/back problem. ☐

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

[redacted]

Appendix D: Permission to contact form (part 1)



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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:

[redacted]

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): ____________________

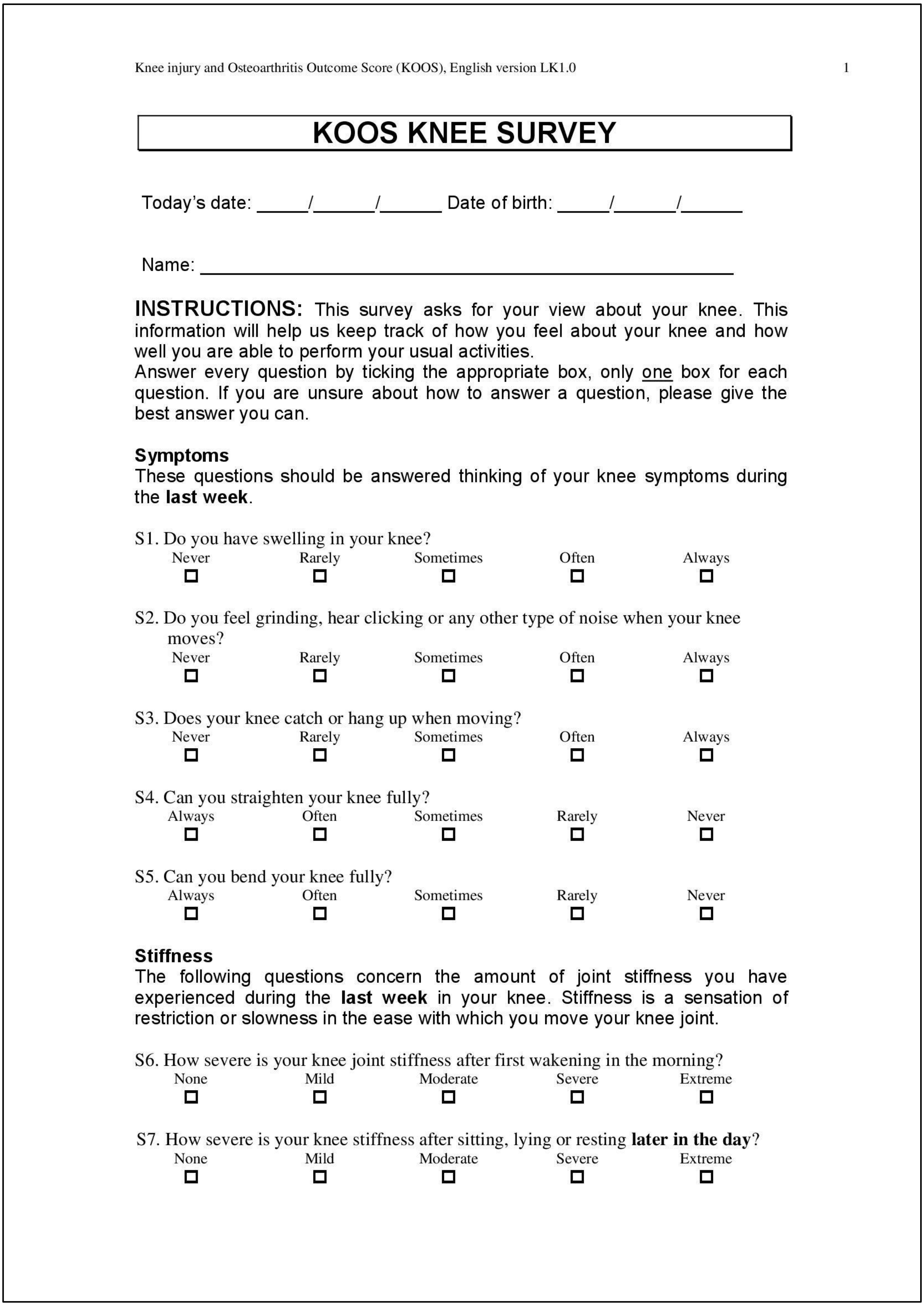
Operation date (if applicable): ____________________

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

[redacted]

Appendix E: Knee Injury and Osteoarthritis Outcome Score (KOOS, Part 1)



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

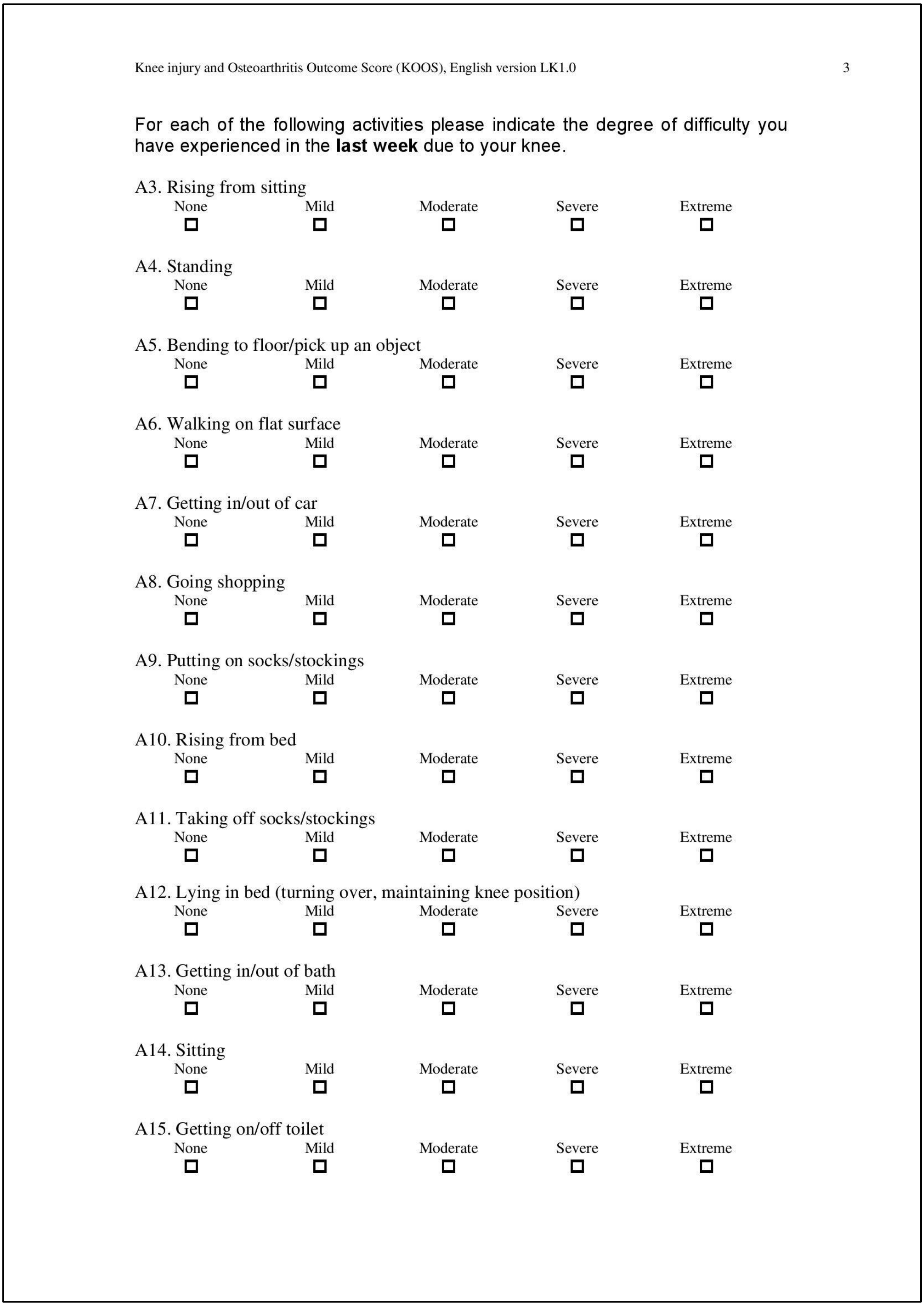
The following questions concern your physical function. By this we mean your ability to move around and to look after yourself. For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your knee.

A1. Descending stairs

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A2. Ascending stairs

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐



Knee injury and Osteoarthritis Outcome Score (KOOS), English version LK1.0 3

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?

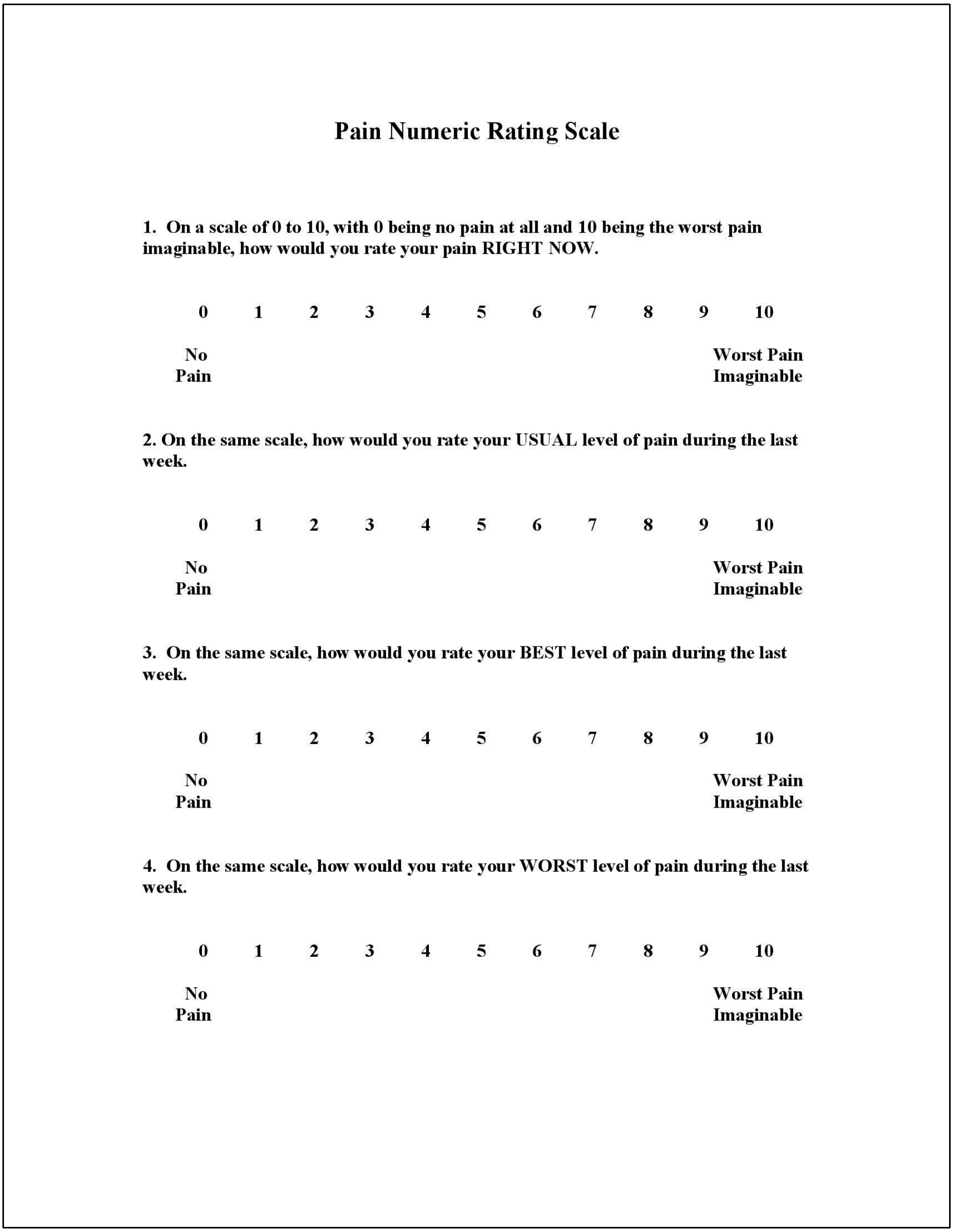
Not at all	Mildly	Moderately	Severely	Extremely
☐	☐	☐	☐	☐

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 F: Numeric Pain Rating Scale (NPRS, Part 1)



Pain Numeric Rating Scale

1. On a scale of 0 to 10, with 0 being no pain at all and 10 being the worst pain imaginable, how would you rate your pain RIGHT NOW.

0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
No Pain										**Worst Pain Imaginable**

2. On the same scale, how would you rate your USUAL level of pain during the last week.

0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
No Pain										**Worst Pain Imaginable**

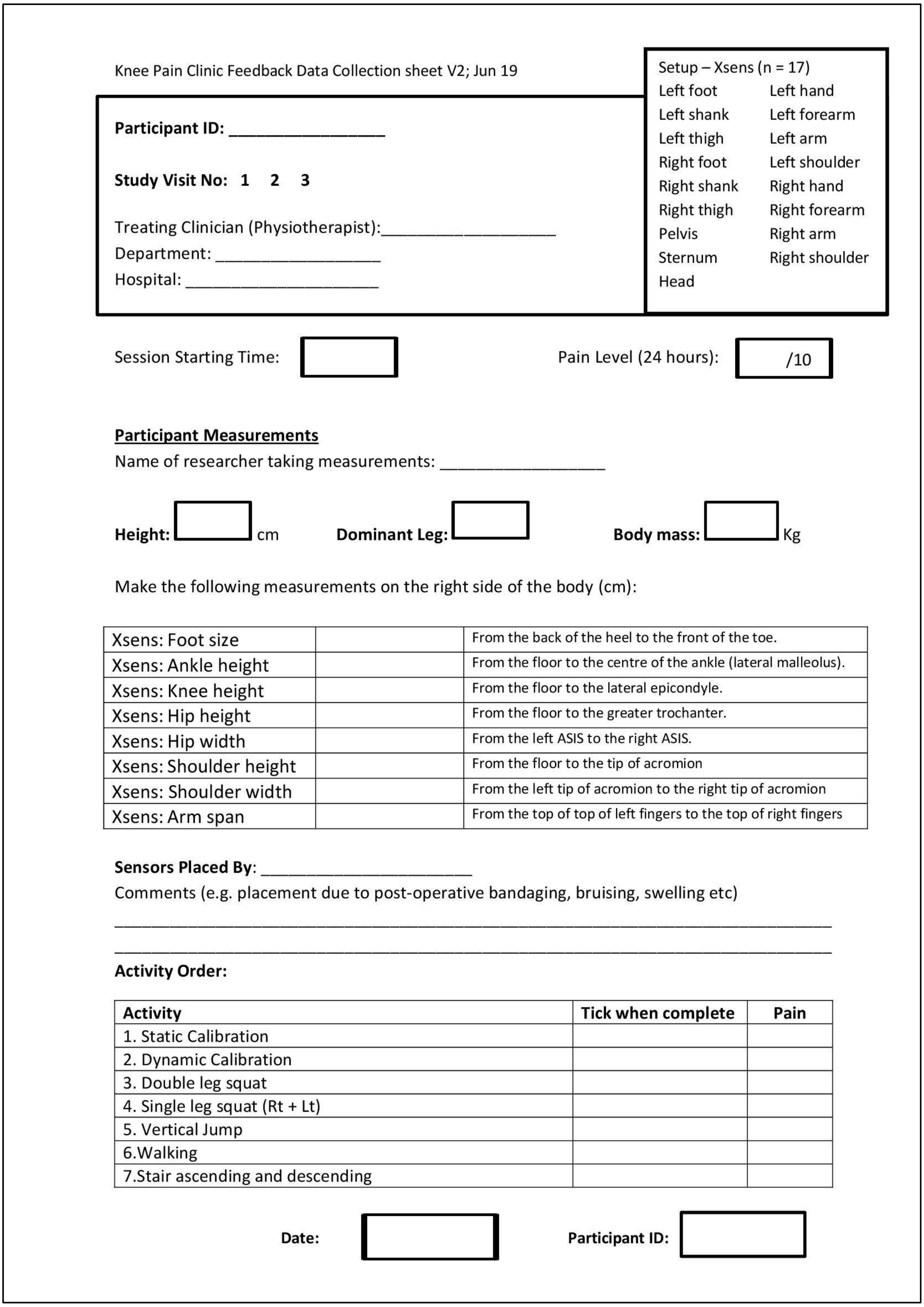
3. On the same scale, how would you rate your BEST level of pain during the last week.

0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
No Pain										**Worst Pain Imaginable**

4. On the same scale, how would you rate your WORST level of pain during the last week.

0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
No Pain										**Worst Pain Imaginable**

Appendix G: Data collection sheet (Part 1)



Knee Pain Clinic Feedback Data Collection sheet V2; Jun 19

Participant ID: ________________

Study Visit No: 1 2 3

Treating Clinician (Physiotherapist):__________________
Department: _________________
Hospital: ____________________

Setup – Xsens (n = 17)
Left foot
Left shank
Left thigh
Right foot
Right shank
Right thigh
Pelvis
Sternum
Head
Left hand
Left forearm
Left arm
Left shoulder
Right hand
Right forearm
Right arm
Right shoulder

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 V2; 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 V2; Jun 19

Notes:

Date:

Participant ID:

Appendix H: Interpretations of the movement analysis kinematic reports for knee pain individual during the performance of gait, DLS, SLS, VJ, SA and SD in the sagittal and frontal planes at the hip, knee and ankle joints

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

Appendix I: Example of the colour-coded technique used during DLS movement analysis using the standardised reporting template. Same technique was used for gait, SLS, VJ, SA and SD

Joint	Altered movement pattern	Number of participants
Hip	increased peak flexion at maximum squat	3
	decreased peak flexion at maximum squat	2
	decreased ROM throughout the cycle	1
	None	16
Knee	increased peak flexion at maximum squat	3
	decreased flexion at early descent	2
	increased flexion ROM at early descent and late ascent	1
	None	16
Ankle	increased peak dorsiflexion at maximum squat	3
	decreased dorsiflexion ROM throughout cycle	4
	increased flexion ROM throughout cycle	3
	decreased peak dorsiflexion at maximum squat	2
	None	10
ROM= range of motion		

Appendix J: Normality testing results for all outcome variables tested in the sagittal and frontal planes during gait as an example (Part 1 for the SQA).

	Limbs	Shapiro-wilk (*p*< 0.05)	Normality result
Gait Sagittal			
HS-Hip	KPPL	.438	Normal
	KPNPL	.733	Normal
	HDL	.674	Normal
	HNDL	.239	Normal
HS-Knee	KPPL	.931	Normal
	KPNPL	.149	Normal
	HDL	.978	Normal
	HNDL	.520	Normal
HS-Ankle	KPPL	.200	Normal
	KPNPL	.815	Normal
	HDL	.930	Normal
	HNDL	.365	Normal
Gait Frontal			
HS-Hip	KPPL	.006*	Not Normal
	KPNPL	.047*	Not Normal
	HDL	.592	Normal
	HNDL	.916	Normal
HS-Knee	KPPL	.143	Normal
	KPNPL	.948	Normal
	HDL	.448	Normal
	HNDL	.269	Normal
HS-Ankle	KPPL	.107	Normal
	KPNPL	.699	Normal
	HDL	.313	Normal
	HNDL	.267	Normal

HS= joint angle at heel-strike for the hip, knee, and ankle. **KPPL=** knee pain painful limb, **KPNPL=** knee pain non-painful limb, **HDL=** healthy dominant limb, **HNDL=** healthy non-dominant limb. *= statistically significant result (*p*< 0.05)

	Limbs	**Shapiro-wilk ($p < 0.05$)**	**Normality result**
Gait Sagittal			
ROM-Hip	KPPL	.226	Normal
	KPNPL	.784	Normal
	HDL	.353	Normal
	HNDL	.656	Normal
ROM-Knee	KPPL	.090	Normal
	KPNPL	.661	Normal
	HDL	.705	Normal
	HNDL	.069	Normal
ROM-Ankle	KPPL	.116	Normal
	KPNPL	.072	Normal
	HDL	.352	Normal
	HNDL	.129	Normal
Gait Frontal			
ROM-Hip	KPPL	.183	Normal
	KPNPL	.325	Normal
	HDL	.845	Normal
	HNDL	.070	Normal
ROM-Knee	KPPL	.201	Normal
	KPNPL	.384	Normal
	HDL	.001*	Not Normal
	HNDL	.001*	Not Normal
ROM-Ankle	KPPL	.586	Normal
	KPNPL	.147	Normal
	HDL	.835	Normal
	HNDL	.558	Normal

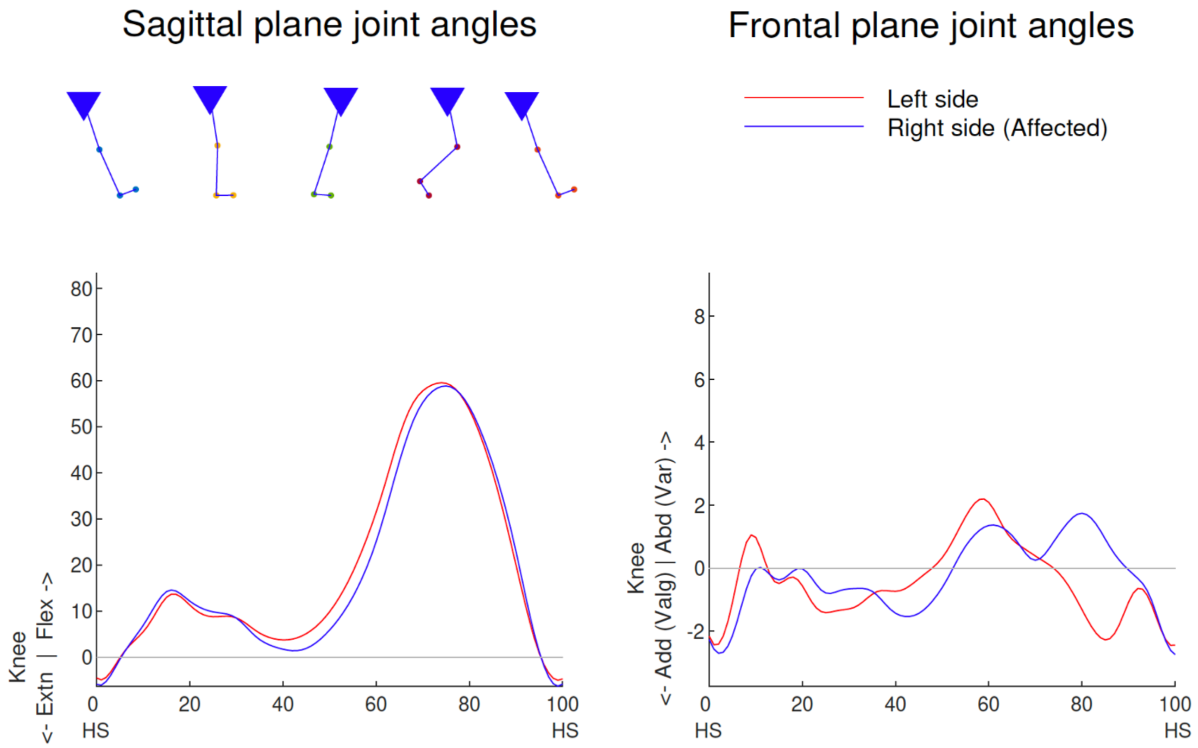
ROM= range of motion during the whole movement cycle. **KPPL=** knee pain painful limb, **KPNPL=** knee pain non-painful limb, **HDL=** healthy dominant limb, **HNDL=** healthy non-dominant limb. *= statistically significant result ($p < 0.05$)

	Limbs	**Shapiro-wilk (*p*< 0.05)**	**Normality result**
Gait Sagittal			
PKF-Hip	KPPL	.447	Normal
	KPNPL	.996	Normal
	HDL	.636	Normal
	HNDL	.503	Normal
PKF-Knee	KPPL	.027*	Not Normal
	KPNPL	.241	Normal
	HDL	.287	Normal
	HNDL	.049*	Not Normal
PKF-Ankle	KPPL	.524	Normal
	KPNPL	.414	Normal
	HDL	.634	Normal
	HNDL	.356	Normal
Gait Frontal			
PKF-Hip	KPPL	.046*	Not Normal
	KPNPL	.935	Normal
	HDL	.295	Normal
	HNDL	.025*	Not Normal
PKF-Knee	KPPL	.595	Normal
	KPNPL	.073	Normal
	HDL	.167	Normal
	HNDL	.008*	Not Normal
PKF-Ankle	KPPL	.859	Normal
	KPNPL	.116	Normal
	HDL	.618	Normal
	HNDL	.582	Normal

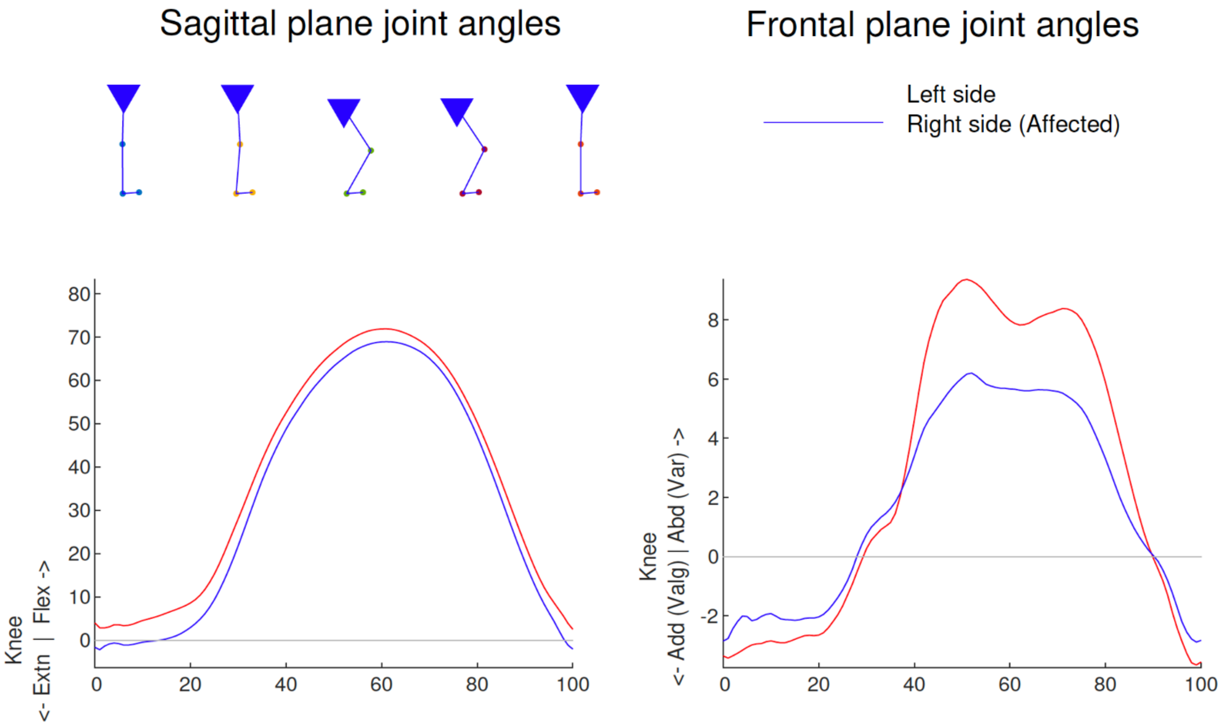
PKF= joints angle at peak knee flexion for the hip, knee, and ankle. **KPPL=** knee pain painful limb, **KPNPL=** knee pain non-painful limb, **HDL=** healthy dominant limb, **HNDL=** healthy non-dominant limb. *= statistically significant result (*p*< 0.05)

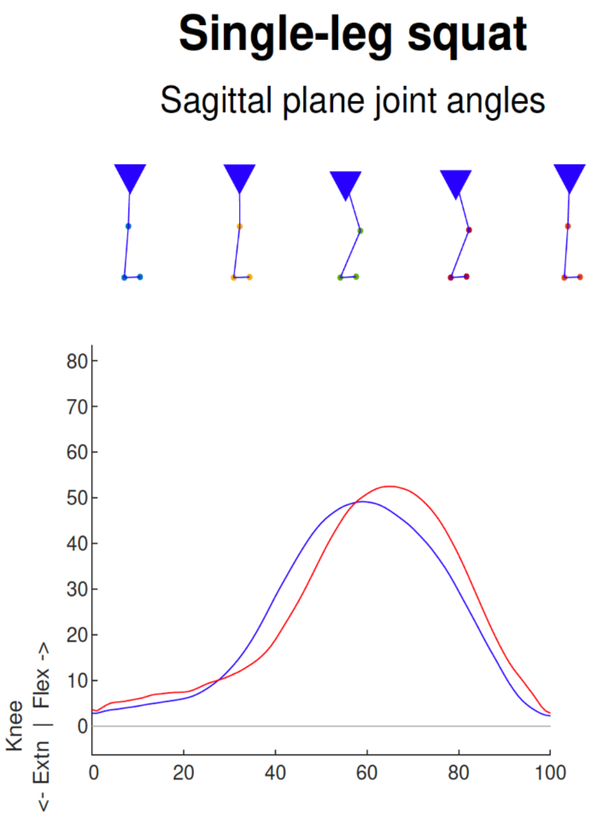
Appendix K: Examples of waveform movement cycles for each of the selected activity (Part 1, SCI of kinematic waveform data)

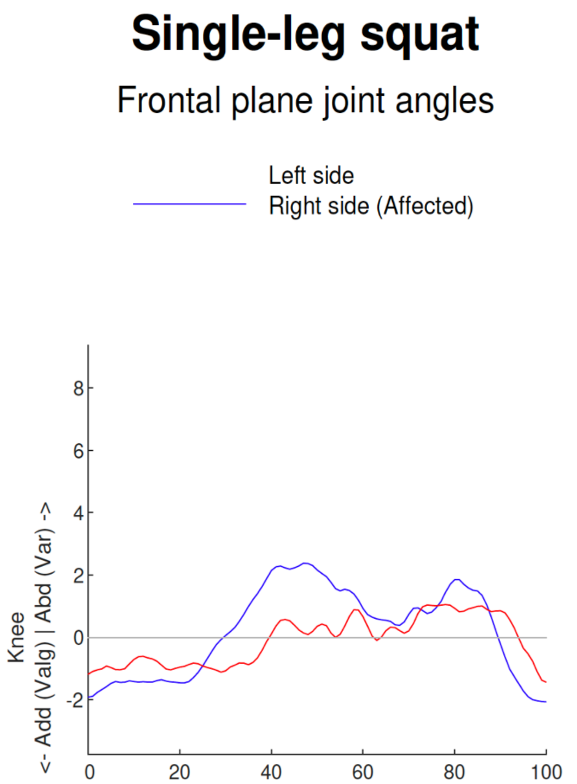
Walk

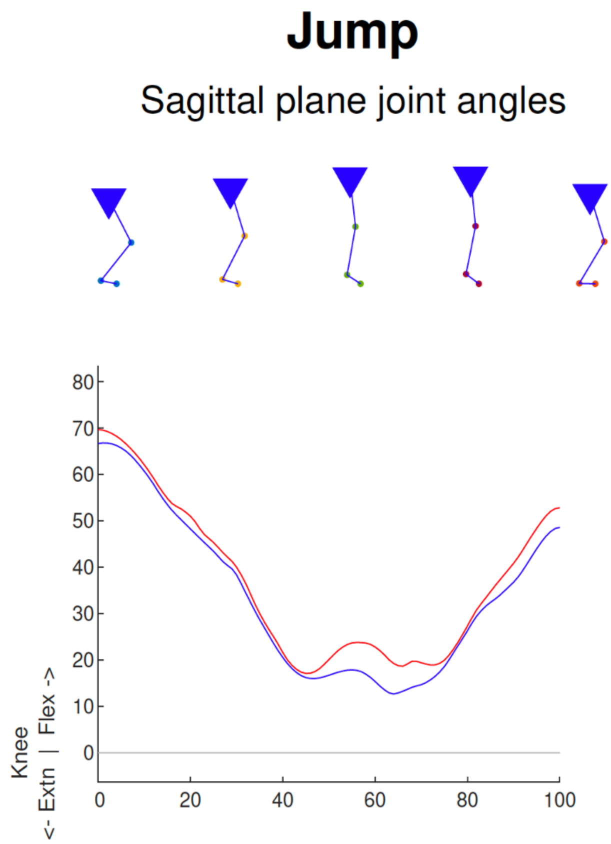


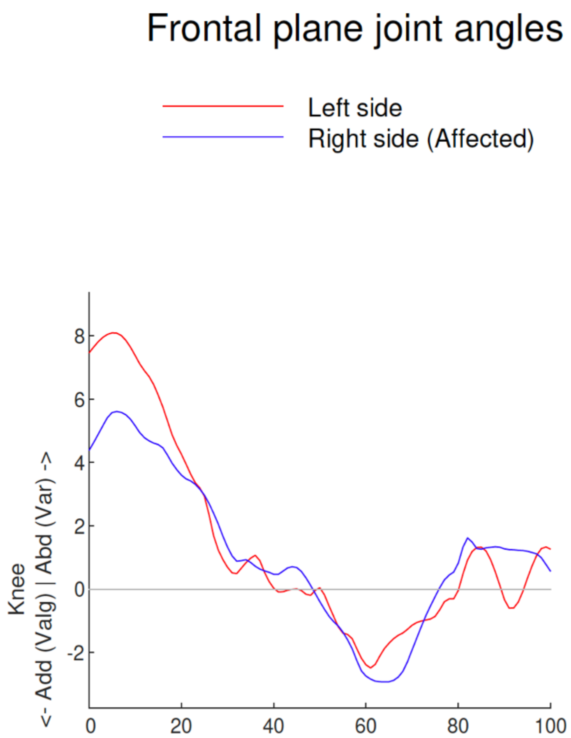
Double-leg squat



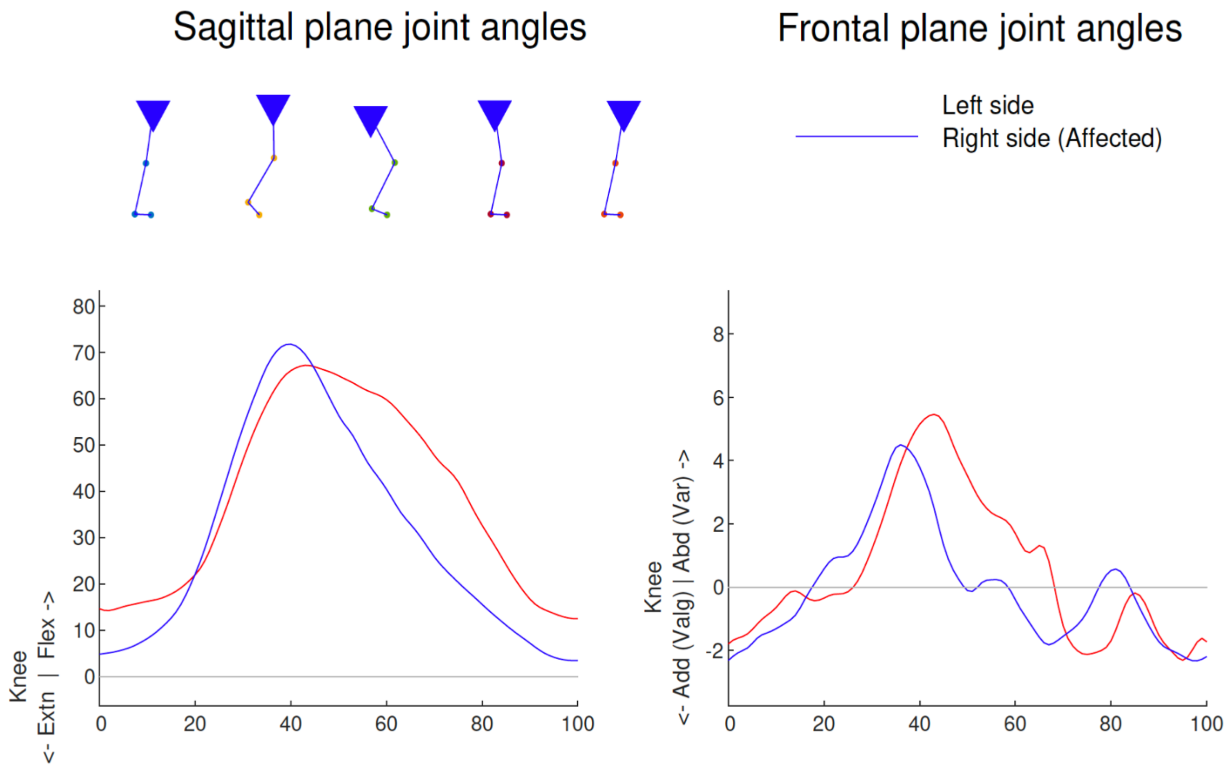

Single-leg squat
Sagittal plane joint angles
Knee
<- Extn | Flex ->
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100


Single-leg squat
Frontal plane joint angles
Left side
Right side (Affected)
Knee
<- Add (Valg) | Abd (Var) ->
8
6
4
2
0
-2
0
20
40
60
80
100

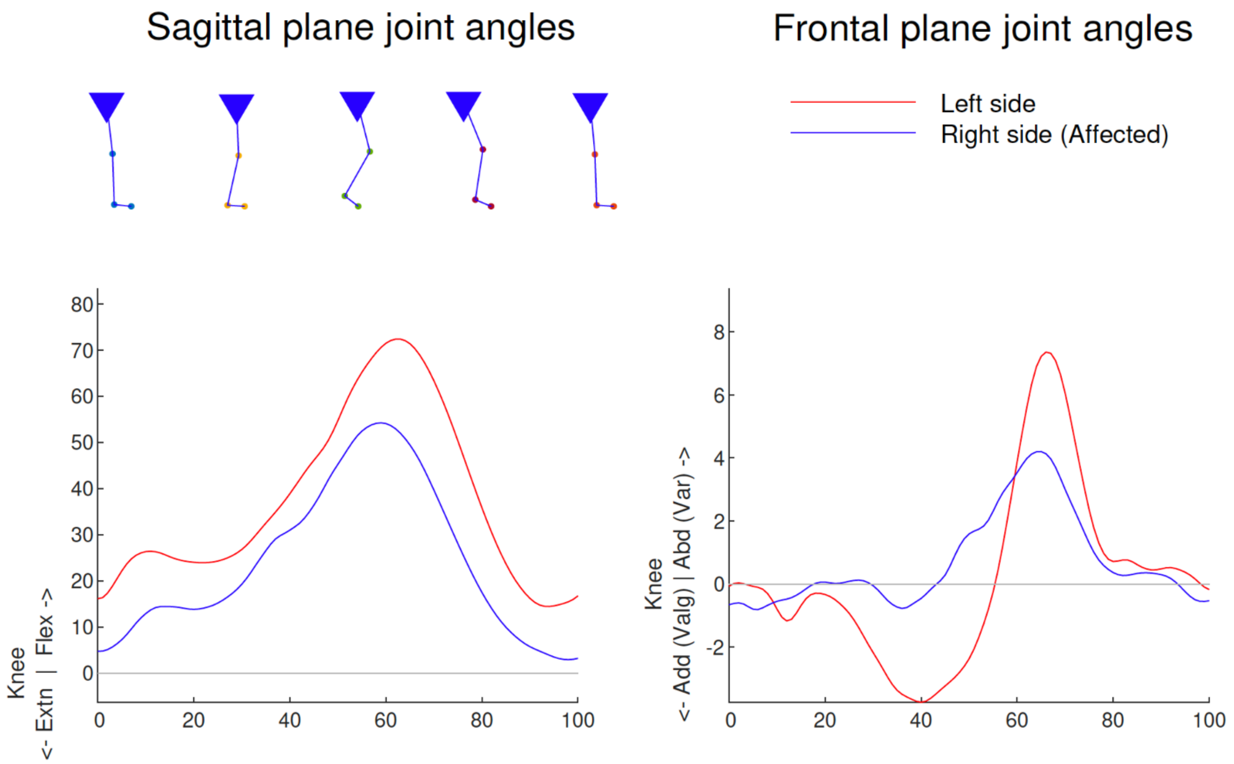

Jump
Sagittal plane joint angles
Knee
<- Extn | Flex ->
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100


Frontal plane joint angles
Left side
Right side (Affected)
Knee
<- Add (Valg) | Abd (Var) ->
8
6
4
2
0
-2
0
20
40
60
80
100

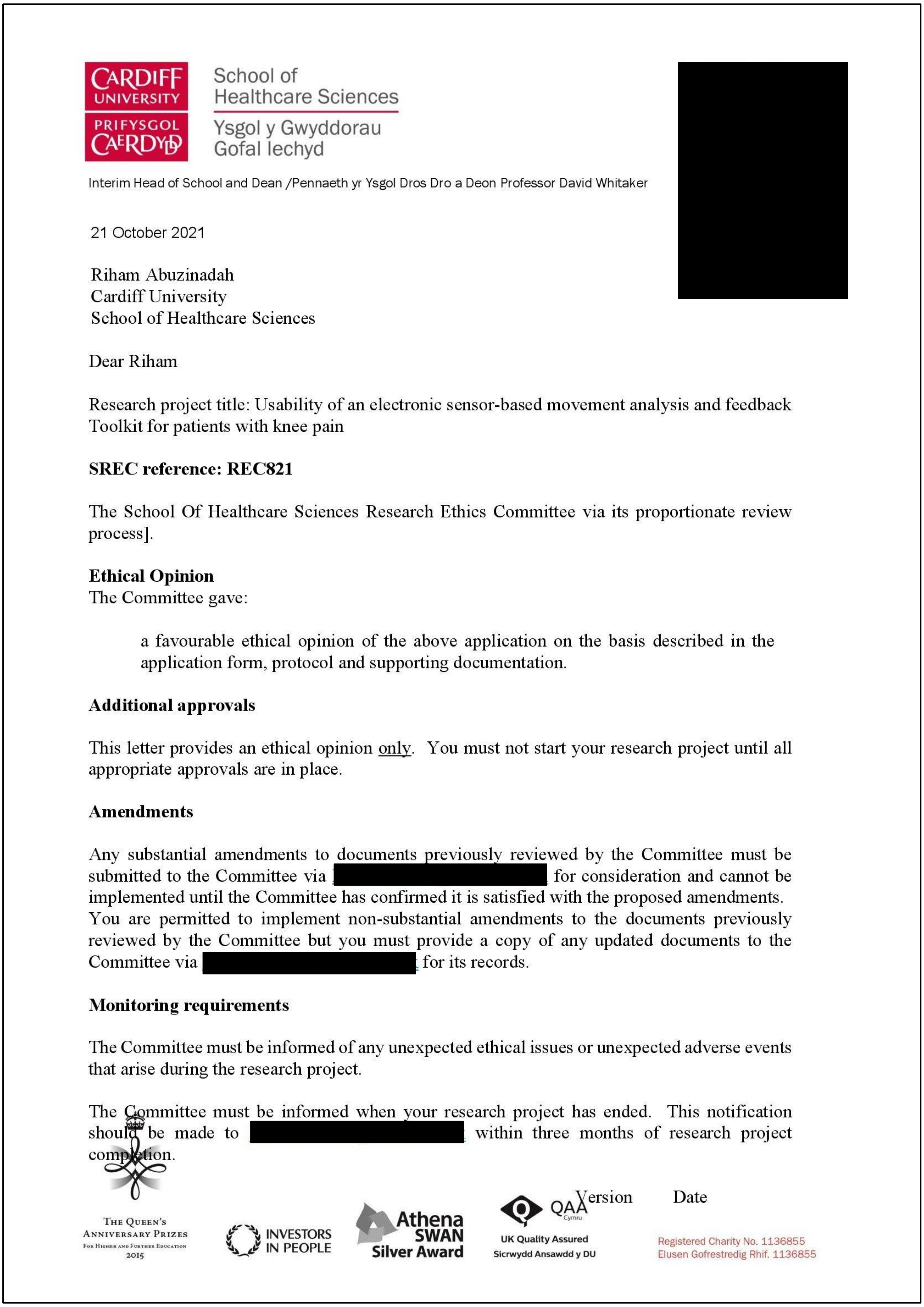
Stairs ascent



Stairs descent



Appendix L: Ethical approval for Part 2



CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD
School of Healthcare Sciences
Ysgol y Gwyddorau Gofal Iechyd

Interim Head of School and Dean /Pennaeth yr Ysgol Dros Dro a Deon Professor David Whitaker

[redacted]

21 October 2021

Riham Abuzinadah
Cardiff University
School of Healthcare Sciences

Dear Riham

Research project title: Usability of an electronic sensor-based movement analysis and feedback Toolkit for patients with knee pain

SREC reference: REC821

The School Of Healthcare Sciences Research Ethics Committee via its proportionate review process].

Ethical Opinion
The Committee gave:

> a favourable ethical opinion of the above application on the basis described in the application form, protocol and supporting documentation.

Additional approvals

This letter provides an ethical opinion only. You must not start your research project until all appropriate approvals are in place.

Amendments

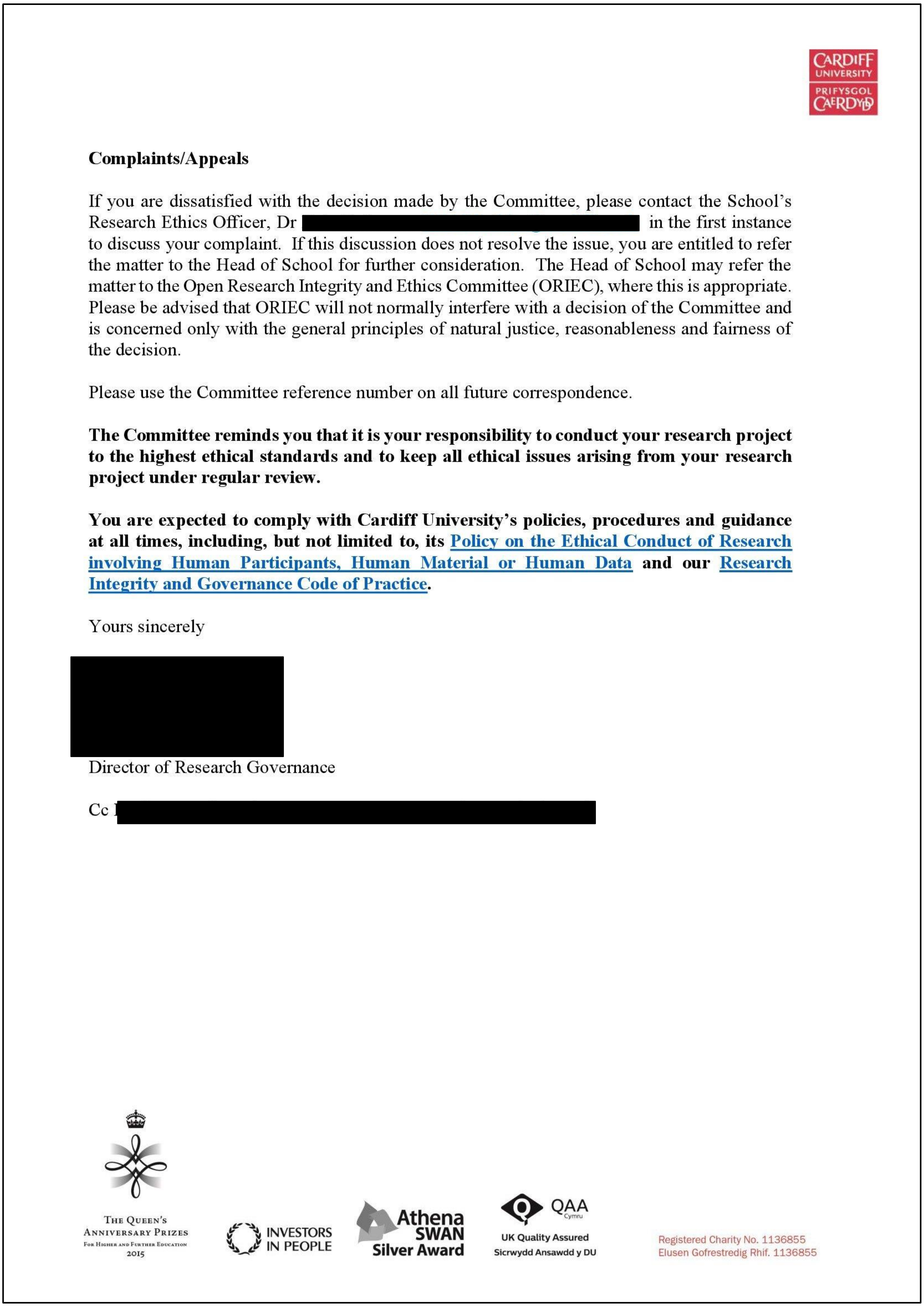
Any substantial amendments to documents previously reviewed by the Committee must be submitted to the Committee via [redacted] for consideration and cannot be implemented until the Committee has confirmed it is satisfied with the proposed amendments. You are permitted to implement non-substantial amendments to the documents previously reviewed by the Committee but you must provide a copy of any updated documents to the Committee via [redacted] for its records.

Monitoring requirements

The Committee must be informed of any unexpected ethical issues or unexpected adverse events that arise during the research project.

The Committee must be informed when your research project has ended. This notification should be made to [redacted] within three months of research project completion.

Version Date



Complaints/Appeals

If you are dissatisfied with the decision made by the Committee, please contact the School's Research Ethics Officer, Dr [redacted] in the first instance to discuss your complaint. If this discussion does not resolve the issue, you are entitled to refer the matter to the Head of School for further consideration. The Head of School may refer the matter to the Open Research Integrity and Ethics Committee (ORIEC), where this is appropriate. Please be advised that ORIEC will not normally interfere with a decision of the Committee and is concerned only with the general principles of natural justice, reasonableness and fairness of the decision.

Please use the Committee reference number on all future correspondence.

The Committee reminds you that it is your responsibility to conduct your research project to the highest ethical standards and to keep all ethical issues arising from your research project under regular review.

You are expected to comply with Cardiff University's policies, procedures and guidance at all times, including, but not limited to, its Policy on the Ethical Conduct of Research involving Human Participants, Human Material or Human Data and our Research Integrity and Governance Code of Practice.

Yours sincerely

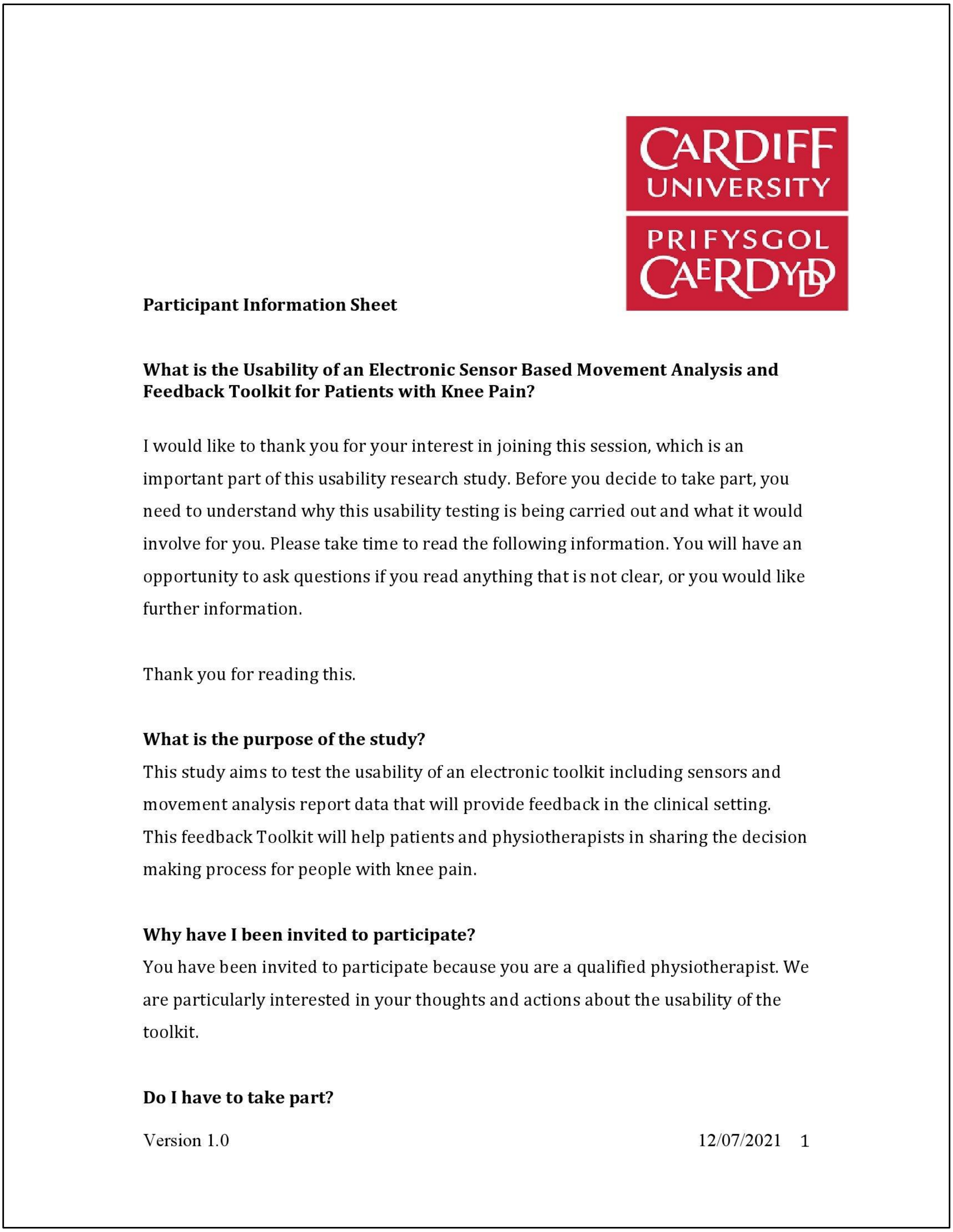
[redacted]

Director of Research Governance

Cc [redacted]

Registered Charity No. 1136855
Elusen Gofrestredig Rhif. 1136855

Appendix M: Participants’ information sheet and consent form for Part 2



Participant Information Sheet

What is the Usability of an Electronic Sensor Based Movement Analysis and Feedback Toolkit for Patients with Knee Pain?

I would like to thank you for your interest in joining this session, which is an important part of this usability research study. Before you decide to take part, you need to understand why this usability testing is being carried out and what it would involve for you. Please take time to read the following information. You will have an opportunity to ask questions if you read anything that is not clear, or you would like further information.

Thank you for reading this.

What is the purpose of the study?

This study aims to test the usability of an electronic toolkit including sensors and movement analysis report data that will provide feedback in the clinical setting. This feedback Toolkit will help patients and physiotherapists in sharing the decision making process for people with knee pain.

Why have I been invited to participate?

You have been invited to participate because you are a qualified physiotherapist. We are particularly interested in your thoughts and actions about the usability of the toolkit.

Do I have to take part?

No, your participation in this research project is entirely voluntary and it is up to you to decide whether or not to take part. We will describe the steps of the study in this information sheet. If you agree to take part, we will ask you to sign a consent form. If you decide not to take part, you do not have to explain your reasons and it will not affect your legal rights. You are free to withdraw from the study at any time without giving a reason.

If you are Cardiff University students, participating in this research project will have no effect on your education or progression through your studies.

What will taking part involve?

Once you have agreed to take part in this study, you will be invited to attend for an interview at anytime suitable for you using zoom application. You will be asked to sign a consent form, which will be sent to you as an electronic link before the interview. You will be asked to sign it with your full name and signature (as an eSignature) and email this back to the researcher. The online data collection session will last for a maximum of 60 minutes., During this session the researcher will give you an introduction to the Toolkit, training on how to use the toolkit and time to practice using it so that the participant has some familiarity with the toolkit.

The researcher will then outline a list of tasks for the participant to complete as part of a study to test the usability of the toolkit. Participants will be asked to perform the tasks given to them while vocalising their thoughts. The researcher will watch the participants' behavior and attitude toward the system while they are doing the usability test and write down the key elements. The researcher will also note the starting and ending time of each subject for completing the tasks.

After completion of the tasks, participants will be asked to complete the System Usability Scale questionnaire that should be completed at the end of the session. This meeting will be audio and/or video recorded.

Will I be paid for taking part?

No, you will not be paid for your participation in this study. You should be aware that any data you provide will be treated as a gift, and you would not be credited if this research project results in the development of a new treatment/ method/ test/ assessment.

What are the possible benefits of taking part?

There will be no direct advantages or benefits to you from taking part, but your contribution will help us to improve the Toolkit and will lead to a future development of a new promising intervention for physiotherapists treating people with knee pain.,

What are the possible risks of taking part?

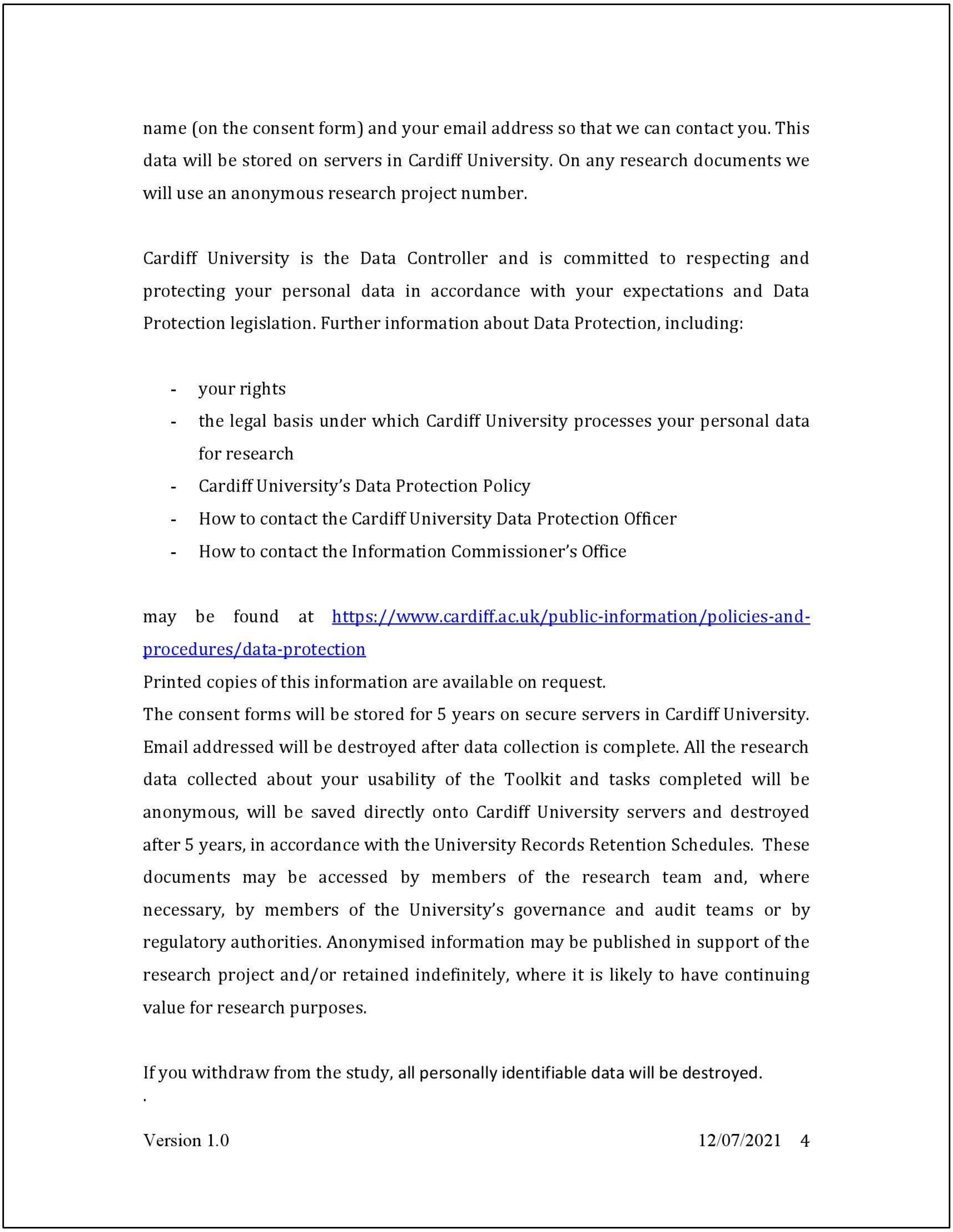
There are no direct risks to taking part in this study other than time burden. All information will be stored confidentially and anonymously. We will be securely storing the consent form on Cardiff University servers. You will not be identifiable from taking part in this study

Will my taking part in this research project be kept confidential?

All information about you that is gathered will be kept strictly confidential and any personal information you provide will be managed in accordance with data protection legislation. Please see 'What will happen to my Personal Data?' (below) for further information.

What will happen to my Personal Data?

Personal data, according to the General Data Protection Regulation (GDPR) means any information relating to an identifiable living person who can be directly or indirectly identified in particular by reference to an identifier. This may include information such as an individual's name, address, email address or date of birth. The only personal identifiable data that will be used in this project will be your



name (on the consent form) and your email address so that we can contact you. This data will be stored on servers in Cardiff University. On any research documents we will use an anonymous research project number.

Cardiff University is the Data Controller and is committed to respecting and protecting your personal data in accordance with your expectations and Data Protection legislation. Further information about Data Protection, including:

- your rights
- the legal basis under which Cardiff University processes your personal data for research
- Cardiff University's Data Protection Policy
- How to contact the Cardiff University Data Protection Officer
- How to contact the Information Commissioner's Office

may be found at https://www.cardiff.ac.uk/public-information/policies-and-procedures/data-protection
Printed copies of this information are available on request.
The consent forms will be stored for 5 years on secure servers in Cardiff University. Email addressed will be destroyed after data collection is complete. All the research data collected about your usability of the Toolkit and tasks completed will be anonymous, will be saved directly onto Cardiff University servers and destroyed after 5 years, in accordance with the University Records Retention Schedules. These documents may be accessed by members of the research team and, where necessary, by members of the University's governance and audit teams or by regulatory authorities. Anonymised information may be published in support of the research project and/or retained indefinitely, where it is likely to have continuing value for research purposes.

If you withdraw from the study, all personally identifiable data will be destroyed.
.

Who has reviewed this research project?

This research project has been reviewed and given a favorable opinion by the School Healthcare Sciences Research Ethics Committee, Cardiff University.

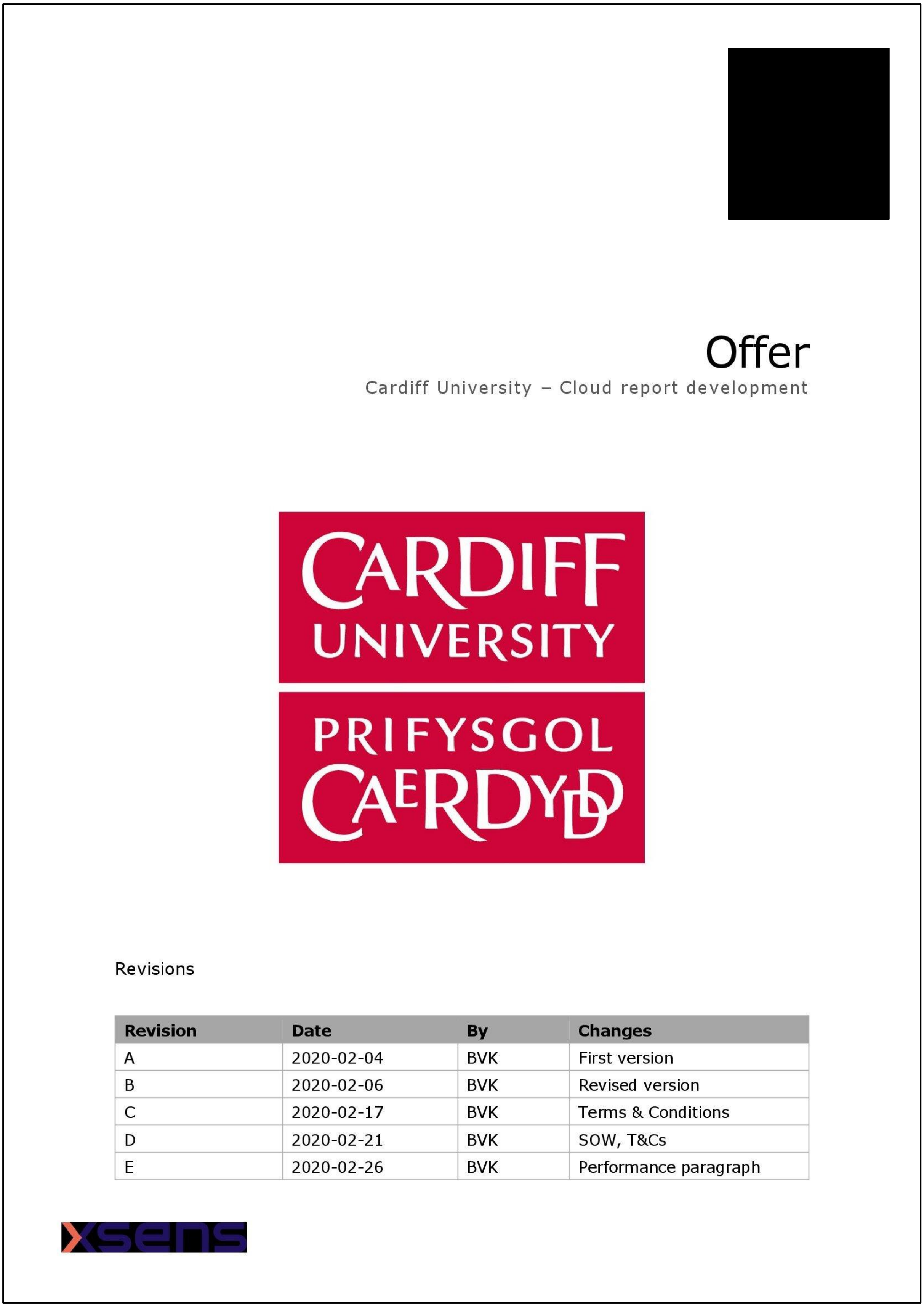
Further information and contact details

Should you have any questions relating to this research project, you may contact us during normal working hours:

Name: [redacted]
Phone number: [redacted]
Email: [redacted]

Thank you for considering taking part in this research project. If you decide to participate, you will be given a copy of the Participant Information Sheet and a signed consent form to keep for your records.

Appendix N: Agreement with X-Sens for the electronic reporting tool



[redacted]

Offer

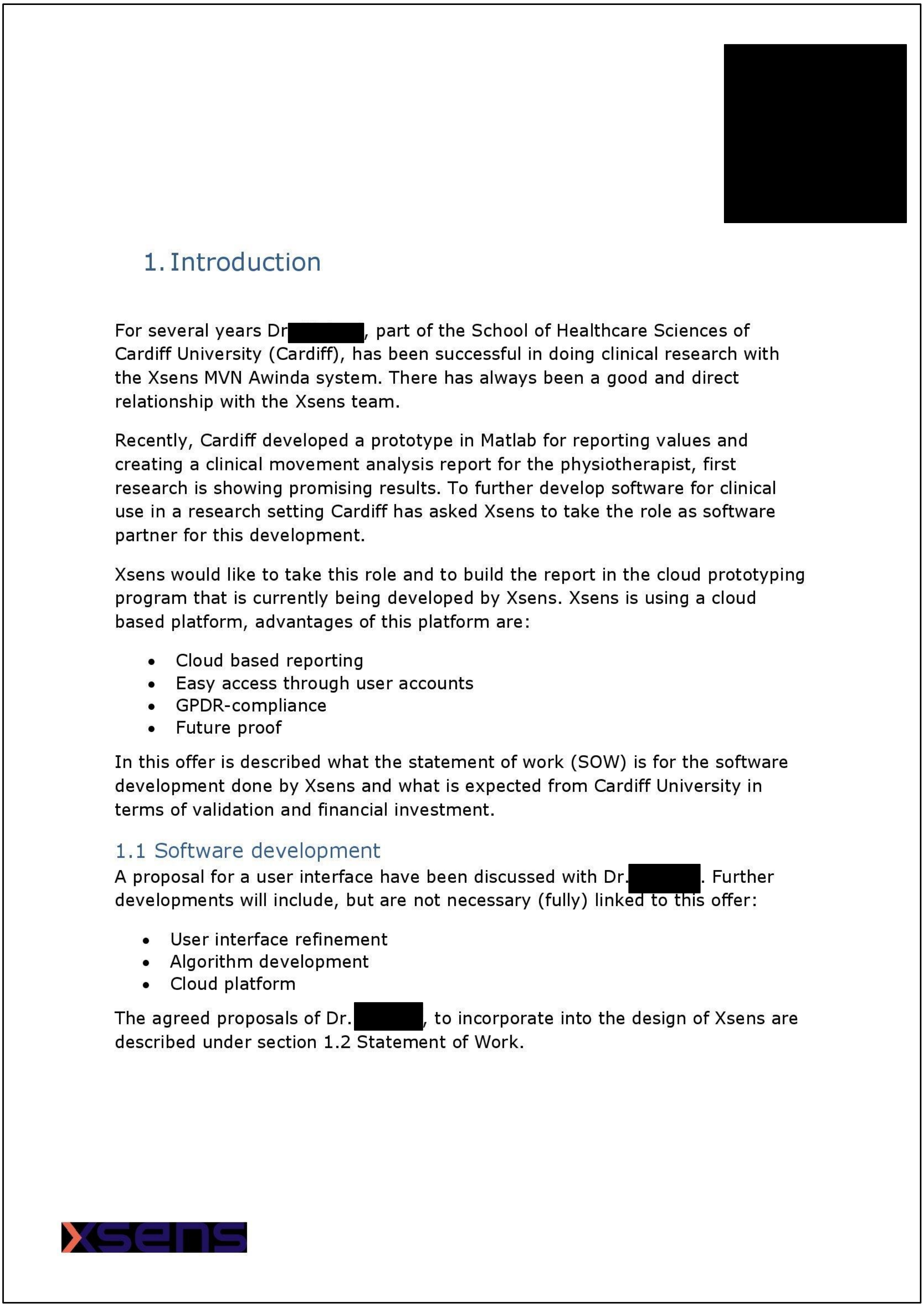
Cardiff University – Cloud report development

Revisions

Revision	Date	By	Changes
A	2020-02-04	BVK	First version
B	2020-02-06	BVK	Revised version
C	2020-02-17	BVK	Terms & Conditions
D	2020-02-21	BVK	SOW, T&Cs
E	2020-02-26	BVK	Performance paragraph

[redacted]

Contents



[redacted]

1. Introduction

For several years Dr[redacted], part of the School of Healthcare Sciences of Cardiff University (Cardiff), has been successful in doing clinical research with the Xsens MVN Awinda system. There has always been a good and direct relationship with the Xsens team.

Recently, Cardiff developed a prototype in Matlab for reporting values and creating a clinical movement analysis report for the physiotherapist, first research is showing promising results. To further develop software for clinical use in a research setting Cardiff has asked Xsens to take the role as software partner for this development.

Xsens would like to take this role and to build the report in the cloud prototyping program that is currently being developed by Xsens. Xsens is using a cloud based platform, advantages of this platform are:

- Cloud based reporting
- Easy access through user accounts
- GPDR-compliance
- Future proof

In this offer is described what the statement of work (SOW) is for the software development done by Xsens and what is expected from Cardiff University in terms of validation and financial investment.

1.1 Software development

A proposal for a user interface have been discussed with Dr.[redacted]. Further developments will include, but are not necessary (fully) linked to this offer:

- User interface refinement
- Algorithm development
- Cloud platform

The agreed proposals of Dr.[redacted], to incorporate into the design of Xsens are described under section 1.2 Statement of Work.

[redacted]

1.2 Statement of work

In agreement with Dr. [redacted] the following tasks will be taken into account in the design of the report:

- Be able to enter a user ID for user filing purposes
- Be able to select which side is injured
- Make selection for a list of executed exercise and reporting
- Select the joints of interest
- Select one or multiple mvn(x) files to include for reporting
- Synchronized dynamic view of Avatar
- Plot waveforms windowed per exercise
- Be able to remove outliers
- Means of left and right will be plotted over each other
- Add annotations manually with auto-incremental alpha label, at a stated point in the graph and will be shown in report
- PDF of report is available

1.3 Role of Cardiff

Cardiff will play a role in the development of the report by using its expertise for:

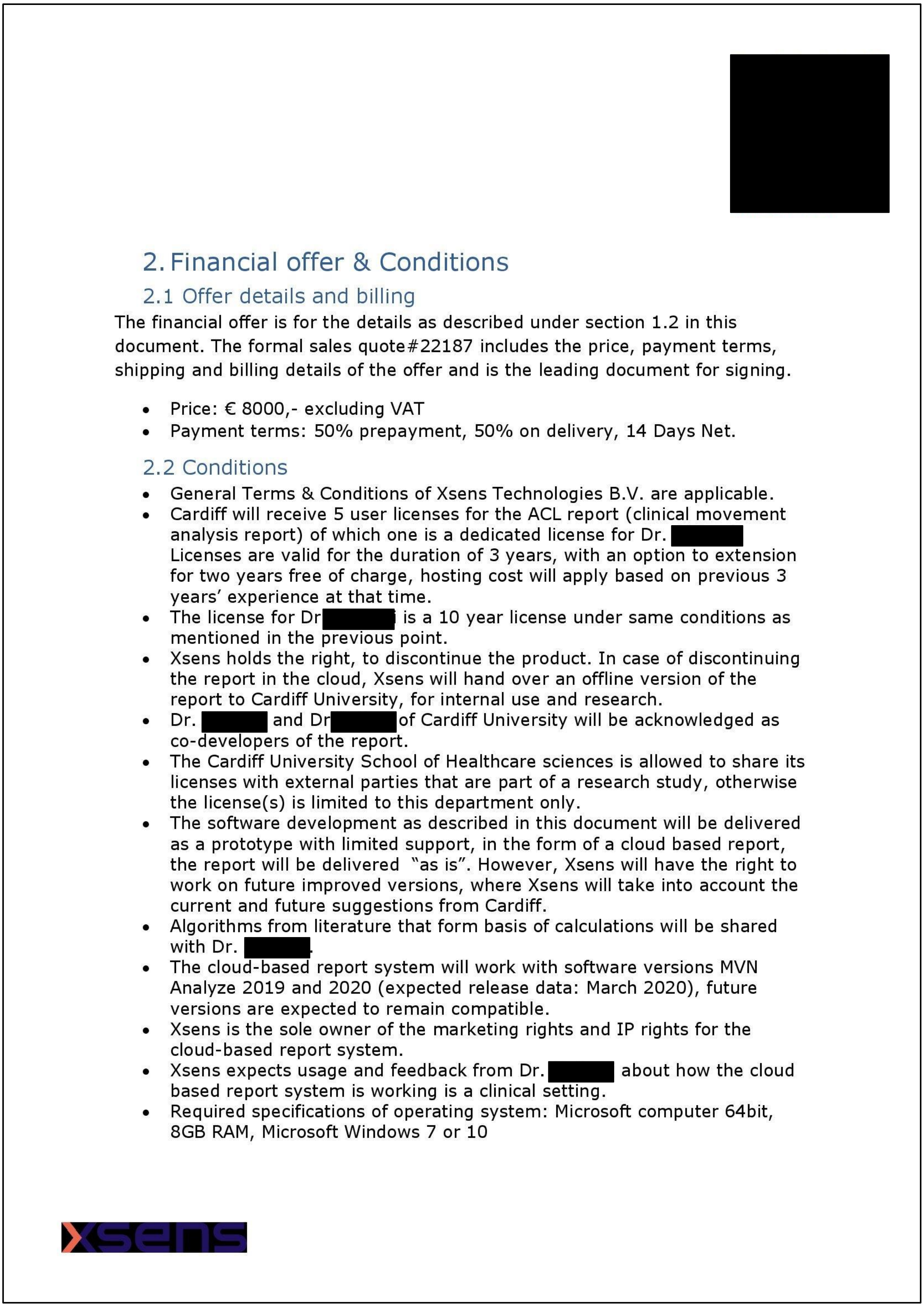
- Doing validation study on the report
- Suggestions for naming of parameters
- Sharing insights on algorithm used
- Accepting the deliverable as described under section *1.1* and *1.2*

1.4 Acceptance

After review and testing of the report, Cardiff will verify with Xsens that all the items as described under section *1.2 Statement of work* are included in the report and accept the software final version. However this will not be limiting future improvements of the report.

1.3 Performance

The accuracy of reported results will depend on the quality of the typical quality of data delivered by the MVN Awinda system (i.e., common pros and cons of the system need to be accounted for). The clinical movement analysis report will assume a 'normal biomechanical model' of the subject as well as the presence of a continues walk in the recorded file.



[redacted]

2. Financial offer & Conditions

2.1 Offer details and billing

The financial offer is for the details as described under section 1.2 in this document. The formal sales quote#22187 includes the price, payment terms, shipping and billing details of the offer and is the leading document for signing.

- Price: € 8000,- excluding VAT
- Payment terms: 50% prepayment, 50% on delivery, 14 Days Net.

2.2 Conditions

- General Terms & Conditions of Xsens Technologies B.V. are applicable.
- Cardiff will receive 5 user licenses for the ACL report (clinical movement analysis report) of which one is a dedicated license for Dr. [redacted] Licenses are valid for the duration of 3 years, with an option to extension for two years free of charge, hosting cost will apply based on previous 3 years' experience at that time.
- The license for Dr[redacted] is a 10 year license under same conditions as mentioned in the previous point.
- Xsens holds the right, to discontinue the product. In case of discontinuing the report in the cloud, Xsens will hand over an offline version of the report to Cardiff University, for internal use and research.
- Dr. [redacted] and Dr[redacted] of Cardiff University will be acknowledged as co-developers of the report.
- The Cardiff University School of Healthcare sciences is allowed to share its licenses with external parties that are part of a research study, otherwise the license(s) is limited to this department only.
- The software development as described in this document will be delivered as a prototype with limited support, in the form of a cloud based report, the report will be delivered "as is". However, Xsens will have the right to work on future improved versions, where Xsens will take into account the current and future suggestions from Cardiff.
- Algorithms from literature that form basis of calculations will be shared with Dr. [redacted].
- The cloud-based report system will work with software versions MVN Analyze 2019 and 2020 (expected release data: March 2020), future versions are expected to remain compatible.
- Xsens is the sole owner of the marketing rights and IP rights for the cloud-based report system.
- Xsens expects usage and feedback from Dr. [redacted] about how the cloud based report system is working is a clinical setting.
- Required specifications of operating system: Microsoft computer 64bit, 8GB RAM, Microsoft Windows 7 or 10

[redacted]

This agreement has been agreed on by:

Xsens Technologies B.V.

Signature: ____________________________

Name: ____________________________

Title: ____________________________

Date: ____________________________

Cardiff University

Signature: ____________________________

Name: ____________________________

Title: ____________________________

Date: ____________________________

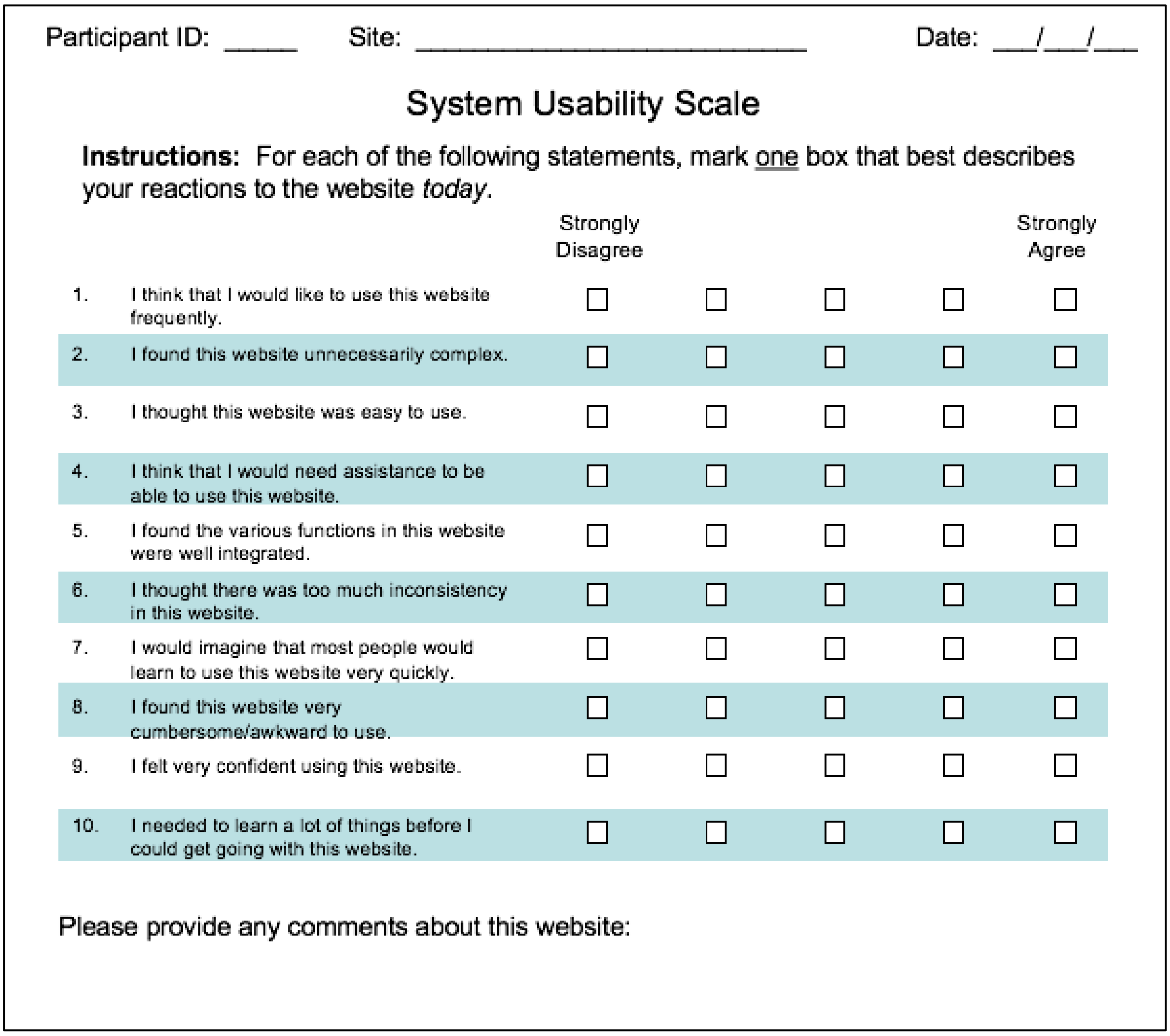
Appendix O: Types and descriptions of errors (Part 2)

Types of errors executed while interpreting gait reports		
Users	**Type of error**	**Description of error**
A	1: navigation	mistake when moving from one page to another
	7: input device	participant mis-tapping and pressed on another bottom on the joint category
	1: navigation	opened wrong page for comparing between 2 participant's report
	2: Layout	participant was not sure which column is for which participant
	4: wording and information	wrong answer due to lack of information
B	2: layout	confused about opening a file name
	3: handling	Participant process incorrect information for what this page is about,
	4: Wording	misunderstood the wording right and left
	4: Wording	participant did not understand the meaning of n
	6: Interface design	was not sure about colours.
C	4: wording and information	in task 1 participant thought all parameters are for left leg only due to the presented picture
	5: technical.	to open page for task 2 participant unintentionally complained about the system taking time open the page
	6: interface design.	Participant unintentionally asked about right and left for what since the font size for hip joint was small
	6: interface design.	When asked about peak knee flexion, participant asked on the graphs which plane is this (small font size)
	6: interface design.	wrong answer and got confused by the colours

D	1: navigation:	participant did not know how to move from one page to another
	5: technical.	Participant unintentionally complained about a sound due to lots of energy needed from the system
	3: handling.	Participant did not know how to find the knee joint
	7: input device	Mis-tapping, pressed on the wrong place for writing a note
	3: handling	Participant did not know how to compare between 2 participants
	2: layout	Wrong answer for the question and did not notice the color difference
E	4: wording and information	participant thought all parameters are for left leg only due to the presented picture.
	5: technical	Participant unintentionally complained about the slow system
	6: interface design	participant unintentionally complained about the small font size above each graph (flex/ext- abd/add)
	2: layout.	Participant got confused by the place where he/she should write a note
	2: Layout.	Participant got confused and could not find participants number on the screen to compare as it was by the trial number
F	4: wording.	Participant unintentionally complained about the naming of sentences like “contact event counter”
	6: interface design	Participant complained about the small font size for the percentage of swing phase on the tables.
	1: navigation	Participant did not easily know how to go to gait graph page
	3: handling	Participant did not know how to deal with changing the joint from hip to knee

	2: Layout	For comparing between 2 participants, the user did not know which data was for which participant (no participants ids) and was confused
	6: Interface design	Participant complained about the font size.
	1: navigation	Participant provided wrong answer for heal-strike question

Appendix P: System Usability Scale (SUS) Questionnaire for Part 2



Participant ID: _____ Site: ____________________________ Date: ___/___/___

System Usability Scale

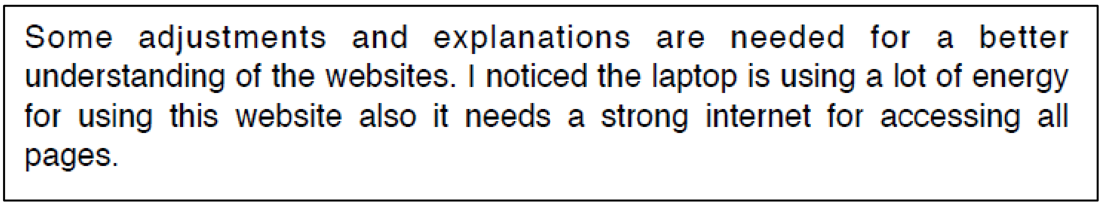
Instructions: For each of the following statements, mark <u>one</u> box that best describes your reactions to the website *today*.

		Strongly Disagree				Strongly Agree
1.	I think that I would like to use this website frequently.	☐	☐	☐	☐	☐
2.	I found this website unnecessarily complex.	☐	☐	☐	☐	☐
3.	I thought this website was easy to use.	☐	☐	☐	☐	☐
4.	I think that I would need assistance to be able to use this website.	☐	☐	☐	☐	☐
5.	I found the various functions in this website were well integrated.	☐	☐	☐	☐	☐
6.	I thought there was too much inconsistency in this website.	☐	☐	☐	☐	☐
7.	I would imagine that most people would learn to use this website very quickly.	☐	☐	☐	☐	☐
8.	I found this website very cumbersome/awkward to use.	☐	☐	☐	☐	☐
9.	I felt very confident using this website.	☐	☐	☐	☐	☐
10.	I needed to learn a lot of things before I could get going with this website.	☐	☐	☐	☐	☐

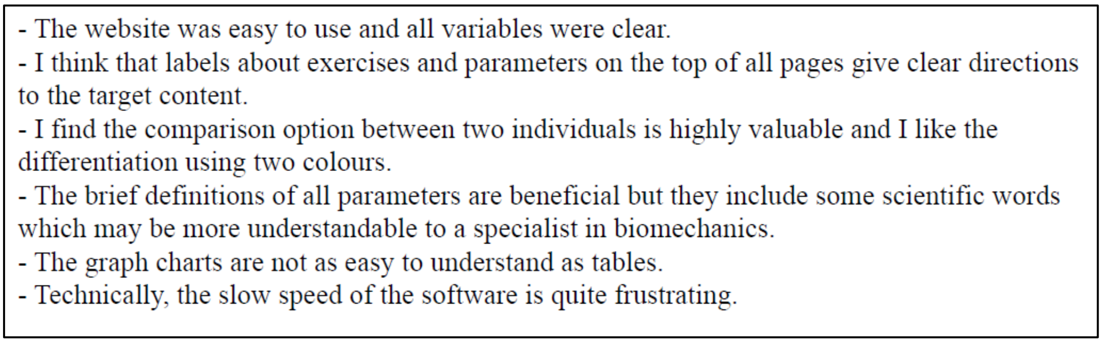
Please provide any comments about this website:

Appendix Q: Participants comments on the E-reporting tool from SUS questionnaire (Part 2)

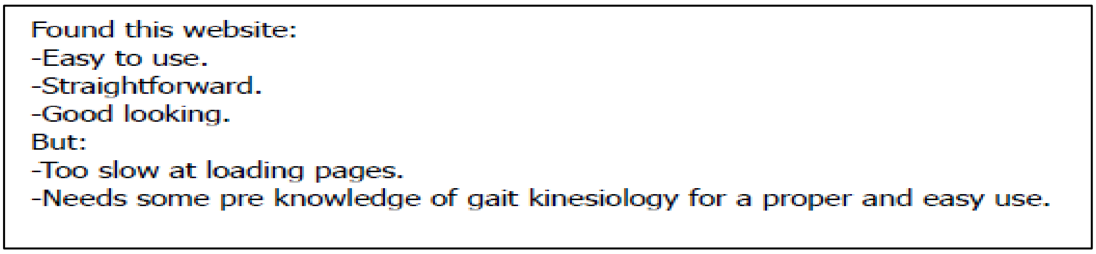
Please provide any comments about this website:



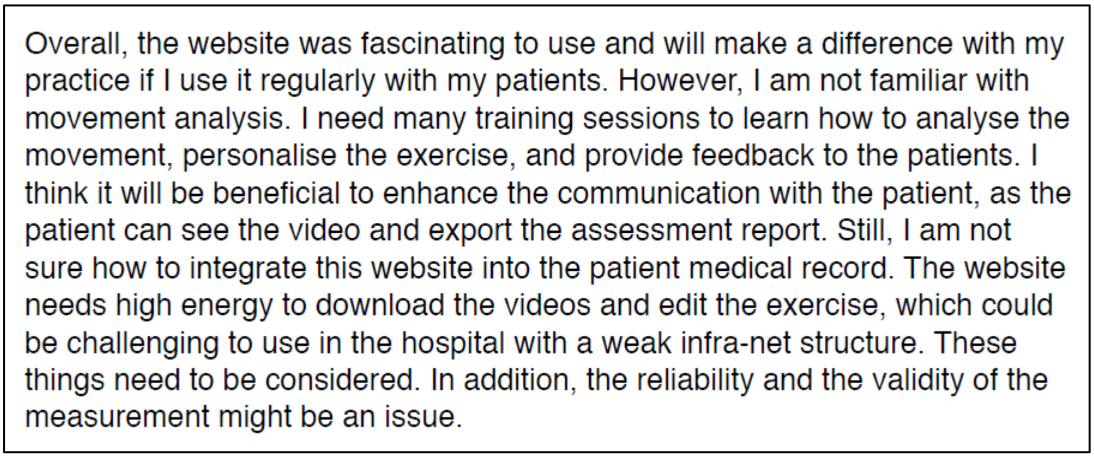
Some adjustments and explanations are needed for a better understanding of the websites. I noticed the laptop is using a lot of energy for using this website also it needs a strong internet for accessing all pages.



- The website was easy to use and all variables were clear.
- I think that labels about exercises and parameters on the top of all pages give clear directions to the target content.
- I find the comparison option between two individuals is highly valuable and I like the differentiation using two colours.
- The brief definitions of all parameters are beneficial but they include some scientific words which may be more understandable to a specialist in biomechanics.
- The graph charts are not as easy to understand as tables.
- Technically, the slow speed of the software is quite frustrating.



Found this website:
-Easy to use.
-Straightforward.
-Good looking.
But:
-Too slow at loading pages.
-Needs some pre knowledge of gait kinesiology for a proper and easy use.



Overall, the website was fascinating to use and will make a difference with my practice if I use it regularly with my patients. However, I am not familiar with movement analysis. I need many training sessions to learn how to analyse the movement, personalise the exercise, and provide feedback to the patients. I think it will be beneficial to enhance the communication with the patient, as the patient can see the video and export the assessment report. Still, I am not sure how to integrate this website into the patient medical record. The website needs high energy to download the videos and edit the exercise, which could be challenging to use in the hospital with a weak infra-net structure. These things need to be considered. In addition, the reliability and the validity of the measurement might be an issue.