Evaluation Of The Acceptability And Usability Of A Digital Biomechanical Biofeedback Toolkit For The Physiotherapy Management Of Chronic Knee Pain

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Abstract

Introduction: Chronic knee pain (CKP) causes considerable burden on peoples' quality of life and everyday activity. For effective care of CKP, novel solutions including digital health interventions are required. While exercises are widely regarded as a key therapeutic approach and biofeedback is considered effective particularly in enhancing patient engagement, both lack objective assessment methods, such as movement analysis, to guide and inform personalised exercise prescriptions in the clinic. Furthermore, adherence to home exercise programmes remains low, and current digital health interventions rely primarily on patient-reported outcome measures (PROMs). Therefore, complementing traditional assessments supplemented with movement analysis in the context of digital health interventions could be an effective strategy to adopt. However, there are still gaps on whether such interventions are acceptable and usable to influence clinical decision making of exercise prescription, engage CKP individuals with their condition management, track progress, and encourage home exercise adherence.

Aim: To evaluate the acceptability and usability of a digital biomechanical biofeedback toolkit (DBBT) for the physiotherapy management of individuals with chronic knee pain. **Objectives:** (1) To explore the acceptability and usability of the DBBT, (2) To observe changes in biomechanical parameters, including kinematics and spatiotemporal measures, before and after the use of the DBBT, (3) To observe perceived changes in PROMs responses over the duration of the study.

Methods: A mixed-methods study was conducted using a pre-post experimental design. The study was ethically approved from Cardiff University ethics committee and twenty-five individuals with CKP were eligible to participate and consented to take part in the study. Inclusion criteria were adults aged 18 years or older with self-reported knee osteoarthritis and activity-related pain, reporting knee pain on most days for at least three months with an average severity of ≥4/10. Exclusion criteria included non-knee musculoskeletal pain, contraindications to exercise, pain due to malignancy, fractures, or inflammatory arthritis, recent knee surgery (within 12 months), recent new treatments (within 12 weeks), concurrent physiotherapy, or previous knee arthroplasty. Participants engaged with the DBBT for a duration of two weeks. The DBBT components are: (1) Xsens wearable sensors to collect gait data

via MVNX Analyze software; (2) MotionCloud, which processed this data and generated gait reports; (3) Kinduct web platform to create participant profiles, deliver personalised exercise programmes, send reminders, and track exercise and PROMs completion; and (4) Kinduct mobile app, used by participants at home to view exercises, receive reminders, log exercises, and submit PROMs. Acceptability was evaluated through semi-structured interviews using the theoretical framework of acceptability (TFA), analysing all seven constructs deductively. Usability was assessed using the system usability scale (SUS) and usage adherence rates of two tasks including logging exercise sessions and submitting PROMs. Supplementary outcomes included kinematics and spatiotemporal parameters, and PROMs including validated measures for pain, disability, and psychological factors as follow, WOMAC, Tampa Scale, PHQ-9, SES6G, and NPRS.

Results: There were (n = 14) male participants and (n = 11) female participants with a mean age of 37 ± (16.03) years. The mean BMI was 26 ± (2.9) kg/m². Acceptability was high, as indicated by thematic analysis findings structured using the TFA. Participants' responses reflected strong alignment with key TFA components including affective attitude, perceived effectiveness, and intervention coherence. These perceptions were shaped by specific DBBT features including personalisation, visual biomechanical biofeedback gait report, reminding system, video demonstrations, and exercise logging and PROMs submission features. Usability was also high with an excellent SUS score (81.2), and high adherence rates for both exercise logging (63%) and PROMs submission (72%). Supplementary kinematic, spatiotemporal, and PROMs data further contextualised these findings, showing participant movement and symptom profiles consistent with similar clinical populations and reinforcing the relevance of the DBBT in home-based rehabilitation settings.

Conclusions: The DBBT was found to be highly acceptable and usable in a mixed-methods evaluation involving individuals with CKP. Participant engagement was shaped by key features including visual biomechanical biofeedback gait report, reminding system, video demonstrations, and exercise logging and PROMs submission features, which aligned with core components of the TFA. Usability was supported by a high SUS score and adherence to both exercise logging and PROMs submission. Supplementary biomechanical and self-reported data contextualised

these findings and confirmed the DBBT's relevance to this population. The DBBT offers a promising, personalised approach to technology-enhanced physiotherapy and warrants further investigation in larger-scale studies. However, the relatively small sample size, limited clinical testing environment, and potential for minor measurement variability in kinematic data collection may limit the generalisability of the findings and should be considered when interpreting the results.

Keywords: Chronic knee pain, digital health, biomechanical biofeedback, wearable sensors, physiotherapy, acceptability, usability, mobile health, gait analysis, exercise prescription.

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List of Abbreviations

(-) Negative.

(+): Positive.

↑: Maximum.

↓: Minimum.

3D: Three Dimensional.

BMI: Body mass index.

CASP: Critical Appraisal Skills Programme.

CKP: Chronic knee pain.

CM: Centimetre.

DBBT: Digital Biomechanical Biofeedback Toolkit.

G: Group.

GC: Gait Cycle.

IMUs: Inertial Measurement Units.

JBI: Joanna Briggs Institute.

KAM: Knee Adduction Moment.

KFA: Knee Flexion Angle.

LH: Lateral Hamstring.

M.S.: Mohammad Subahi.

M/S: Meter per Second.

M: Meter.

Mean ± (SD): Mean and Standard Deviation.

MH: Medial Hamstring.

Min: Minute.

MRC: Medical Research Council.

n: Number.

NPRS: Numerical Pain Rating Scale.

OA: Osteoarthritis.

PAM: Patient Activation Measure.

PCC: Population, Concept, and Context.

PFOA: Patellofemoral Osteoarthritis.

PHQ-9: Patient Health Questionnaire.

PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

PROMs: Patient/participant Reported Outcome Measures.

ROM: Range of motion.

S: Second.

sEMG: Surface Electromyography.

SES6G: The Self-efficacy for managing chronic disease 6-item scale (SES6G).

SUS: System Usability Scale.

TFA: Theoretical and Conceptual Framework of Acceptability.

TIDieR: Template for Intervention Description and Replication.

TSK: Tampa Scale for Kinesiophobia.

VS.: Versus.

WEMWBS: Warwick-Edinburgh Mental Wellbeing Scale.

WOMAC: Western Ontario and McMaster Universities Osteoarthritis Index.

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Finally, words can't describe my feelings while I'm writing this Acknowledgement, so nothing to say better than saying

{وَآخِرُ دَعْوَاهُمْ أَنِ الْحَمْدُ لِلَّهِ رَبِّ الْعَالَمِينَ}

Dedication

To the beloved memory of my grandfather, Al-Shiekh Mohammad bin Darweish Subahi AlSulaimani.

Your belief in me was the key that unlocked my potential. Your support, your wisdom, and the way you treated me with a special kind of love and care, these are the things that shaped me into the person I am today.

Your words, your presence, and your faith in my journey still echo in my heart. You guided me with quiet strength, and your encouragement lit the path that led me to this moment.

This thesis is not just a culmination of years of study; it is a gift to you. I pray that it brings peace to your soul, as your memory brings purpose to mine.

May Allah have mercy on you and grant you the highest place in Jannah.

Dissemination Statement

Parts of this PhD research have been previously disseminated in academic and professional settings. The scoping review protocol developed during the course of this study was formally registered at osf.io/37jka. to ensure transparency and methodological rigor.

An abstract based on the scoping review, now presented as a full chapter in this thesis, was published and presented at **The European Society for Movement Analysis in Adults and Children Conference (ESMAC)**. These preliminary outputs contributed to scholarly discussions and were instrumental in shaping the final version of the chapter and the overall thesis.

All content presented in this thesis is the original work of the author unless otherwise stated, and due credit has been given to all referenced sources. This work adheres to the academic integrity and ethical standards required by Cardiff University and relevant research bodies.

Chapter 1

Introduction

1.1. Background and rationale

Chronic knee pain (CKP) is defined as pain in or around the knee joint that persists for more than three months and represents a significant musculoskeletal health issue globally (Treede et al. 2019). The most common causes include osteoarthritis (OA), overuse syndromes like patellofemoral pain syndrome (PFPS), anterior knee pain, inflammatory disorders such as rheumatoid arthritis (RA), and tendon-related conditions including patellar tendinopathy (Challoumas et al. 2021; Malliaras et al. 2015). CKP not only limits physical activity but also contributes to psychological distress, social isolation, and increased risk of comorbidities such as cardiovascular disease and obesity (Challoumas et al. 2021).

Physiotherapy remains a cornerstone in the management of CKP, with strong evidence supporting the efficacy of therapeutic as they provide pain relief and functional improvements that enhance quality of life for individuals with CKP, particularly knee OA (Lawford et al. 2024), foster muscle strength and joint stability that may delay symptoms progression (Zeng et al. 2021), and offer psychological benefits including reduced anxiety and improved mood that motivate continued physical activity (Svensson et al. 2021). Typically, physiotherapy involves a combination of supervised in-clinic sessions and home-based exercise programmes. However, a critical challenge in achieving optimal outcomes is ensuring patient adherence to prescribed exercises, particularly when patients are required to continue their rehabilitation independently at home (Jack et al. 2010).

1.2. Challenges in home-based physiotherapy and digital health solutions

Low adherence to home exercise programmes is a well-documented barrier to successful physiotherapy outcomes (Yalew et al. 2022). Factors contributing to poor adherence include lack of motivation, uncertainty about correct exercise technique, limited feedback, and insufficient personalisation of exercise regimens (Bassett 2003; Peek et al. 2016). In response, digital health interventions have emerged as

innovative tools to support and enhance physiotherapy delivery. These interventions, which include mobile applications and web-based platforms, offer features such as exercise demonstration, progress tracking, and communication channels with healthcare providers (Merolli et al. 2024).

Despite their promise, most digital health solutions for CKP management are limited in two keyways. First, they predominantly rely on patient-reported outcome measures (PROMs) to monitor progress (Mesa-Castrillon et al. 2024; Rafiq et al. 2021; Nelligan et al. 2021). While PROMs such as pain scores and self-reported function are valuable, they are inherently subjective and may not fully capture changes in movement quality or biomechanics (Collins et al. 2011). Second, many digital exercise programmes are generic, providing standardised exercise programmes rather than personalising interventions to the unique needs and impairments of each patient. This lack of personalisation can reduce engagement, limit effectiveness, and fail to address the specific biomechanical deficits contributing to CKP (Li et al. 2021).

1.3. The need for objective and personalised digital interventions

Personalisation and objective assessment are increasingly recognised as essential components of effective rehabilitation (Pelosi et al. 2024). Advances in wearable sensor technology and digital biomechanics have opened new opportunities for collecting detailed, objective data on movement patterns in real-world settings. Wearable sensors, such as inertial measurement units (IMUs), can capture kinematic and spatiotemporal parameters of gait and other functional movements with high accuracy (Kobsar et al. 2020). This technology enables physiotherapists to move beyond subjective reports and gain deeper insights into patients' movement impairments.

Importantly, wearable sensors can facilitate the delivery of personalised exercise programmes by identifying specific deficits in gait or movement, allowing interventions to be personalised to address these impairments (Zhang et al. 2024). Additionally, the feedback provided by wearable sensors can be shared with patients as biofeedback, promoting greater awareness of movement quality and potentially enhancing motivation and adherence (Argent et al. 2019). Despite these advantages, the integration of wearable sensor technology into routine clinical

practice for CKP management remains limited. Existing digital health interventions have yet to fully leverage the potential of objective biomechanical data and personalised feedback to optimise outcomes for individuals with CKP.

1.4. Development of a digital biomechanical biofeedback toolkit (DBBT)

To address these gaps, this PhD project developed a comprehensive digital biomechanical biofeedback toolkit (DBBT) designed to enhance the physiotherapy management of CKP. The DBBT integrates four key components to provide a seamless, data-driven, and personalised rehabilitation experience:

1. **Xsens wearable sensor technology**: Utilising advanced inertial sensors, the Xsens system collects detailed gait data, capturing kinematic and spatiotemporal parameters through the MVNX Analyze software. This allows for objective assessment of lower limb movement patterns outside of traditional laboratory environments.
2. **MotionCloud online platform**: This web-based platform processes the raw gait data collected by the Xsens sensors and generates comprehensive, user-friendly gait reports. These reports provide physiotherapists and patients with clear visualisations and summaries of movement quality and impairments, which can be used to inform exercise prescription and be shared as a biomechanical biofeedback.
3. **Kinduct digital platform**: Kinduct serves as the central hub for participant management, enabling the creation of individualised profiles that include personalised exercise programmes. The platform also facilitates the scheduling of reminders and allows researchers to track and monitor participants' exercise completion and self-reported outcome submissions.
4. **Kinduct athlete mobile application**: Designed for ease of use in home settings, the mobile app delivers exercise reminders, provides video demonstrations of prescribed exercises, and enables participants to log completed exercises and submit self-reported outcomes such as pain and function scores.

By combining these components, the DBBT aims to address the limitations of existing digital health interventions by providing objective, personalised, and engaging support for individuals with CKP throughout their rehabilitation journey.

1.5. Importance of evaluating acceptability and usability

Before such a toolkit can be widely implemented in clinical practice, it is essential to evaluate its acceptability and usability among users. The Medical Research Council (MRC) framework for developing and evaluating complex health interventions emphasises the importance of assessing these factors during the development phase (Craig et al. 2008). Acceptability refers to how well the intended users perceive the intervention as appropriate, satisfying, and relevant to their needs (Sekhon et al. 2017), while usability focuses on the ease with which users can interact with the toolkit to achieve their goals (Nielsen 1994).

Evaluating acceptability and usability is a critical precursor to feasibility and effectiveness studies, as interventions that are not well-accepted or easy to use are unlikely to be adopted or have meaningful impact in real-world settings. Insights gained from this evaluation can inform further refinement of the DBBT, ensuring that it meets the needs of end-users and is positioned for successful implementation and scale-up. This, the aim of the current study is to evaluate the acceptability and usability of a digital biomechanical biofeedback toolkit (DBBT) for the physiotherapy management of individuals with CKP.

1.6. Research question and objectives

Guided by the above considerations, this PhD project seeks to address the following primary research question:

“Is a digital biomechanical biofeedback toolkit (DBBT) acceptable and usable to individuals with chronic knee pain?”

To answer this question, the study is structured around the following objectives:

1.6.1. Research objectives

(1) To explore the acceptability and usability of the DBBT.

(2) To observe changes in biomechanical parameters, including kinematics and spatiotemporal measures, before and after the use of the DBBT

(3) To observe perceived changes in PROMs responses over the duration of the study.

1.7. Structure of the thesis

This thesis is organised as follows:

- **Chapter 1** Introduction of the thesis.
- **Chapter 2** Integrated background with literature review.
- **Chapter 3** Scoping review.
- **Chapter 4** Synthesis chapter of the literature review and the scoping review.
- **Chapter 5** Methodology chapter.
- **Chapter 6** Results chapter.
- **Chapter 7:** Discussion chapter.
- **Chapter 8:** Conclusion chapter.

In summary, this research aims to bridge the gap between technological innovation and clinical application by evaluating a novel digital biomechanical biofeedback toolkit for the management of CKP. By focusing on acceptability and usability this project seeks to lay the foundation for future feasibility and effectiveness studies, ultimately contributing to more personalised, objective, and effective physiotherapy interventions for individuals living with CKP.

Chapter 2

Integrated Background with Literature Review

2.1. Introduction

This chapter provides a comprehensive review of current research on the management of CKP, with a particular focus on the role of digital health in addressing adherence challenges associated with exercise programmes. It explores emerging exercise-based digital health technologies and identifies key gaps in their implementation, particularly the lack of personalisation and biofeedback. Additionally, the chapter examines biomechanics and gait analysis as potential solutions to these limitations, particularly the role of kinematics in exercise prescription. A central theme of this chapter is the potential of wearable sensor technologies to deliver biomechanical biofeedback. This discussion lays the foundation for the following scoping review chapter, which explores how wearable sensor technology has been utilised to provide such feedback.

The literature review adopts a narrative approach to ensure a coherent and structured flow, focusing on two key areas: (1) the role of digital health in supporting exercise for individuals with CKP, and (2) the impact of CKP on gait, including biomechanics, movement analysis, and feedback mechanisms. To inform this review, a systematic literature search was conducted using the PICO framework (Population, Intervention, Comparator, Outcomes), relevant databases, and key search terms The included studies were critically appraised using the Critical Appraisal Skills Programme (CASP) tool for both quantitative and qualitative research (Appendix 1). As a narrative literature review necessitates background context, key research details are reported to interlink ideas effectively, provide a comprehensive overview of the literature, and establish the context of each study (Ferrari 2015). Lastly, the search strategy has been placed in the appendices for organisational clarity (Appendix 2).

2.2. Chronic knee pain

CKP is defined as pain in or around the knee joint that persists for more than three months and represents a significant musculoskeletal health issue globally (Treede et al. 2019). CKP can result from a range of underlying conditions with diverse pathologies, clinical features, and demographic patterns (Callaghan and Selfe 2007). These include degenerative diseases such as osteoarthritis (OA), overuse syndromes like patellofemoral pain syndrome (PFPS), anterior knee pain, inflammatory disorders such as rheumatoid arthritis (RA), and tendon-related conditions including patellar tendinopathy (Kobayashi et al. 2016; Smith et al. 2018). Despite differing aetiologies, these conditions often produce shared outcomes such as persistent pain, mobility restrictions, and functional limitations, which collectively affect individuals' quality of life and place a substantial burden on healthcare systems (NICE 2022).

Among these, knee OA is the most prevalent cause of CKP in older adults (Langworthy et al. 2024). It is characterised by progressive degeneration of articular cartilage, synovial inflammation, and subchondral bone remodelling and can affect any of the knee's three compartments: medial tibiofemoral, lateral tibiofemoral, and patellofemoral (Lespasio et al. 2017 and Smith et al. 2018). CKP also affects younger individuals, especially those engaged in high levels of physical activity (Rathleff et al. 2019). Additionally, PFPS and tendinopathy are also common in younger population, often linked to biomechanical overload or altered movement patterns (Crossley et al. 2016).

The burden of CKP extends beyond physical symptoms. In the UK, musculoskeletal disorders such as OA and RA are estimated to cost the NHS up to £120 billion over the next decade and are responsible for the loss of approximately 28 million working days annually (Versus Arthritis 2021; NICE 2022). Consultation data from general practices in England show increasing demand for knee-related care beginning from age 45, peaking between 75 and 84 years, and showing higher prevalence in women (Yu et al. 2015). Furthermore, CKP is often accompanied by reduced physical activity, psychological distress, and poor self-management capacity, all of which complicate long-term outcomes (Hurley et al. 2007).

Therefore, it is essential to recognise CKP as a complex and burdensome condition that demands targeted attention. Given the multifactorial nature and rising impact of CKP, especially among ageing and active populations, there is a growing need to improve its management through accessible, effective, and long-term care strategies (Smith et al. 2018; NICE 2022).

2.3. Management of chronic knee pain

Effective management of CKP relies on a multimodal, evidence-based approach that integrates physical rehabilitation, education, and symptom control to address the complex interplay of mechanical, behavioural, and psychological contributors to pain and disability (Bennell et al. 2018; Fernandes et al. 2013; NICE 2022). International guidelines and systematic reviews consistently recommend non-surgical interventions such as therapeutic exercise, weight management, and structured self-management programmes as foundational components of care (Fransen et al. 2015; OARSI 2019). These interventions aim not only to alleviate symptoms but also to improve physical function, foster long-term behavioural change, and prevent clinical deterioration (Bannuru et al. 2019).

Therapeutic exercise is widely recognised as the primary intervention in the conservative physiotherapeutic management of CKP, with robust evidence supporting its efficacy in reducing pain, improving physical function, and enhancing quality of life (Fransen et al. 2015 and Bennell et al. 2018). Programmes that incorporate aerobic, resistance, neuromuscular, and aquatic exercise modalities are consistently recommended in clinical guidelines (NICE 2022 and Fernandes et al. 2013).

With growing attention to the role of exercise in managing CKP, a range of modalities has been explored to maximise patient benefit. These include strength training, cardiovascular conditioning, balance exercises, and mind–body practices such as yoga and Tai Chi, each contributing to improvements in both biomechanical control and psychosocial well-being (OARSI 2019).

Expanding on this, Mo et al. (2023) conducted a systematic review and network meta-analysis involving 39 studies and 2,646 participants, categorising exercise interventions into five groups: aquatic exercise, stationary cycling, resistance training, traditional exercise, and yoga. Their findings demonstrated significant

improvements across a range of patient-reported outcome measures, including the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), the 6-minute walk test (6-MWT), the visual analogue scale (VAS), and the Knee Injury and Osteoarthritis Outcome Score (KOOS), further highlighting the clinical relevance of structured, diverse exercise programmes for individuals with CKP.

The findings in Mo et al. (2023) study highlighted that, despite variability, all five categories were able to improve knee OA in terms of pain relief, joint stiffness, limited knee function, and quality of life. On the other hand, a systematic review and individual participant data meta-analysis by Holden et al. (2023) included a total of 91 studies and a total of (n = 4241) participants. Holden et al. (2023) found that there was an overall small positive effect of exercise therapy on pain levels and physical function compared to non-exercise controls. The researchers questioned this effect in clinical importance, specifically in the medium (6 months) and long terms (12 months). Additionally, Holden et al. (2023) highlighted that those with high pain severity and lower physical function at baseline benefited more from therapeutic exercise compared to those with lower pain levels and better physical function at baseline.

Multiple methodological and analytical differences across both studies could explain the differing findings. Mo et al. (2023) conducted a network meta-analysis to compare different exercise modalities while Holden et al. (2023) performed an individual patient data meta-analysis to investigate patient-specific factors in detail. Direct comparisons become more complex due to the variability in outcome measures since different studies may use unique primary outcome measures or set separate clinical significance thresholds. Holden et al. (2023) demonstrated that exercise outcomes are affected by baseline pain severity levels which emphasises the importance of patient characteristics, unlike Mo et al. (2023) who applied a more precise exercise classification that could inform exercise intervention identification.

Also, the time frame of the analysis shows variation since Holden et al. (2023) examined the clinical importance of short term (12 weeks), medium- and long-term effects while Mo et al. (2023) focused on only short-term outcomes. More, Holden et al. (2023) review findings highlights that the evidence supports the benefits of therapeutic exercises for individuals with knee OA in the short term, which could be

in line to Mo et al (2023) findings. Hence, the clinical meaning of medium and long-term effect of exercise interventions have yet to be conclusively determined.

However, therapeutic exercises remain important for several reasons despite the uncertainties surrounding their long-term effects. Firstly, they provide relief from pain and improvement in physical function, which can enhance the quality of life for individuals with CKP (Lawford et al. 2024). Secondly, engaging in regular therapeutic exercise fosters muscle strength and joint stability, which can contribute to better overall joint health and potentially delay the progression of conditions such as KOA (Zeng et al. 2021). Finally, the psychological benefits associated with exercise, such as reduced anxiety and improved mood, are well-documented and can further motivate patients to maintain an active lifestyle (Hallgren et al. 2021). Therefore, while the duration of therapeutic effects may vary, the short-term and broader benefits of exercise interventions underscore their critical role in the management of CKP (Fransen et al. 2014). Yet, the aim to investigate and achieve more evidence in therapeutic exercises effect on the medium and long terms remain required.

One important factor that could play a major role in identifying the long-term effects of therapeutic exercise is exercise adherence (Ley and Putz 2024). Adherence can be defined as how closely a patient follows their prescribed exercise programme in terms of frequency, intensity, duration, and technique (Bailey et al. 2017). Additionally, the efficacy of exercise interventions has been found to be largely impacted by adherence (Nelson et al. 2022). Nelson et al. (2022) further highlighted that long-term adherence is often poor or untested, particularly when patients transition to unsupervised home-based exercise sessions. Thus, adherence is crucial in the context of physiotherapeutic exercises, as the desired outcomes and achievement of exercise goals are typically realised over time when exercise plans and home-based programmes are followed consistently and correctly (Essery et al. 2017; Peek et al. 2016).

Furthermore, in their review of systematic reviews, Ley and Putz (2024) analysed 19 systematic reviews encompassing 205 trials. The authors identified several techniques that could enhance adherence to physiotherapeutic exercises, including motivational interventions, behaviour change programmes to increase patient self-efficacy, graded activities, booster sessions with physiotherapists, and monitoring

and feedback interventions. However, a study by Peters et al. (2023), which aimed to evaluate traditional methods used to enhance adherence to therapeutic exercise, such as education programmes, coaching, problem-solving support, and resources provisioning, found that these approaches did not consistently achieve desired adherence rates over a long-term duration of 12–18 months. Interestingly, Peters et al. (2023) emphasised that leveraging technology, such as web-based and mobile health platforms, may be optimal for increasing adherence, particularly in home settings. For this, the following section will discuss the use of digital health intervention, mainly exercise-based, with people with CKP.

2.4. Digital health interventions

Recent advancements in digital health technologies have introduced novel opportunities for managing CKP, particularly by promoting exercise and physical activity. A growing body of literature has examined the use of mobile applications and digital platforms to support exercise programmes in CKP populations. This section reviews the current evidence on digital health interventions, focusing on their efficacy, acceptability, and usability. While these concepts are important, it is worth noting that not all included studies explicitly assessed acceptability or usability as formal outcomes, and the degree to which these constructs were measured varied across the evidence base.

Acceptability has been defined as a “multi-faceted construct that reflects the extent to which people delivering or receiving a healthcare intervention consider it to be appropriate, based on anticipated or experiential cognitive and emotional responses to the intervention” (Sekhon et al. 2017.*p4*). Usability refers to the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a given context of use (ISO 2018). Evaluating the acceptability and usability of digital health interventions is particularly important because they directly influence user engagement and the overall success of the intervention (Simblett et al. 2018).

A search strategy was developed (Appendix 2) and a total of 18 studies were identified from the literature search in this area. All the included studies recruited individuals with CKP, with knee OA being the major studied disorder. Additionally, the included studies have used digital health interventions utilising either mobile

applications or digital websites. By the end of this section, Table 1 presents a summary of the key research characteristics of the included studies.

Seven studies (Yamamoto et al. 2022; Joseph et al. 2023; Joseph et al. 2022; Weber et al. 2024; Thiengwittayaporn et al. 2023; Nelligan et al. 2021; and Gell et al. 2024) specifically focused on the delivery of exercise-based interventions through digital platforms in individuals with CKP. Although these studies varied in their aims and outcome measures, they were collectively discussed and critically appraised to explore how digital health interventions have been applied to support exercise engagement within this population.

Yamamoto et al. (2022) recruited 20 individuals with knee OA and utilised a mobile application that provided an unsupervised home exercise programme. The app provided feedback by displaying exercise videos at the top of the screen and allowed participants to observe themselves performing the exercises through the front-facing camera at the bottom of the screen. Participants were evaluated at two timepoints. The outcome measures included pain levels that was assessed via the numerical pain scale. Pain levels were significantly decreased ($p = 0.01$), with a mean ± (standard deviation) of 58 ± (27.3) at baseline and 41.7 ± (30.3) after 12 weeks. Stiffness was also significantly reduced ($p < 0.001$), from 14.4 ± (8.2) to 10.7 ± (6.7).

The researchers attributed these improvements to high adherence, which was monitored through usage tracking (mean adherence rate: 82.4% ± 15.3). However, the feedback mechanism relied on visual self-observation, without supervision or real-time guidance from a specialist. Participants were primarily responsible for monitoring and adjusting their own movements based on what they observed. In digital exercise interventions, the absence of verified or guided feedback may reduce the accuracy of movement execution, potentially limiting outcomes or increasing the risk of maladaptive patterns (Brennan et al. 2020).

Joseph et al. (2023) evaluated a 12-week web-based aerobic exercise programme involving 25 participants with knee OA and 4 with hip OA. The website included several features as follows, an information page outlining recommended OA treatments, a weekly-updated aerobic programme, a page explaining the benefits of exercise, and motivational emails sent weekly. Adherence was relatively high, with 15 participants (51.7%) using the website consistently throughout the 12 weeks.

While there is no universally accepted benchmark for adherence in such interventions, the authors considered this rate to be high. They justified this by noting its comparability to other research and to their earlier findings (Joseph et al. 2022), where the same website's usability was evaluated in a similar population.

Joseph et al. (2022) used the system usability scale (SUS), a widely recognised psychometric instrument that evaluates the perceived usability of technological systems across ten standardised items, measuring effectiveness, efficiency, and user satisfaction (Brooke 1996), and the score was 77.5, indicating good usability (Bangor et al. 2009). A limitation of the intervention in Joseph et al. (2023) was the lack of interactive elements. The programme consisted primarily of static web content and weekly motivational emails, with no mechanisms for feedback or guided exercise supervision, unlike the approach used by Yamamoto et al. (2022), who incorporated interactive features to support engagement and execution.

Weber et al. (2024) assessed the usability and preliminary effectiveness of a mobile application among 32 individuals with OA (n = 20 knee OA, n = 9 hip OA, n = 3 both). The app delivered a 12-week exercise and physical activity education programme, with video demonstrations and a schedule of two to three exercises per day, two to three days per week. Usability was evaluated using SUS, which scored 71.3, reflecting good usability (Bangor et al. 2009). Preliminary outcomes included satisfaction, pain levels, and joint range of motion (ROM). The average satisfaction score was 23.8 out of a maximum of 31, indicating generally positive satisfaction rate (Weber et al. 2024). Pain levels assessed using the knee injury and osteoarthritis outcome Score (KOOS). KOOS scores improved from 62.5 ± (16.8) at baseline to 68.3 ± (16.1) after the intervention.

Additionally, Weber et al. (2024) highlighted that changes in ROM, measured with a goniometer, were modest. For example, knee flexion improved from 125.0 ± (13.4) to 126.8 ± (15.4), and hip flexion from 101.2 ± (17.1) to 115.5 ± (9.0). A notable limitation was the absence of features that provided participants with direct feedback on performance or progress. Without such mechanisms, users may lack the motivation and confidence needed to stay engaged or adjust their behaviour (Simblett et al. 2018). Also, the ROM was measured using a subjective tool (goniometer), which can be prone to inter-rater variability and may lack the precision

required to detect small but clinically meaningful changes in joint mobility (Norkin and White 2016).lastly, the ROM was assessed from prone position limiting the functional assessment of the knee joint in functional tasks like walking, that provide more clinically relevant information about knee function (Boekesteijn et al. 2022)

Across these three studies, a shared limitation was the delivery of generalised exercise programmes that were not personalised to individual needs, such as movement capacity, or functional goals. Personalisation can generally be defined, based on Hornstein et al. (2023), as a purposefully designed variation between individuals in an intervention's therapeutic elements or structure, including the content, order, guidance, and communication of the intervention emphasising that true personalisation targets the individual level rather than broader groups. This lack of personalisation may reduce the intervention's relevance and effectiveness, particularly for individuals with varying degrees of impairment. The research by Davergne et al. (2023) and Zangger et al. (2023) highlighted that personalised exercise-based digital interventions could result in increased engagement and adherence leading to improved clinical outcomes because they better match user needs, abilities and expectations. Furthermore, none of the studies employed objective assessments of movement to guide the exercise prescription process. The absence of such assessments limits the ability to detect functional changes or adapt interventions appropriately, which are factors increasingly recognised as essential in digital rehabilitation (Hulleck et al. 2022).

Thiengwittayaporn et al. (2023) conducted a single-blind randomised controlled trial (RCT) with 82 patients with knee OA to evaluate a mobile application compared to conventional educational handouts for guiding an exercise programme. Participants were randomly assigned to either the mobile application group (G1, n = 42) or the handout group (G2, n = 40). The app delivered information about OA, its symptoms, treatment options, an assessment of condition severity, exercise instructions, and an exercise plan. Outcomes included ROM (measured with a goniometer), KOOS subscales (symptoms, pain, ADL, sports/recreation, QoL), and the knee society score (KSS). After four weeks, G1 showed improved ROM (from 126.3 ± 7.3 to 129.0 ± 6.5), and significant improvements in symptoms ($p = 0.045$), sports/recreational activities ($p < 0.001$), and QoL ($p < 0.001$). Satisfaction was also significantly higher in the app group ($p < 0.001$). However, the study did not incorporate objective

assessment tools or analyse movement quality or compensatory strategies when prescribing exercises. Without such assessment, exercises may not address the specific functional limitations of each patient, potentially reducing long-term effectiveness (Hulleck et al. 2022).

Nelligan et al. (2021) evaluated a web-based strengthening exercise programme with behavioural text reminders in 206 knee OA patients, using an RCT design. Participants were assigned to either the intervention group (G1, n = 103), which received access to a website with OA information and a self-guided exercise programme, or the control group (G2, n = 103), which received OA information only. Outcome measures included WOMAC (pain), KOOS (quality of life), arthritis self-efficacy scale (ASES for self-efficacy), and engagement rates over 24 weeks. The intervention group showed pain reduction (WOMAC: 26.7 ± 11.8 to 16.6 ± 13.0) and quality of life improvements (KOOS: 35.0 ± 18.0 to 49.9 ± 18.5). ASES scores at follow-up averaged 5.6 ± (1.5), with engagement declining from 97% in the first month to 61% in the final month. However, the study did not specify how exercises were selected or whether they were matched to participants' movement profiles. Tailoring exercises to functional status or biomechanical capacity is essential in musculoskeletal rehabilitation to ensure that programmes are both safe and effective (Sacco and Trombini-Souza 2023). Nonetheless, this study highlighted the value of reminder text messages in maintaining engagement, which is a strategy supported in other digital health research (Schwebel et al. 2018).

Rafiq et al. (2021) examined a mobile health application combined with a lower limb rehabilitation protocol of strengthening exercises involving 114 knee OA patients. Participants were randomised into three groups: rehabilitation with app (G1), rehabilitation without app (G2), and control (G3). The app delivered daily care instructions and a set exercise protocol. The outcomes included WOMAC (pain), the timed up and go (TUG) test (mobility), patient-specific functional scale (PSFS: functional activity), and the Katz activity daily living index. Improvements were noted in all groups, with the largest gains in G1. For instance, WOMAC scores improved from 10.63 ± (2.46) to 7.90 ± (2.42), and mobility (TUG) improved from 12.73 ± (3.47) to 9.79 ± (2.39). Despite these results, the application did not allow for personalised exercise prescriptions based on clinical presentation. Nor did it incorporate reminders or feedback on user progress. In digital rehabilitation,

personalisation and feedback are increasingly recognised as critical for fostering sustained engagement and improving exercise performance (Davergne et al. 2023; Brennan et al. 2020).

Collectively, the studies by Thiengwittayaporn et al. (2023), Nelligan et al. (2021), and Rafiq et al. (2021) share several limitations in their digital exercise interventions. In all three, exercises were delivered in a uniform format, without personalisation based on users' movement impairments, goals, or progression. This generalised approach may limit the clinical effectiveness of interventions for heterogeneous CKP populations. Furthermore, the studies either did not use objective measures to inform exercise choice, or prescription (e.g. movement assessments) or used basic tools like goniometers without integrating biomechanical data into clinical decision-making. Lastly, none of the interventions provided dynamic feedback loops to help participants track and adjust their performance, which is an increasingly important element in digital health for self-management and motivation (Simblett et al. 2018).

Moutzouri et al. (2023) evaluated the efficacy of a 6-week web-based rehabilitation programme combined with an outdoor physical activity plan in 44 knee OA patients. The study was conducted as a randomised controlled trial, with participants divided equally between an intervention group (n = 22) and an outdoor activity group (n = 22). Outcome measures included the KOOS physical function subscale and the numerical pain rating scale (NPRS) as patient-reported outcomes, alongside TUG test as a performance-based objective measure. The intervention group showed a significant improvement in KOOS physical function scores, increasing from 28.6 ± (17.9) at baseline to 76.1 ± (14.5) after 12 weeks ($p = 0.001$).

Further, the outdoor activity group also improved, from 32.3 ± (21.8) to 66.9 ± (12.3), but to a lesser extent. There were no significant between-group differences in NPRS scores. However, TUG results favoured the intervention group, with a mean of 7.8 ± (1.0) seconds compared to 9.8 ± (1.9) seconds in the outdoor activity group after 12 weeks. Despite positive outcomes, the study did not implement a personalised rehabilitation plan informed by individual assessments. Exercises were prescribed without first evaluating joint health or functional capacity, an essential step in digital musculoskeletal care to ensure exercises are clinically appropriate (Hulleck et al. 2022). This limitation reduces the potential to optimise outcomes or detect

compensatory movement patterns that may influence pain or functional recovery over time.

Godziuk et al. (2023) evaluated the acceptability and preliminary effectiveness of a web-based digital intervention among 102 patients with knee OA. Of these, 53 participants took part in semi-structured interviews to explore their experiences and perceptions. The intervention included OA-specific content delivered weekly via email, exercise videos with instructional guidance, and access to online video conferencing. Preliminary effectiveness was assessed using the Short Form (36) Health Survey (SF-36) to measure quality of life (QoL) and an arthritis-specific self-efficacy scale targeting pain and function. Overall, participants expressed positive views toward the platform, particularly in relation to the exercise video content. However, a frequently reported drawback was the lack of exercise personalisation. Participants noted that the exercise content was too generic and not tailored to their needs, preferences, or limitations. Quantitative data showed modest improvements in QoL and self-efficacy: the SF-36 score increased from 33.0 ± (21.5) to 39.7 ± (24.0), and the pain score improved from 35.7 ± (18.3) to 40.1 ± (18.8) after 12 weeks.

Gell et al. (2024) conducted a qualitative study to explore the views of 18 physiotherapists and 17 individuals with knee OA regarding the use of mobile applications for prescribed home exercise. Participants interacted with three commercial exercise apps featuring home-based programmes, exercise tracking tools, reminder systems, instructional videos, and pre-loaded exercise libraries. Through interviews, five major themes emerged: accountability, data-driven support, communication enhancement, the duality of technology, and barriers and facilitators.

Patients consistently highlighted that receiving reminders and knowing that clinicians could track their progress improved their sense of accountability and motivation (Gell et al. 2024). Similarly, therapists reported that digital tracking and reminders were useful tools to reinforce adherence. However, participants noted a lack of meaningful feedback on their condition, progress, or treatment adjustments. Patients desired real-time or personalised feedback, while therapists advocated for the inclusion of a chat feature and the ability to upload custom videos to deliver personalised verbal cues. The absence of these features represents a missed opportunity, as evidence

indicates that feedback mechanisms, such as biofeedback or summary data, support user motivation, engagement, and reinforce correct movement patterns in digital health contexts (Giggins et al. 2013 and Brennan et al. 2020).

Additionally, Gell et al. (2024) identified several key facilitators from participants responses that supported the use of mobile exercise applications such as exercise tracking and the potential to reduce reliance on in-person visits. However, participants also reported notable barriers such as complex interface design, limited adaptability for users with different needs or digital skills, and data security concerns. These mixed findings suggest that while mobile applications can promote communication and improve adherence, their long-term success depends on optimising usability and ensuring that features are flexible and responsive to individual preferences. Importantly, participants recommended incorporating biofeedback and objective movement assessments to enhance clarity and support correct exercise execution.

Together, the studies by Godziuk et al. (2023) and Gell et al. (2024) emphasise the value of user engagement, structured content, and clinician involvement. However, both studies also underscore a recurring limitation: the absence of personalised feedback, real-time monitoring, and personalised exercise content. These omissions may restrict the clinical relevance and motivational value of digital exercise interventions. Personalisation and feedback loops are core pillars of effective digital rehabilitation, as they foster greater self-efficacy, enhance adherence, and promote safer, more targeted exercise performance (Davergne et al. 2023)

Teepe et al. (2022) explored pain outcomes following the use of a mobile application among individuals with knee OA. The app offered a structured set of knee OA exercises, and participants received weekly feedback over a 12-week period. Pain was measured using a verbal NPRS (0–10), with findings indicating a reduction from baseline to follow-up. The authors emphasised the role of feedback in enhancing adherence to the exercise programme. However, the application did not include features such as reminders, exercise tracking, or video demonstrations. Additionally, the feedback provided was based solely on subjective pain scores, without integrating objective performance data. Although pain reduction was observed, the improvement was less substantial than in other studies using real-time, performance-

based feedback mechanisms (e.g., Yamamoto et al. 2022). The exclusive use of self-reported outcomes, without objective verification, limits the capacity to detect meaningful functional changes and may reduce the precision of clinical monitoring ((Nielsen et al. 2017 and Cook et al. 2011).

Biebl et al. (2021) evaluated a mobile application developed to support accurate execution of six therapeutic knee OA exercises. The app used the mobile camera to analyse movement and provide real-time audiovisual feedback. Participants stood approximately two metres from the device, and the system delivered corrective cues during exercise performance. The findings demonstrated that the tool successfully guided participants toward correct technique. However, the application focused solely on this feedback function and did not incorporate broader features such as

lised exercise programming, reminders, or progression tracking. These omissions limit the application's overall utility for home-based rehabilitation. Nevertheless, the study importantly illustrates that digital health tools can support safe and accurate exercise execution, an increasingly critical aspect of unsupervised digital rehabilitation for optimising outcomes and reducing risk (Zmerly et al. 2023 and Ramakrishnan et al. 2022). However, the absence of personalisation limits the intervention's ability to fully maximise its therapeutic potential.

Mesa-Castrillon et al. (2024) assessed the effectiveness of a 3-month mobile health intervention for knee OA in a sample of 59 participants. The application offered a personalised exercise and physical activity plan, supported by teleconsultations and real-time video streaming for feedback. Outcome measures included the WOMAC and PSFS, both collected at baseline, 3 months, and 6 months. Results showed improvement in WOMAC scores (from 34.8 ± 17.6 to 23.6 ± 18.7) and in PSFS scores (from 11.5 ± 5.1 to 18.0 ± 6.2). However, the study reported no statistically significant changes between baseline and 6 months. This could be due to the lack of objective baseline assessments to identify functional deficits and guide targeted intervention. Although the intervention involved experienced physiotherapists, it was unclear whether the exercises were adapted over time. The absence of performance-based reassessments and progression plans restricts the intervention's responsiveness to individual recovery trajectories, an essential feature for effective personalisation (Davergne et al. 2023).

These three studies, Teepe et al. (2022), Biebl et al. (2021), and Mesa-Castrillon et al. (2024), underscore important advances in digital rehabilitation for CKP including feedback integration and remote supervision. However, they also highlight persistent limitations. Most notably, all relied heavily on patient-reported outcome measures (PROMs), without incorporating objective functional assessments such as gait analysis or ROM. While PROMs provide valuable insights into symptom experience, they cannot replace the granularity or clinical precision offered by biomechanical data. Furthermore, personalisation was inconsistently applied, and feedback was often limited or not linked to participants movement. Addressing these gaps is vital to improve the safety, adaptability, and long-term value of digital health interventions in musculoskeletal care (Hulleck et al. 2022; Brennan et al. 2020; Zmerly et al. 2023).

Shewchuk et al. (2021) conducted a mixed-methods study using a self-management mobile application with 18 knee OA patients. The application included symptom tracking, activity goal-setting, red flag alerts, and activity suggestions. Over six weeks, the PROMs used focused on quality of life and patient activation. While quality of life showed a modest improvement, from 0.77 ± (0.13) at baseline to 0.67 ± (0.26), only the patient activation measure (PAM-13) score improved significantly (from 80.4 ± 9.1 to 87.9 ± 9.7). Additionally, although 71% found the app user-friendly and 65% deemed it reasonably efficient, the SUS score was 57.8, indicating below-average usability (Bangor et al. 2009). Interviews revealed several limitations: participants could not add notes to their symptom logs; goal-setting was difficult without therapist input; reminders were absent; and the app lacked personalised exercise options and an exercise library. These usability issues could likely have contributed to lower user satisfaction. Importantly, the study relied exclusively on PROMs, without integrating objective measures to support clinical interpretation or guide adjustments.

Furthermore, Pelle et al. (2021) and Stevenson et al. (2024) both evaluated mobile applications for promoting physical activity and self-management in people with knee OA. Pelle et al. (2021) conducted an exploratory study within a larger RCT involving 214 participants. Their app included features such as self-monitoring, goal-setting, and reminder systems. Among the 113 active users who completed goal activities, the mean SUS score was 69.2, suggesting above-average usability (Bangor et al. 2009). The reminder feature was particularly effective in promoting engagement.

However, the exercise routines were not personalised to individual needs. Stevenson et al. (2024), using a mixed-methods design with 38 participants, assessed a different application offering educational content, physical activity guidance, social support functions, and questionnaires. Ten participants provided qualitative feedback, highlighting increased motivation and information access as key benefits. However, usability limitations were also noted, including a lack of personalised exercises, no video demonstrations, and technical issues. The study also measured confidence in self-management using the musculoskeletal health questionnaire (MSK-HQ), which improved after 12 weeks. Step counts were continuously recorded throughout the entire 12-week period and increased from 9102 ± (3514) to 9596 ± (3694) steps. Despite these gains, feedback on physical activity was not used to guide clinical decisions or customise prescriptions.

Together, these two studies reinforce the importance of usability and behavioural support features, such as reminders and social connectivity. However, both also highlight a significant limitation: the absence of exercise personalisation and the failure to integrate feedback into care planning. These limitations weaken the capacity of digital interventions to respond dynamically to user needs. Moreover, like several earlier mentioned studies, Pelle et al. (2021) and Stevenson et al. (2024) relied heavily on PROMs and general activity metrics, without using objective functional data to assess or adapt exercise programmes (Davergne et al. 2023; Uhlrich et al. 2023).

Pila et al. (2023) and Stern et al. (2022) explored the use of digital decision-support websites for surgical planning in OA patients. These platforms generated reports based on PROMs, which were then used to inform discussions about knee or hip replacement. Pila et al. (2023) assessed the acceptability of the reports via qualitative interviews and found that participants generally appreciated receiving feedback on their health. However, they expressed a strong desire for reports that included clearer explanations of the surgical decision-making process and post-operative expectations. Critically, participants wanted to understand how their condition affected their function and movement, an information that was missing due to the report's reliance solely on PROMs. The authors noted that users preferred the inclusion of objective data to validate surgical decisions. Similarly, Stern et al. (2022) identified three key benefits from participant interviews: improved understanding of

one's health status, enhanced communication with clinicians, and increased confidence in decision-making. However, like in Pila et al. (2023), the digital reports were based only on self-reported data, lacking objective clinical or biomechanical insights.

Collectively, Pila et al. (2023) and Stern et al. (2022) demonstrate that digital tools can improve patient engagement and clinician–patient communication in surgical decision-making. Nonetheless, both studies underscore a critical limitation: the absence of objective assessments. PROMs, while valuable, do not fully capture functional impairment or movement-related risk factors that are central to surgical appropriateness and planning. The inclusion of functional tests or movement-based metrics could enhance the accuracy and clinical utility of such digital systems (Hulleck et al. 2022 and Zmerly et al. 2023)

In conclusion, this section reviewed 18 studies examining how digital health interventions have been utilised to deliver exercise programmes for individuals with CKP. The evidence demonstrates that mobile and web-based platforms can improve access to care, encourage self-management, and foster adherence through features like reminders, educational content, and remote support. In several cases, these tools were linked to improvements in pain, physical function, and quality of life. However, a recurring shortcoming was the delivery of standardised, non-personalised exercises that did not reflect users' specific functional needs or movement limitations. Additionally, most studies relied heavily on self-reported outcomes, with minimal use of objective measures to guide or evaluate intervention effectiveness. While some systems incorporated feedback, it was rarely linked to real-time performance or biomechanics. These limitations indicate that, despite their potential, digital interventions must evolve toward more personalised and data-informed approaches.

Notably, one way to achieve this personalisation is through the integration of objective assessments of joint biomechanics in the context of developing exercise-based digital health interventions, which can be particularly valuable in conditions such as CKP (Zmerly et al. 2023). These assessments can provide critical insight into movement impairments, enabling more targeted and responsive exercise prescriptions. Accordingly, the following section will explore biomechanical aspects of

CKP in the context of gait analysis, as gait is a fundamental human movement and a crucial tool for clinical assessment and rehabilitation planning.

Table 1 Summary of digital health interventions studies

Author(s) / year	Aim(s)	Design	Sample size	Intervention	Technology features	Outcome measures	Findings
Yamamoto et al. (2022)	To assess exercise adherence rates in patients with KOA. to determine the effect of home exercise using this application and the factors for its continuation using outcome measures.	Small-scale, open-label, single-arm pilot study – using pre and post testing. Quantitative	(n = 20) KOA patients.	Mobile application (LongLifeSupport)	Unsupervised home exercise programme. It has 2 displays: (a) upper display that has exercise videos. (b) lower display that has participant's own body using a built-in camera in the mobile device for real-time feedback.	Adherence rate: the percentage of the total number of completed exercise dates/(total number of exercise days {84} X100. Satisfaction: using a questionnaire post-test. VAS	The mean and SD of the adherence to using the app was 82.4 (15.3). The pain in VAS was significantly reduced pre-test vs post-test (pre= 58 (27.3) post = 41.7(30.3) with p= 0.01 Pain and stiffness were significantly reduced pre = 14.4(8.2) vs post 10.7(6.7) and p= <0.001 Overall high adherence and satisfaction rates.
Joseph et al. (2023)	To describe adherence to a 12-week web-	Single-are feasibility study.	(n = 29) patients. (n= 4) with hip	Web-based (AktiWeb) aerobic	The website provides the following:	Adherence rate was measured the number of	Half of the participants (n = 15, 51.7%) adhered to the digital

	based aerobic exercise programme. to identify barriers for exercising in patients with hip or knee osteoarthritis.	Quantitative	OA. (n = 25) with knee OA.	exercise programme.	recommended core treatment for OA. Exercise programme. Benefits of exercise. Weekly reminders via email.	completed exercise diary.	exercise programme from home. The most common reasons for not adhering to the exercise programme was sickness followed by joint pain.
Joseph et al. (2022)	To explore the feasibility of a web-based exercise programme delivered by a patient organisation to patients with hip and/or knee OA.	Pre-post single-arm feasibility study. Quantitative.	(n = 26) knee OA. (n = 4) hip OA.	Web-based (AktiWeb) aerobic exercise programme.	The website provides the following: aerobic exercise programme. recommended core treatment for OA. Exercise programme. Benefits of exercise. Weekly reminders via email	Website usability using SUS. Satisfaction (5-point Likert scale) by asking participants about the level of exercises (too easy, just right, too hard). Comprehensibility (5-point Likert scale) by asking about the exercise programme was	SUS = 77.5 IQR. VO2peak has increased from 25.05 (5.93) to 26.88 (6.79). 86% of the participant were satisfied using the website indicating that the exercise levels were 'just right'. EQ-5D-5L from 0.79 (0.14) to 0.85 (0.11). VAS from 61.9 (15.1) to 70.5 (18.3). Self-efficacy pain: from 57.4 (13.6) to 56.5

						easy or not to comprehend. Cardiorespiratory fitness by testing the (VO2peak) on a treadmill. Joint-related disability by KOOS. Health-related QoL by EQ-5D-5L. Pain using VAS. Self-efficacy using the Norwegian Arthritis Self-efficacy Scale (ASES).	(12.2). Symptoms: from 54.6 (10.9) to 58.1 (-14.6). Overall, was found to be feasible, acceptable and safe in patients with hip and knee OA
Shewchuk et al. (2021).	To assess the overall usability and quality of the mobile application. Ability to improve patient self-management behaviour	Mixed methods Quantitative: questionnaire surveys. Qualitative: Semi-structured	(n = 18) Knee OA patients	Self-management mobile application	Symptoms tracking. Goals. Activities. Red flags.	Quality of life using European Quality-of-Life 5-Dimension 5- level questionnaire (EQ-5D-L5). Preference-based measures for	EQ-5D-L5: changed from mean = 0.77(0.13) to 0.67(0.26), which shows an improvement in QoL. PAM was significantly changed between the

	Effectiveness in improving QoL.	interviews.				describing and evaluating health covering mobility, self-care, usual activities, pain or discomfort, and anxiety or depression). Patient activation measure (PAM-10) used for patient knowledge, skills, and confidence towards their own health. PAM-13 used for assessing patients activation in relation to their engagement in self-management of their disease. Usability using SUS	two timepoint in which mean was = 80.4(9.1) to 87.9(9.7), (P=.01) App quality and usability: 53% reported the app facilitated appropriate navigation. 65% reported reasonably efficient. 71% reported used friendly. 88% indicated the app was nor confusing. 88% reported that the app offered appropriate graphs. 77% indicated that the app displayed correct and relevant information about their chronic condition. SUS score = 57.8, indicating

							marginal acceptability and usability. The qualitative part (refer to table 3 in the study).
Weber et al. (2024)	To assess the usability of the app-based Join 2Move programme for people with hip and/or knee OA. preliminary effectiveness of the programme on pain and physical functioning over twelve weeks was investigated.	Two-armed assessor-blinded, RC pilot study. Quantitative	(n = 60) Knee and hip OA. (n = 20) knee OA (n = 9) hip OA (n = 3) both. (n= 32) included in the usability and preliminary effectiveness. (n = 28) included only in the preliminary effectiveness.	Join2Move mobile application	12-week exercise programme. Physical activity and education programme. For exercises, two to three videos for two to three exercise days per week. The exercises videos change every week. The exercises were ready built in based on NEMEX programme that focuses on (core	Usability by SUS. Satisfaction o – 10 scale on how satisfied you are I general with the app. Hip and knee ROM	SUS = 71.3. Satisfaction = 23.8 / 32 Koos pain as follows, Baseline intervention: 62.5(16.8) After 12 weeks of use: 68.3(16.1) showing an improvement. Baseline: knee flexion/extension = 125.0(13.4)/0.3(5.7) Knee flexion/extension after 12 weeks: 126.8(15.4)/-3.5(5.5). showing an improvement.

					stability, postural function, postural orientation, lower extremity muscle strengthening, and functional exercises) aiming to reduce pain and improve function.		Baseline hip flexion/extension: 101.2(17.1)/16.5(6.7) Hip flexion/extension after 12 weeks: 115.5(9.0)/17.1(6.2). Baseline hip abduction: 33.0(11.6) Hip abduction after 12 weeks: 32.9(3.3).
Rafiq et al. (2021)	To investigate the effectiveness of the lower limb rehabilitation protocol (LLRP) combined with mobile health (mHealth) applications on knee pain, mobility, functional activity and activities of	Single-blind RCT Quantitative	(n = 114) in total with knee OA. G1 (n = 38) rehabilitation group with mHealth. G2 (n = 38) rehabilitation group without mHealth. G3 (n = 38) control group.	Mobile application	Mobile app that offers lower limb rehabilitation protocol (LLRP) + Instruction of daily care (IDC).	WOMAC for knee pain symptoms. Timed up and go (TUG) for mobility assessment. Patient-Specific Functional Scale (PSFS) for functional activity measurement. The Katz Index of independence in ADL for ADL	Baseline mean and SD. WOMAC: G1/ 10.63(2.46) G2/ 9.10(2.32) G3/ 9.26(2.62). TUG score: G1/ 12.73(3.47) G2/ 10.48(2.08) G3/ 10.87(2.17) Katz ADL: G1/ 3.89(1.42) G2/ 4.26(0.97) G3/ 4.21(0.66) PSFS: G1/ 3.89(1.42) G2/

	daily living (ADL) among knee osteoarthritis (OA) patients who were overweight and obese.					assessment.	4.61(0.87) G3/ 4.21 (0.66) Post 3-months of using the mobile application: WOMAC: G1/ 7.90(2.42) G2/ 7.67(2.36) G3/ 8.87(2.80) TUG score: G1/ 9.79(2.39) G2/ 9.58(2.03) G3/ 10.75(2.23) Katz ADL: G1/ 5.15(0.88) G2/ 4.65(0.78) G3/ 4.34(0.65) PSFS: G1/ 7.21(1.10) G2/ 5.62(1.15) G3/ 4.65(1.39) Overall, patients who were assigned to the RGw-mHealth had signifcantly less pain, faster mobility, better functional activity, and better ADL scores

							over a 3-month period than patients in the RGwomHealth and CG
Thiengwittayaporn et al. (2023)	To evaluate if the use of this mobile app could improve the accuracy of rehabilitation of knee OA patients, compared to conventional educational handouts. to compare the clinical outcomes between mobile app use and conventional educational handouts use in knee OA patients.	Single-blind RCT Quantitative	(n = 82) knee OA G1 (n = 42) mobile application group G2 (n = 40) handout group	Mobile application 'Love your knee'	Mobile app that provides basic knowledge of the disease and the symptoms. Available treatment options. Personalised assessment of the stage of severity. Appropriate exercise instruction.	Patient ability to perform three prescribed exercises. Knee ROM vis goniometer. KOOS for pain and symptoms, ADL, sport and recreational activities, and QoL. KSS for satisfaction	G1: Pretest vs after 4 weeks ROM: 126.3±7.3 vs. 129.0±6.5 KOOS: Symptoms (sig 0.045)/ 67.3±13.3 vs. 70.7±11.0 Pain/ 72.0±6.8 vs.73.3±7.2 ADL/ 71.6±9.0 vs. 80.4±9.8 Sports and recreational activities (sig <0.001)/ 70.5±5.2 vs 80.9±9.0 QoL (sig <0.001) 69.5±6.2 vs. 79.6±10.7 KSS: Satisfaction (sig. <0.001)/ 23.0±3.0 vs. 25.2±0.8 Functional activity score/

							56.3±3.5 vs. 59.5±5.2 supports the hypothesis that the developed mobile app is an effective way to deliver rehabilitation education and instruction to knee OA patients. The results show that OA patients using this app were able to exercise correctly and enjoyed usage their exercise regimen with significant improvement of symptom progression as indicated by KSS and KOOS category scores. Thus, the use of our mobile app for short-term disease

							maintenance and treatment of OA benefits patients and represents a potential approach for long-term rehabilitation
Pelle et al. (2021)	To document the use and usability of the dr. Bart app and to examine intensity of use of the app and its relation with HCU and clinical outcomes.	Exploratory design as part of an RCT Quantitative	(n =214) knee OA	Mobile application 'Dr.Bart'	Self-management. Engage knee/hip OA patient with their treatment. Utilising Fogg model for behavioural changes and motivation. Self-monitoring. Send reminders. Sets short term goals.	Usability via SUS. Use through quantifying	SUS after 6 months: People who logged in but no activity (n = 20) vs. people who were active but they chose one goal only (n = 38) vs. people who were active with completing multiple goals (n= 113): 51.3 (15.5) (N = 9) vs. 52.0 (16.2) (N = 10) vs. 69.2 (16.9) (N = 63). In total, participants logged in 7006 times, chose 1062 goals, completed 884 unique

							goals and completed 9229 goals over the 26 weeks, Among the participants, 171 (79.9%) were active with logins, 151 (70.6%) were active with choosing goals and 113 (52.8%) were active with completing goals. The remaining 20.1% of participants did not log in to the app over the course of the study
Stevenson et al. (2024)	To assess the usability of the iKOALA intervention over a 12-week duration and to assess its impact on indices of	Mixed methods	(n = 38) knee OA	Mobile application 'iKOALA'	A mobile application that offers: Personalised PA guidance, which is done through answering questions that	MSK-HQ for chronic pain and symptoms. Acute symptoms questionnaire for level of confidence, fatigue, pain, sleep quality, and ability	Quantitative: MSK-HQ/ a significant change (p=<0.001) from 32 points to 40 points. Significant change in the level of confidence (p=<0.001) from 2 to

	musculoskeletal health, symptoms, and PA in a broad range of individuals with diagnosed knee KOA.				detect their PA levels and preference and provides them with a plan of activities. Education library. Social support where they can have a chat forum and connect to other iKOALA users.	to walk. Use via the actual use of the mobile app measured by the level of activities. Semi structured interviews to assess the usability, experience on using the app, features, potential use.	4 point out of 4. Significant change in the symptoms like pain, fatigue, and ability to walk (p=>0.001) No of steps in actual use show that ability to walk increased from mean 9102±3514 to 9596±3694 after 12 weeks. Qualitative: 10 participant took part in the interview: Advantages/ benefits = motivation. + features like having the needed relevant information in accessible in the app. Disadvantages/ technical issue and lack of exercise

							personalisation like being able to create own specific activities.
Stern et al. (2022)	To explored patients' perspectives on the benefts of receiving feedback on PROMs in the context of a web-based personalised decision report to guide care for their hip or knee osteoarthritis	Qualitative descriptive interview	(n = 24) hip and knee OA (n = 13) hip OA (n = 11) knee OA	Web-based	Websites to show personalised patient reported outcome measures in a form of a report	Patients perspectives	Identified three major themes and subthemes: Theme 1: Providing Information About My Health Status Subthemes: Teaching something new. Confrming what know. Providing frame of reference Theme 2: Fostering Communication Between Patient and Surgeon Subthemes: Setting expectations Asking and answering questions Facilitating shared understanding Theme 3: Building My Confdence and Trust

							Subthemes: Gaining confdence regarding treatment outcomes Facilitating or afrming treatment decision Increasing trust in surgeon Overall, Patients described actual and hypothetical benefts of receiving feedback on PROMs in the context of a personalised web-based decision report for THA/TKA, including for those who had already decided to undergo surgery before seeing the surgeon. Specifcally, they reported benefts

							related to information, communication, and confdence, which they positioned within a broader lens of patient-centered care.
Nelligan et al. (2021)	To evaluate the effects of a self-directed web-based strengthening exercise and physical activity programme supported by automated behaviour-change text messages on knee pain and function for people with knee OA.	RCT Quantitative	(n = 206) knee OA Baseline/ G1 (n = 103) intervention group. G2 (n = 103) control group. Follow-up/ G1 (n = 91) intervention group. G2 (n = 92) control group.	Web-based intervention	A website that provides a prescribed strengthening exercise programme with behaviour-change text messages to improve adherence.	Intervention group: Access for a website that provides information on OA and self-directed strengthening exercise programme. Control group: Access to website that provide the OA information only. WOMAC for knee pain. KOOS for pain. KOOS for sport and	Mean and SD – G1 vs. G2 WOMAC: Baseline/ 26.7 (11.8) vs. 25.0 (12.2) Follow-up (24 weeks)/ 16.6 (13.0) vs. 20.7 (13.9) KOOS pain: Baseline/ 50.8 (16.0) vs. 53.1 (14.6) Follow-up (24 weeks)/ 69.1 (17.0) vs. 60.5 (19.1) KOOS sport: Baseline/ 31.7 (19.2) vs. 30.0 (21.5) Follow-up (24 weeks)/ 47.7 (23.0) vs. 39.6 (26.4) KOOS QoL: Baseline/ 35.0 (18.0)

						recreation. KOOS for QoL ASES for self-efficacy and satisfaction (out of 7 – higher no. indicates better satisfaction). Engagement by the percentage of the participants who used the website	vs. 34.3 (15.7) Follow-up (24 weeks)/ 49.9 (18.5) vs. 43.3 (21.4) ASES (SEE): Baseline/ 60.6 (21.5) vs. 58.8 (18.6) Engagement: website access was 97% in the first month and 61% in the final month Follow-up (24 weeks)/ 55.4 (22.7) vs. 52.7 (20.0) ASES (satisfaction - only on follow-up): 5.6 (1.5) 4.4 (1.7) out of 7
Moutzouri et al. (2023)	To compare the efficacy of a 6-week web-based rehabilitation programme enhanced with outdoor	2-arm prospective randomised controlled trial	(n = 44) knee OA. G1: BWR-OPA: Blended web-based rehabilitation-outdoor	Website: Blended web-based rehabilitation-outdoor physical activity	A website that provides a prescribed plan of a rehabilitation programme and an outdoor physical activity.	Patient reported: KOOS for physical function Numerical pain rating scale (NPRS) for average knee pain. Objective	Sig differences between the groups in the performance-based objective measures: Increase of 30% in the intervention group vs.

	structured PA and advice to self-manage pain and physical function in KOA patients compared to an outdoor PA programme alone; secondarily, maintenance of the outcomes at mid-term (3-month follow-up period) is examined.		physical activity: (n = 22). G2: outdoor physical activity (n = 22)			outcomes like TUG and sit to stand. TAMPA for psychological aspects.	the study group (p<0.005). No sig in the patient reported outcome measures (such as pain) 12-weeks. G1 vs G2 KOOS physical function 'sig p= 0.001': Baseline: 28.6 (17.9) vs. 32.3(21.8) 12 weeks: 76.1 (14.5) vs. 66.9 (12.3) NPRS Baseline: 5.5 (0.8) vs. 5.8 (0.9) 12 weeks: 2.4 (1.3) vs. 3.2 (1.1) TUG test (s) 'sig p=0.001': Baseline: 11.1 (1.4) vs 11.2 (1.9) 12 weeks: 7.8 (1.0) vs 9.8 (1.9)
Godziuk et al (2023)	To evaluate the acceptability and preliminary	Mixed methods.	(n = 102) KOA (n = 53) acceptability	Web-based digital intervention	OA specific content sent by email every week.	Acceptability by qualitative interviews.	Acceptability: Positive perspectives. Themes: (1) tailored

	effectiveness of a 12-week digital nutrition, exercise, and mindfulness self-care intervention for adults with advanced knee OA waiting for an orthopaedic consult.		evaluation.	My Viva plan	Exercise videos and instructions. Free attendance online 'ask the expert's 30 minutes weekly videoconference.	Preliminary effectiveness: Change in QoL, well-being, mindfulness, and self-efficacy score. _ baseline vs. 12 weeks Health related QoL via 36-Item Short Form Health Survey (SF-36) (0 – 100). Well-being was determined using the Warwick-Edinburgh Mental Wellbeing Scale (WEMWBS) (14 – 60). Mindfulness via Mindfulness Questionnaire (FFMQ) Arthritis-specific self-	and reliable information (2) preferences for online or offline content. Engagement with the resources was both positively and negatively influenced by intervention-level design and delivery factors. the majority of participant responses identified positively with the exercise videos. personalisation to knee OA and the body size and age of the person demonstrating exercises was relatable, making patients more

						efficacy regarding pain, function, and other symptoms was assessed with the Arthritis Efficacy Scale (score range of 1–10 for each domain)	comfortable engaging with the exercises. that when tailoring wasn't perceived by patients, there was less engagement with resources. Preliminary effectiveness: Baseline vs 12-weeks: SF-36: Physical functioning 33.0 (21.5) vs. 39.7 (24.0) Pain 35.7 (18.3) vs. 40.1 (18.8) Warwick Mental Well-being 50.3 (10.1)vs. 50.1 (9.6) Arthritis Self-E□cacy Scale Pain 5.4 (2.1) 5.5 (2.2) Function 6.9 (1.8) 7.1 (1.9) Overall, preliminary effectiveness in

							improving self-efficacy for chronic disease management, and aspects of quality of life related to pain and physical functioning.
Gell et al. (2024)	Examine physical therapists and knee OA patients' perspectives on mobile apps for prescribed home exercises.	Qualitative focused group. Semi-structured interviews.	N=18 PTS N=17 individuals with knee OA	Three commercial mobile apps	For home exercise programmes Tracking option Reminder system Video demonstration Pre-made exercise library	Usability Functionality Exercise completion	Qualitative: Theme1: Accountability 1. through reminders and tracker/ enhance accountability for home exercise completion especially through the reminders. 2. Ability to record exercise completion 3. Knowledge that their PTs would see their exercise completion Theme2: Data-driven Both PTs and patients found sharing data

							about exercise completion, ease and difficulty of exercises, reasons for not completing the exercises, and progression for excises completion were beneficial. Patients preferred adding contextual feedback that could inform of treatment changes. Theme3: Communication boost Patients liked having a chat feature embedded in the app. Enhancement of the interaction between the PTs and the patients. PTs thought apps with features for

							therapists to create their own videos would enhance communication of tailored verbal cues for posture or moments. Theme4: Duality of technology the easy management of using technology by the patients especially with video instructions and reminder features were the most reported feature by both physio and patients Theme5: Barrier and facilitators
Teepe et al. (2022)	Explores the clinical outcomes of Vivira (hereafter	Incomplete matched block design	Total of 517 participants KOA	Mobile application 'Vivira 'Conformité	It consists of a series of specific exercises that include a	Baseline vs post 12-weeks Self-reported pain scores:	(Initial pain score assessed with the verbal-numerical rating scale (VNRS)

	referred to as “programme”), a smartphone-based programme for unspecific and degenerative pain in the back, hip, and knee before it received regulatory approval for use in the German statutory health insurance system			‘Européenne (CE)’	multidimensional progression module. In brief, participants were guided through a pain and functional assessment at baseline and were prompted to provide multiloop feedback (ie, after each exercise, as well as on a weekly and monthly basis) as to whether they could complete the individual exercises presented and whether these exercises caused any complaints. If		>0/10) 2.97(1.91) vs. 1.95 (1.18)

					a complaint, primarily any pain sensation, was reported, the progression module was paused, and the intensity of the exercise programme was reassessed. Overall pain score assessments were collected every week, and a follow-up functional assessment was prompted every month.		
Biebl et al. (2021)	To evaluate the ability of Motion Coach to detect	Prospective cohort study.	(n = 24) knee OA	Mobile application 'Motion Coach	A mobile app that aims to correct the exercises from	WOMAC.	Total score 65 (43) Pain 16 (11) Stiffness 7 (5) Physical function

	and correct form during physiotherapeutic exercises in patients with osteoarthritis.			app’	home by providing personalised feedback on how to perform the exercise. (6 selected exercises) – Hip extension bent leg Knee flexion (leg curl) Strengthening hip extensors Strengthen hip abductors Strain front of thigh Elongation of the hip flexors correction of osteoarthritis-specific exercises, Motion Coach provides instructions		42 (31) This finding was valid for all investigated exercises and subgroup analysis. These findings validate the ability of Motion Coach to detect form during exercise and provide audiovisual feedback to users with preexisting musculoskeletal conditions.

					visually through an iPad's screen and acoustically via headphones to the participants. How: e audiovisual feedback on exercise form in real time, Motion Coach uses the camera stream of a user's mobile device and artificial intelligence–based image processing. Users place their device on the ground approximately 2 meters away, tilted slightly so they can be seen in the		

					frame of view of the camera		
Pila et al (2023)	Investigate patients' acceptability of a personalised web-based decision report for total knee or hip replacement and identifies opportunities to refine the report.	Qualitative interviews.	(n = 25) knee or hip OA. (n = 13) hip (n = 11) knee	Website	Patients' responses to generate personalised PRO (patient reported outcomes)-based decision repost. SO basically, the self-reported outcomes were completed by patients digitally on the website, which provides a receipt of decision report that is visual feedback.	Acceptability	Themes: Content of report 'whole package' as it tells patients the surgery decision and what would happen after the surgery. Patients wanted to know how their condition is affecting their movement when physical function report was presented, which lacks. Also, patients said the number (the pain score) is subjective and lacks objective supportive objective measure. A patient said: next to the left

							knee pain, I saw 69. Is there a reason it is not an 89 or 49? I mean there must be, but what is it? How precise is this supposed to be? Presentation of the data on the report It was easy to read but they said it lacks self-explanatory and it needs a visiualise option PRO. Engagement They highlighted that they increased the engagement in communication with the surgeons.
Mesa-Castrillon et al. (2024)	To evaluate the effectiveness of a three-month	A parallel, two-group, pragmatic,	(n = 59) knee OA	Mobile application 'PhysiApp'	The exercise programme was designed	Self-reported questionnaires. PSFS WOMAC	PSFS Ehealth vs usual care: Baseline: 11.5 (5.1) vs. 11.8

	physiotherapist-delivered eHealth physical activity programme compared with usual care to improve function in adults with low back pain or knee osteoarthritis in rural Australia	superiority, randomised controlled trial			individually and tailored according to participants' preferences, participants' individual goals (specific, measurable, achievable, realistic or relevant, and timed) The eHealth teleconsultation included the video call features of the PhysiApp software, with examples of exercises streamed while the participant performed	Pain and Self-efficacy questionnaire	(5.9). After 6 months: 18.0 (6.2) vs. 14.0 (5.8) WOMAC: Baseline: 34.8 (17.6) vs 34.2 (20.9) After 6 months: 23.6 (18.7) vs. 29.3 (21.2) QoL: Baseline 48.1 (14.9) vs 47.4 (14.5) After 6 months: 61.7 (16.7) vs 56.6 (17.4) Changes were not sig. In conclusion, a three-month physiotherapist-delivered eHealth physical activity and exercise intervention is effective and provides clinically meaningful improvements in physical function

					exercises in real time and with verbal consent obtained before the participant attempted the exercise		compared to usual care for patients with musculoskeletal conditions residing in rural communities. The eHealth intervention appears to be more effective for people with a primary complaint of low back pain than for those with knee osteoarthritis, although this should be further evaluated in future studies. However, to a lesser extent, the eHealth intervention was also effective in reducing disability and improving quality of life, but it was not

							likely to improve pain, the mental component of quality of life, coping skills, and moderate–vigorous physical activity participation. These findings support using real-time teleconsultations consisting of physical activity planning and tailored resistance training programmes delivered through online platforms, such as Physitrack, to improve function for those living with chronic musculoskeletal pain with limited access to care in rural areas.

2.5. Biomechanics of chronic knee pain

In relation to CKP, understanding the biomechanics of joints is an important factor in its management (OARSI 2013). Biomechanics can be defined as “the study of the structure and function of biological systems by means of the methods of mechanics” (Hatze 1974. *p189*). Moreover, a study by Andriacchi et al. (2013) demonstrated that applying biomechanical principles in knee-related conditions can influence joint health and support better clinical outcomes. While their research focused on OA, the underlying concepts are relevant to the broader CKP population. Specifically, the authors identified that biomechanical markers, and functional biomechanics can serve to (1) detect changes in condition severity and (2) evaluate the impact of rehabilitation interventions, such as exercise therapy, in an objective manner. Therefore, understanding the biomechanics of functional activities like walking in people with CKP may play an important role in optimising treatment and improving daily function.

Biomechanical analysis typically involves four key parameters: kinematics, kinetics, spatiotemporal measures, and muscle activity. Among these, kinematics and kinetics are the primary components. Kinematics refers to the analysis of joint angles, body segment movements, ROM, and orientation without considering the forces involved. In contrast, kinetics focuses on the mechanical forces and joint moments that drive movement (Song et al. 2023). Muscle activity analysis examines muscle performance by assessing the electrical signals produced during muscle contractions (Merletti and Farina 2016). Lastly, spatiotemporal parameters capture the timing and distance-related aspects of gait, including walking speed, stride and step length, cadence, and the duration of each gait phase (Hollman et al. 2011).

Further, when designing exercise-based interventions using gait analysis, selecting the most appropriate biomechanical parameter is a critical step. Different biomechanical parameters offer distinct insights into movement patterns, joint stress, and neuromuscular performance (Koldenhoven et al. 2020; Farrell et al. 2020). The choice depends on the clinical goals and target population. For instance, spatiotemporal parameters have proven especially useful in stroke rehabilitation. Farrell et al. (2020) found that aerobic exercise led to improved step length asymmetry, which moderately correlated with increased gait speed. This highlights how specific parameters can illuminate progress in particular groups.

Focusing on a single parameter also allows for a streamlined, practical method to evaluate the effects of exercise. Koldenhoven et al. (2020) demonstrated this by using cadence and contact time to assess intervention effectiveness in runners with lower leg pain. Such targeted approaches reduce data overload and facilitate meaningful clinical interpretations. Also, attempting to analyse all parameters simultaneously may create confusion and dilute the practical value of the findings especially in busy clinical settings with limited time and resources (Mohan et al. 2022). Hence, identifying the most informative parameter to support personalised exercise prescription for individuals with CKP is important. This approach aligns with the latest calls in rehabilitation science for data-driven, individualised care (Abedi 2024; NICE 2024).

Moreover, biomechanical assessment is crucial for personalising exercise programmes, enhancing results across various groups (Zhang et al. 2024). Previous studies showed that some exercise programmes yield limited positive outcomes for individuals with CKP (Ferber et al. 2015; Kobsar et al. 2015). The research by Kobsar et al. (2015) was on individuals with knee OA. The researchers found that many participants did not respond well to hip strengthening exercises. This study underscored the importance of pre-intervention kinematic evaluations to predict individual exercise responses, noting that neglecting personal factors like hip kinematics and patient-reported outcomes can hinder programme effectiveness. As a result, such programmes may fail to achieve meaningful improvements in function or pain relief for CKP patients.

Ferber et al. (2015), on the other hand, suggested that standard exercise programmes often overlook individual biomechanical needs, particularly in managing patellofemoral pain syndrome. They emphasised that without a personalised approach tailored to specific biomechanics and movement patterns, success is unlikely. Their study on athletic runners revealed unique movement patterns absent in standard programmes. Furthermore, both Kobsar et al. (2015) and Watari et al. (2016) argued that exercise interventions might not effectively enhance function or reduce pain due to their inability to address movement changes during performance.

Additionally, studies indicated that pain can lead to various movement alterations, from slight changes in muscle activity to avoidance behaviours (Roland 1986; Lund et al. 1991; Hodges and Tucker 2011). Consequently, individuals with CKP may adapt their movement patterns to mitigate pain, potentially prolonging discomfort (Hodges and Tucker 2011). These altered patterns could lead to increased pain and movement limitations (Hodges and Tucker 2011). Therefore, it is essential for physiotherapists to identify specific movement patterns in CKP patients to personalise exercise programmes and monitor progress (Farrokhi et al. 2015). Mills et al. (2013) further highlighted significant gait parameter differences between individuals with and without CKP, reinforcing the need for comprehensive biomechanical evaluations in developing personalised exercise programmes. Gait analysis can provide valuable insights into biomechanical changes within the CKP population, laying the groundwork for a deeper exploration of gait mechanics in the next section.

2.6. Human gait and gait analysis

Gait, or walking, is a series of lower extremities movements that have a rhythmic characteristic resulting in a forward progression of the human body by utilising the minimal energy expenditure (Amin et al. 2022). Additionally, gait is considered as a complex movement that can be described as an interaction of joint ROM, bony alignment, and neuromuscular activity (Chambers and Sutherland 2002). Furthermore, in physiotherapy, gait is considered one of the commonly studied natural human activities and gait characteristics make it an exceptionally practical and commonly utilised analysis task in physiotherapy clinics (Hobani et al. 2022). The analysis of human gait provides benefits like identifying movement abnormalities that are indicative of various health issues including CKP, allowing for targeted management plans, providing biomechanical insights for identifying different movement patterns and stability, and improving rehabilitation outcomes that occur (Baker 2006).

Gait analysis is a systematic approach to monitoring, recording, analysing, and helps interpret human locomotion patterns, particularly walking or running. It employs both observational and instrumental approaches to evaluate body movements, mechanics, and muscle activation (Baker 2006 and Mohan et al. 2020). Furthermore, gait is characterised by a commonly used term, gait cycle (GC), which is a

complicated cyclical pattern of body movements that happens when walking on two feet and involves each lower limb's stance and swing phases alternating. One foot makes the first touch with the ground to start the gait cycle, which ends when the same foot contacts the ground once more (Hulleck et al. 2022). The GC includes two phases that are also divided into other subphases. Table 2 shows the GC phases and subphases in more detail.

Table 2 Gait Cycle Phases

Phase	Sub-phase	Percentage of gait cycle	Description
Stance Phase (60% of the GC)	Initial Contact (Heel Strike)	0%	Foot touches the ground, initiating weight acceptance
	Loading Response (Foot Flat)	0-10%	Weight acceptance continues, shock absorption
	Mid-stance	10-30%	Single leg support, body moves over stationary foot
	Terminal Stance (Heel Off)	30-50%	Heel rises, body weight over forefoot
	Pre-swing (Toe Off)	50-60%	Preparation for swing phase, weight transfer to opposite limb
Swing phase (40% of the GC)	Initial Swing	60-73%	Foot leaves ground, leg accelerates forward
	Mid-swing	73-87%	Limb advancement, foot clearance
	Terminal Swing	87-100%	Limb deceleration, preparation for next initial contact

GC = Gait cycle. % = Percent.

Moreover, any physiological or pathological changes in the body might greatly affect the gaits biomechanics. Such situations might cause compensatory changes in gait patterns that can have an even greater impact on total movement efficiency and mechanics, emphasising the complex relationship between internal body changes and biomechanical consequences (Perry and Burnfield 2010). Therefore, the following section will include a synthesis of research studies that evaluated biomechanical changes in gait within CKP population. Moreover, although the section aims to present research about CKP population, the majority of the included studies recruited individuals with knee osteoarthritis based on the literature search findings. Further the included studies are varied in its aims and objectives. However, the analysis of the included studies will circulate around the point of deciding the optimal biomechanical parameter that informs the clinical decision making of exercise prescription. Additionally, a summarising table (2.3.) presenting the key characteristics of the included studies is presented in the end of this section.

2.7. Impact of chronic knee pain on gait

The following section presents the biomechanical changes associated with CKP and their relevance to selecting a biomechanical parameter for exercise-based interventions using gait analysis. In this section, two main subthemes are included, (1) comparative analysis of gait parameters, and (2) movement compensation and patterns. Lastly, a search strategy was developed for this section and is presented in (Appendix 2).

2.7.1. Comparative analysis of gait parameters

Six studies by (Fukaya et al. 2019 a; Byrnes et al. 2022; Fukaya et al. 2019 b; Richards et al. 2018; Ismailidis et al. 2021; Bensalma et al. 2019) evaluated the kinematics, kinetics, and spatiotemporal parameters during gait of people with CKP.

Fukaya et al. (2019a) looked at the biomechanical parameters and they illustrated that the knee adduction moment (KAM) increases the load on the medial compartments of the knee joint. To reach this conclusion, the authors conducted a comparative study involving individuals with early-stage knee OA and those with established knee OA. They employed three-dimensional motion analysis and inverse dynamics to assess frontal plane kinetics and kinematics during walking. Ground reaction forces were measured using force plates, and joint moments were

calculated to determine the extent of medial loading on the knee. Their findings indicated that KAM is a key kinetic indicator of knee OA severity, as it was significantly higher in individuals with established OA compared to those with early-stage OA.

However, Fukaya et al. (2019a) also observed that angular changes, particularly in hip joint kinematics, played a crucial role in increasing KAM. Specifically, they identified a significant relationship between hip joint abduction and increased KAM, with a significant difference ($p = 0.02$) observed when comparing the two groups. This finding suggests that as hip abduction increases, there is a corresponding rise in medial loading on the knee's medial compartments, ultimately leading to an elevated KAM. Furthermore, the authors emphasised that this increase in hip abduction occurred throughout most of the stance phase, including the initial contact, midstance, and terminal stance sub-phases.

Additionally, Fukaya et al. (2019 a) found that, in light to the previous findings, the knee joint of those with established OA had a significantly greater varus angle during the whole stance phase ($p = <0.01$) compared to those with early-stage knee OA. Thus, Fukaya et al. (2019a) findings could be interpreted that KAM can be identified through kinematic analysis by observing increased hip abduction and knee varus angle, without the need for kinetic analysis. This can potentially support the choice of using kinematic gait analysis when prescribing exercises, as clinician decision-making would be clearer when observing those signs from a kinematic gait analysis perspective. In addition, by identifying specific gait deviations, movement asymmetries, and compensatory strategies, kinematic gait analysis enables clinicians to tailor exercises that target the patient's unique deficits. This ensures a well-structured and personalised exercise plan that addresses the individual's specific biomechanical needs (Kobsar et al. 2015). Further, this can be added to the ability of the kinematic analysis to be conducted from out-of-lab environment, which increases that possibility of using the kinematic measurements on their own in an uncontrolled setting (Strohrmann et al. 2012).

The findings of Fukaya et al. (2019 a) were in line with those of Byrnes et al. (2022) systematic review study. In patients with knee OA, the authors found that hip kinematics (position description) significantly influenced the increase of KAM, as

greater hip abduction was associated with increased KAM. This information supports the idea that the kinematics of lower limb joints are important indicators of kinetics. Thus, kinematic analysis could provide objective details that help identify movement patterns contributing to excessive joint loading. By understanding these patterns, clinicians can design targeted exercises to modify movement mechanics, reduce excessive joint stress, and improve functional outcomes, thereby guiding personalised exercise prescription.

Additionally, Byrnes et al. (2022) highlighted inconsistencies in KAM findings across studies, as KAM varied depending on factors such as gait modifications (e.g., speed or out-toeing gait), individual characteristics (e.g., body weight and age), and idiopathic orthopaedic deformities. This variability suggests that KAM alone may not be a reliable indicator for guiding clinical decisions of exercise prescription. Byrnes et al. (2022) also noted that knee moments, such as the knee flexor moment, could increase or decrease due to kinematic changes, further emphasising the importance of kinematic data in assessing joint function.

The study by Fukaya et al. (2019 b) reinforce the findings of the previous studies. However, the authors focused on knee kinematics at stance phase. The researchers found that when knee varus angle, specifically, at the early stance phase is large, the first peak external KAM that occurs in the early stage of the mid stance tends to become large. Additionally, the control of the varus angle in the early stance suggests the possibility of reducing the mechanical load of the knee joint by the external KAM (Fukaya et al. 2019 b). The authors concluded with highlighting the relationship between KAM and the movement of the knee joint emphasising on the effectiveness of understanding this relationship for the rehabilitation approaches to manage or prevent the progression of knee OA condition. This supports the link between joints kinetics and kinematics in individuals with CKP.

Furthermore, in line to the previous studies, Richards et al. (2018) provided similar findings of having KAM as a strong predictor of the forces applied on the medial knee joint during the stance phase. However, the researchers added that knee flexion moment was also an important parameter to consider when analysing gait of individuals with knee OA. The researchers illustrated that testing the impact of changing the force moments in individuals with knee OA was mainly dependent on

gait patterns changes (e.g., toe-in gait), which agrees with the previous studies that indicating the gait patterns is essential when assessing individuals with CKP. This indicate that when kinematic of joint angles changes, it results in moment changes, supporting the choice of kinematic data to inform objective exercise prescription.

The study by Ismailidis et al. (2021) compared between a knee OA group with an asymptomatic control group in an out-of-lab environment (walking for 20 meters) at a self-selected speed. The authors used inertial measurement units (IMUs) sensors to detect and compare the kinematic and the spatiotemporal parameters between the groups. The authors found that the knee OA group showed a significant lower maximum dorsiflexion of the ankle joint in the stance phase ($p = <0.001$) within the knee OA group compared to the asymptomatic controls. Also, the authors found the overall ankle ROM was significantly lower in the OA group vs. the asymptomatic group. In the knee joint, the maximum flexion at stance, maximum flexion at swing, and the overall ROM at swing phase were significantly lower in knee OA group compared to the asymptomatic group ($p = 0.001$, $p = < 0.001$, and $p = < 0.001$, respectively). The authors also highlighted walking speed was lower in knee OA group. This study indicates the sensitivity of the functional assessment of the kinematical measures, when using the IMU in an out-of-lab environment and provided several significant differences between the groups.

More, the cross-sectional study by Bensalma et al. (2019) gathered the biomechanical data from ($n = 166$) patients with knee OA. The authors conducted a multivariate analysis, a statistical technique that is employed to investigate the relationships and effects of multiple variables (Tabachnick and Fidell 2007), to investigate the relationship between kinematics and the clinical parameters of knee OA condition. The researchers considered kinematic variables as knee OA biomarkers using BIPED biomarker classification (Burden of Disease, Investigative, Prognostic, Efficacy of Intervention and Diagnostic). This classification was investigated in Bensalma et al. (2019) research in relation to pain. The authors found that pain was positively correlated with biomechanical data corresponding to kinematic parameters in the frontal plane (abduction/adduction) during the swing phase, kinematic parameters in the sagittal plane (flexion/extension) at the end of the stance phase, and kinematic parameters in the transverse plane (internal/external rotation). In other words, the intensity of pain increased in tandem

with the increase in the kinematic parameters of those planes. This implies that an increase in pain levels is associated with movement alterations in the frontal plane during those phases.

Additionally, the findings indicate that a multivariate analysis of the clinical symptoms and the biomechanical characteristics of knee joint function enables a more comprehensive comprehension of their relationships. This would facilitate a more comprehensive understanding of how biomechanical characteristics can be employed to inform clinical decision-making in the management of CKP. This research can be interpreted in relation to exercise prescription in which it emphasises that understanding the kinematic variables with CKP condition can help identifying knee joint function, which provide insight into the decision making of exercise choices and prescription. Also, using BIPED classification reinforce the objectiveness of the kinematic measures. Thus, it can be used independently to assess joint functions and informs exercise prescription.

2.7.2. Movement compensation and patterns

This section includes studies that examined the impact of CKP on gait patterns. A total of nine studies (Schmitt et al. 2015; Rynne et al. 2022; Farrokhi et al. 2015; Park et al. 2016; Leporace et al. 2021; van der Straaten et al. (2020); Raza et al. 2024; Dai et al. 2023; and Rutherford and Barker 2019) were reviewed to assess changes in gait and movement patterns, as well as compensation strategies. The findings from these studies will be comprehensively linked to exercise prescription approaches to identify key biomechanical measures that should be considered when developing exercise-based interventions for CKP.

The findings of Schmitt et al. (2015) highlighted that in individuals with knee OA, hip flexion was increased, while in both knee OA and ankle OA, hip extension was limited. Additionally, in the knee OA group, ankle ROM (particularly dorsiflexion) was restricted, affecting ankle joint progression. These findings suggest that individuals with OA develop compensation strategies to adapt to joint limitations. Increased hip flexion may aid foot clearance during gait, while reduced hip extension could alter stride length and reduce push-off efficiency. Furthermore, restricted ankle dorsiflexion may lead to altered foot placement or greater reliance on hip and knee movements for forward progression, ultimately impacting overall gait mechanics.

Hence, identifying such compensation strategies are crucial when considering exercise prescription. The authors also found that the hip extension moment was significantly different between the control group and the knee OA group ($p = >0.001$), which is attributed to the founded compensation strategy. The findings of this study suggest that kinematical variable of the lower limb joint can be used to illustrate the functional impairments, which is necessary when designing an exercise programme. Moreover, those findings are supported by a systematic review and meta-analysis by Rynne et al. (2022).

The research by Farrokhi et al. (2015) highlighted another compensation strategy used by individuals with patellofemoral osteoarthritis (PFOA). The authors illustrated that the limited knee flexion angle (KFA) in the stance phase could be due to pain avoidance that leads individuals with PFOA to compensate by increasing hip abduction and decreased knee flexion. The findings also suggest that the limitation of the of the KFA was associated with quadriceps muscle weakness and reduce loading response subphase during the stance phase. The current findings reinforce the previous results from Schmitt et al. (2015) and Rynne et al. (2022) in which the compensation strategies are mostly identified by kinematic measures that are sensitive to functional changes in knee OA population.

Similarly, the findings of Park et al. (2016) highlighted that quadriceps weakness was indicated in knee OA group vs. healthy controls. The authors found that the strength deficit ranged from 13% to 31% in favour of the healthy controls. The researchers identified that the muscle weakness led to kinematic changes and gait alterations. They found that the peak knee adduction angle was lesser in the symptomatic group from the frontal view in people with knee OA. In addition, the peak hip adduction angle was also reduced indicating that the joint kinematical presentation was towards the abduction. Despite that Park et al. (2016) highlighted the muscle activity within knee OA population, the study shows an important value of the kinematic measures as it confirms that any functional alteration that happens due to muscle weakness would directly impact the joint kinematics.

In line with the previous studies, the study by Leporace et al. (2021) illustrated that there are several gait profiles in patients with knee OA, suggesting that the knee adduction moment (KAM) is a surrogate measure of load between lateral and medial

compartments of the knee, which can be detected from the maximum varus and valgus alignments. This finding agrees with the previously mentioned findings of knee positioning alterations is a key factor, impacting the applied forces on the joint. Additionally, pain avoidance was an attribution that the authors highlighted when they observed the limited KFA from the sagittal plane. Leporace et al. (2021) study shows that with kinematic analysis, four different gait profiles were identified among severe knee OA population. This reinforce that with the kinematic analysis, movement patterns and actual functional impairments were detected. This approach can be directly linked to the type of exercise prescribed for those individuals in which, when a specific gait pattern is identified kinematically, the exercises can be tailored, personalised, and targeted to this specific pattern.

Furthermore, van der Straaten et al. (2020) agrees with the included studies in their findings in which they found that there was a reduced knee flexion ROM in both stance and swing phases. What is more in van der Straaten et al. (2020) is that the researchers used IMU sensors and compared their kinematic results with 8 optoelectronic camera motion analysis systems. The IMUs were able to identify the limited knee flexion angle compared to the camera system and between groups (healthy controls vs. unilateral knee OA). This finding emphasises that the kinematic data from either systems can be used to accurately identify the movement behaviour when comparing between groups, which provides more movement analytical options to researchers and clinicians.

In a similar setting, the study by Dai et al. (2023) compared between knee OA group and healthy controls. The authors analysed their kinematics data from the sagittal plane using IMUs and found that there was a significant differences between the groups as follows, both the maximum knee flexion and the maximum knee extensions were significantly reduced in the knee OA group compared to the control group ($p = 0.001$), the ROM of the hip joint from the sagittal plane was significantly reduced in the knee OA group compared to the controls ($p = <0.001$), and both the ankle eversion and adduction were significantly reduced in the knee OA group ($p = <0.001$). Further, the speed and step length were found to be reduced in the symptomatic group. The findings could be interpreted as highlighting the importance of understanding how joints work collectively to coordinate and adapt to changes in the arthritic knee, which may aid in better management of the condition. Lastly, the

study by Rutherford and Barker (2019) used the sEMG to explore the lateral hamstring (LH) and medial hamstring (MH) muscle activation during gait. The authors illustrated that the LH activation was greater than the MH in knee OA individuals compared to healthy controls. Rutherford and Barker stated that the differences between the LH and MH could be due to a compensation strategy. However, such information cannot be interpreted functionally unless kinematic analysis was performed to confirm the developed movement pattern that was developed by the affected group.

Moreover, three studies were conducted by (Ismailidis et al. 2020; Boekesteijn et al. 2022; and Kobsar et al. 2017). Ismailidis et al. (2020) looked at the kinematic and the spatiotemporal measures of the gait using wearable sensor technology. Similarly, Boekesteijn et al. (2022) looked at the kinematic and the spatiotemporal measures of the gait whereas Kobsar et al. (2017) only looked at the kinematics of the gait among individuals with knee OA. Both Ismailidis et al. (2020) and Kobsar et al. (2017) conducted experimental studies. On the other hand, Boekesteijn et al. (2022) conducted a systematic review and meta-analysis. Kobsar et al. (2017) included 43 individuals with knee OA. Similarly, Ismailidis et al. (2020) included individuals with knee OA. However, the authors allocated them into two groups (1) severe knee OA (n = 23) and (2) Asymptomatic group (n = 28). The three studies examined the whole gait cycle with Ismailidis et al. (2020) and Boekesteijn et al. (2022) looking at the sagittal plane and Kobsar et al. (2017) looking at the frontal plane.

The results from Ismailidis et al. (2020) research highlighted that different walking speed have changed the spatiotemporal parameter and joint kinematics among both groups. Interestingly, the researchers highlighted that with self-selected speed, patients with knee OA had a significantly lower walking speed, higher stride duration, lower stride length and lower cadence compared to the control group ($p = 0.001$). The researchers also found smaller peak KFA by 6.8° in the OA patients versus asymptomatic controls during midstance and by 11.0° in early swing phase at normal self-selected speed. However, ankle and hip angles differed between severe versus asymptomatic controls during several phases of the gait cycle. Despite this, while significant spatiotemporal differences in stride duration and cadence still exist, there were no significant differences in sagittal ankle, knee and hip kinematics at a matched speed. This study can be comprehended by illustrating that IMUs can be

used outside of the lab and detect both spatiotemporal parameters and joint kinematics in an uncontrolled environment. Additionally, when the authors clarified the impact of gait speed among the OA population, they highlighted the impact by explaining the effect on joint kinematics. This could be due to the need of having more insight regarding the functional element of the joint and the gait patterns, which supports the usefulness of using kinematics in clinical settings.

The general findings of the systematic review and meta-analysis that included (n = 23) studies and overall (n = 411) knee OA patients by Boekesteijn et al. (2022) show that knee OA individuals walked slower than the healthy controls, which in line with Ismailidis et al. (2020) findings. Also, both swing and stance phase in the OA population were reduced compared to the healthy controls. In addition, Boekesteijn et al. (2022) found that individuals with knee OA exhibited a smaller foot strike and toe-off angle. The study also highlighted the frequent use of IMUs for gait analysis in out-of-lab settings, aligning with previous research. Notably, using IMUs outside the lab allowed individuals with knee OA to walk at a normal speed, enabling the measurement of joint kinematics. This provided valuable insights into gait variability between individuals with knee OA and healthy controls.

Lastly, the study by Kobsar et al. (2017) found that using the IMUs in gait analysis for kinematic gait data can predict the success of rehabilitation interventions in response to muscle strengthening exercises in people with knee OA. The authors suggested that utilising IMUs for kinematic measures can examine different gait patterns across multiple lower limb joints by providing more detailed and effective classification models, this is in line to previously mentioned discussion points. Moreover, the kinematic data obtained from IMUs can be utilised for follow up analysis, as it offers highly responsive data that is sensitive to movement alterations. for instance, if a clinician provided a treatment, they could establish an objective baseline and subsequently monitor progress.

In conclusion, this section highlights that the kinematic measures could be the optimal biomechanical parameter in relation to clinical settings and exercise prescription purposes. This could be due to its ability to indicate the joint functions, used in multiple settings, indicate other measures (kinetics, spatiotemporal parameters, and muscle weakness), sensitive to compensated gait patterns, and

used as a follow up tool for objectively assessing responses to exercise. Furthermore, the most used gait phase for analysis is the stance phase. In terms of the used analysis planes, the frontal plane was the most used with the hip joint. The frontal and the sagittal planes were looked at with the knee joint, and the sagittal plane was commonly used with the ankle joint. The IMUs and the camera Vicon systems were commonly used with the kinematical measures whereas the force plates were commonly used the ground reaction forces, and the surface EMG was used with the muscle activity measurements. Furthermore, the use of IMUs was found to be advantageous in terms of collecting rich kinematic data from out-of-lab environment, being accessible, affordable, portable, and easy to use. This could also provide objective measures that inform setting treatment plans and inform exercise prescription. Further, there are several ways to detect movement alterations within CKP population. Additionally, wearable sensors such as the IMUs can provide information that is beyond the kinematic data, like biofeedback. For this, more details around using wearable inertial measurement units, or sensors are needed in the context of developing health interventions using exercise prescription approach with an integration of biofeedback approach, which is discussed below.

Table 3 Summary of Gait and Biomechanics studies

Author(s) and Year	Study Design	Sample Size	Biomechanical Parameters	Settings	Activity	Gait Phase	Analysis Plane	Joints Analysed
Fukaya et al. (2019a)	Experimental	17 (8 early KOA, 9 established KOA)	Kinematics, Kinetics	In-lab	Gait	Stance	Frontal	Knee, Hip, Ankle
Byrnes et al. (2022)	Systematic Review	42 studies	Kinematics, Kinetics	In-lab	Gait	Stance	Frontal	Knee, Hip, Ankle
Fukaya et al. (2019b)	Experimental	15 (severe KOA)	Kinematics, Kinetics	In-lab	Gait	Stance	Frontal	Knee
Richards et al. (2018)	Experimental	35 (KOA)	Kinematics, Kinetics	In-lab	Gait	Stance	Frontal	Knee
Ismailidis et al. (2021)	Experimental	68 (22 KOA, 46 control)	Kinematics, Spatiotemporal	Out-of-lab (IMUs)	Gait	Entire cycle	Sagittal	Knee, Hip, Ankle
Bensalma et al. (2019)	Cross-sectional	166 (KOA)	Kinematics	In-lab	Gait	Entire cycle	Frontal, Sagittal	Knee
Schmitt et al. (2015)	Experimental	95 (20 KOA, 30 hip OA, 30 ankle	Kinematics, Kinetics	In-lab	Gait	Entire cycle	Not specified	Knee

		OA, 15 control)						
Rynne et al. (2022)	Systematic Review & Meta-analysis	522 KOA, 482 control	Kinematics, Kinetics	In-lab	Gait	Not specified	Not specified	Knee
Farrokhi et al. (2015)	Experimental	Mild PFOA (N= 38), Severe PFOA (N= 44)	Kinematics, Muscle activity	In-lab	Gait	Stance	Not specified	Knee
Park et al. (2016)	Experimental	48 (24 KOA, 24 control)	Kinematics, Muscle activity	In-lab	Gait	Stance	Not specified	Knee
Leporace et al. (2021)	Cross-sectional	42 (KOA)	Kinematics	In-lab	Gait	Stance	Not specified	Knee
van der Straaten et al. (2020)	Experimental	31 (19 KOA, 12 control)	Kinematics	In-lab	Gait	Entire cycle	Not specified	Knee
Raza et al. (2024)	Experimental	80 (60 KOA, 20 control)	Kinematics	Out-of-lab	Gait	Stance	Not specified	Knee
Dai et al. (2023)	Experimental	45 (25 KOA, 20 control)	Kinematics	In-lab	Gait	Stance	Not specified	Knee
Rutherford and Barker (2019)	Experimental	82 (40 KOA, 42 control)	Muscle activity	In-lab	Gait	Not specified	Not specified	Knee
Ismailidis et al. (2020)	Experimental	51 (23 severe KOA,	Kinematics, Spatiotemporal	In-lab & Out-of-	Gait	Entire cycle	Sagittal	Knee

		28 asymptomatic)		lab (IMUs)				
Boekesteijn et al. (2022)	Systematic Review & Meta-analysis	411 KOA, 507 control	Kinematics, Spatiotemporal	Not specified	Gait	Entire cycle	Sagittal	Knee
Kobsar et al. (2017)	Experimental	43 (KOA)	Kinematics	In-lab (IMUs)	Gait	Entire cycle	Frontal	Knee

2.8. Wearable sensor technology and biomechanical biofeedback

According to Luczak et al. (2020), wearable technology, or wearable devices, refers to small electronic and mobile devices, as well as computers with wireless communication capability, built into gadgets, accessories, or clothing that can be worn on the human body, such as body sensors used to estimate movement information that can be used to generate feedback. In their study, Iqbal et al. (2016) defined both body sensors and head-mounted displays; the latter are visual devices with hands-free capabilities mounted to the user's head, whereas body sensors are any wearable or portable device that can detect and record the human body's physiological mechanisms using attachable sensors. The rapid growth of these technologies has created an opportunity for their use in the field of rehabilitation, and the possibility of developing physiotherapy-based biomechanical biofeedback interventions has emerged (Cook 2009). This has made the application of wearable technology for biomechanical biofeedback a growing area of interest for researchers (Ometov et al. 2021).

To contextualise this application, it is important to understand the broader concept of biofeedback. Biofeedback is a mind–body technique in which patients learn to voluntarily control physiological processes that are typically involuntary, in order to improve physical, mental, and emotional wellbeing. This technique requires specialised equipment to convert physiological signals into meaningful visual and auditory cues, typically with the guidance of a trained practitioner (Frank et al. 2010). As explained by Zhang et al. (2010), biofeedback enables patients and clinicians to regulate physical processes that were once considered exclusively under autonomic control. Giggins et al. (2013) categorised biofeedback into two major types: physiological and biomechanical. Physiological biofeedback includes neuromuscular, cardiovascular, and respiratory modalities, providing real-time feedback such as muscle activity, heart rate, or respiratory function. In contrast, biomechanical biofeedback involves measurements of movement, postural control, and force output by the body.

Wearable sensors providing biomechanical information are mainly referred to as inertial measurement units (IMUs), or inertial sensors, and have proven effective in movement and balance applications due to their modest size and portability (Giggins et al. 2013). These sensors estimate three-dimensional (3D) kinematic information of

a body segment, such as orientation, velocity, and gravitational force, through the use of accelerometers and gyroscopes. A gyroscope measures angular velocity, while an accelerometer detects acceleration and gravitational force (Schepers, 2009). Despite the fact that inertial sensors can provide auditory, visual, or tactile feedback to the user (Giggins et al., 2013), their integration into comprehensive toolkits offering biomechanical biofeedback for musculoskeletal (MSK) conditions has not been widely implemented. Biomechanical biofeedback systems also tend to be complex, as one device can generate multiple types of feedback. For example, a force plate may provide feedback not only about force but also about postural control (Giggins et al. 2013). Additionally, biomechanical biofeedback has traditionally been restricted to laboratory-based settings that capture only brief snapshots of movement mechanics. However, advances in wearable sensor technologies now allow this feedback to be collected in free-living environments, offering more ecologically valid and continuous analysis of movement (Wong et al. 2015).

Research exploring wearable sensor use in MSK contexts has largely focused on post-surgical outcomes, joint kinematic measurements, or gait analysis (Small et al., 2019; Niswander et al., 2020; Kobsar et al., 2020), rather than leveraging the biomechanical biofeedback capabilities of such sensors in the management of lower limb OA. To develop innovative interventions, it is important to understand the scope of how wearable sensor technology has been used within the biomechanical biofeedback framework to manage CKP. Accordingly, a scoping review (Chapter 3) was conducted to explore how wearable sensor technology has been applied to provide biomechanical biofeedback for adults with lower limb OA. The decision to focus on individuals with OA, rather than the broader CKP population, was informed by the findings of the literature search, which indicated that OA was the most frequently studied type of CKP. Therefore, the target population in the scoping review comprises individuals with lower limb OA.

2.9. Literature review chapter conclusion

This literature review has comprehensively examined the current evidence surrounding CKP, its management approaches, digital health interventions, and the biomechanical aspects that inform exercise prescription. The synthesis of findings reveals several critical insights that highlight the complexity of CKP management and identify significant gaps in current intervention approaches.

2.9.1. Key findings

The literature establishes CKP as a multifaceted condition affecting diverse populations. Beyond its clinical manifestations, the condition imposes substantial economic burden, with musculoskeletal disorders projected to cost the NHS up to £120 billion over the next decade, whilst encompassing physical limitations, psychological distress, and functional impairments.

Therapeutic exercise has been established as the primary evidence-based intervention for CKP management. Research demonstrated that multiple exercise modalities, including resistance training, aquatic exercise, cycling, traditional exercise, and yoga, all provided significant improvements in patient-reported outcomes. However, the evidence revealed important limitations regarding medium and long-term effectiveness, with exercise adherence emerging as the critical determinant of intervention success. Notably, individuals with higher baseline pain severity and lower physical function demonstrated greater benefit from therapeutic exercise interventions.

The examination of digital health interventions revealed substantial potential for improving care accessibility and patient engagement through features such as reminders, educational content, and remote support. These platforms consistently demonstrated improvements in pain, physical function, and quality of life measures, with generally positive user acceptability and usability ratings. However, a fundamental limitation was consistently identified, which is the delivery of standardised, non-personalised exercise programmes that failed to address individual functional needs and movement limitations. This lack of personalisation was compounded by heavy reliance on patient-reported outcomes without integration of objective functional assessments and limited feedback mechanisms linked to real-time performance.

Biomechanical research demonstrated that individuals with CKP develop distinct movement patterns and compensation strategies that can be objectively quantified through gait analysis. The evidence established that kinematic measures, particularly hip abduction and knee varus angle, could reliably predict kinetic parameters such as knee adduction moment without requiring complex laboratory equipment. Kinematic analysis emerged as the optimal biomechanical parameter due to its ability to indicate joint function across multiple settings, provide insights into joint loading and muscle weakness, demonstrate sensitivity to compensated movement patterns, and serve as an objective assessment tool.

The examination of wearable sensor technology revealed that inertial measurement units could detect significant kinematic differences between individuals with CKP and healthy controls whilst offering practical advantages of portability, affordability, and usability in non-laboratory environments. These sensors demonstrated capacity for objective movement assessment and potential for biomechanical biofeedback applications.

Despite these advances, the literature revealed a critical disconnect. Whilst individual movement patterns in CKP can be objectively assessed, and digital platforms offer enhanced accessibility and engagement, to our knowledge, no studies had integrated biomechanical assessment into digital exercise intervention approaches. This gap represents a significant limitation in current practice, where the potential for personalised, biomechanically informed digital interventions remain unexplored.

Chapter 3: Scoping review

Title: Biomechanical Biofeedback Applications of Wearable Sensor Technology in The Management of Lower Extremity Osteoarthritis: Scoping Review

3.1. Introduction

In line to the previous literature review chapter, wearable sensor technology, such as IMUs, was found to be useful to provide real-time biomechanical data and can be used outside the conventional biomechanics laboratories, giving it the advantage of collecting data from activities, like walking, in an uncontrolled environment. Furthermore, the literature search revealed a limited number of studies that discussed using worn technology to provide biomechanical biofeedback to CKP population. Thus, the current scoping review was conducted to explore this area. Lastly, based on the findings from the previous chapter and the literature search, the most studied type of CKP was osteoarthritis (OA). Hence, the targeted population that are studied in this scoping review are individuals with lower extremity OA. Additionally, this scoping review was structured for publication with its abstract being published and presented in an international conference.

3.2. Background

Osteoarthritis (OA) is a joint and tissue disease that causes pain and function loss (OARSI 2022). Biomechanical biofeedback is an important approach for managing OA as it includes measurements of movement, posture control, and body forces (Giggins et al. 2013). This will aid in detecting disease progression and objectively evaluating rehabilitative interventions (Andriacchi et al. 2013). With the advancement of wearable sensor technology, there is a potential to develop a physiotherapy-based-biomechanical-biofeedback intervention (Cook et al. 2009). To develop new interventions, it is important to understand the scope of how has wearable sensor technology been used to provide biomechanical biofeedback for adults with lower limb OA.

A consideration of the available systematic approaches for reviewing the published literature was taken. However, we decided to conduct a scoping review as the most appropriate method for the aim of the current research.

Scoping review approach is beneficial for studying a large topic and mapping the literature to discover essential concepts (Pham et al. 2014), which in the current study is the concept of the biomechanical biofeedback provided form wearable sensor technology for individuals with lower limbs OA. Additionally, scoping review mapping also help in discovering hypotheses, evidence, or research gaps in a comprehensive and methodical manner. Unlike systematic reviews and meta-analysis studies, scoping reviews do not limit the search to review research trials or need quality assessment (Halas et al. 2015). This form of review, on the other hand, is thorough and methodical in its approach to analysing the scope, range, and nature of research activity in a certain field, and it includes both empirical and conceptual research with wide framed questions (Grimshaw 2010). More specifically, this scoping review was taken because, to our knowledge and based on a broad search of the literature, there is a limited number of randomised controlled trials (RCTs) published in this field, which is an essential factor for conducting systematic reviews (Charrois 2015). For this, this scoping review aimed to explore how wearable sensor technology has been used to deliver biomechanical biofeedback in the management of individuals with lower limb OA.

Lastly, Joanna Briggs Institute (JBI 2020) scoping review guidance was used to structure this scoping review. Following this, we adapted Arksey and O'Malley's (2005) five-stage scoping review framework, along with later refinements, to develop a practical method for reviewing a large body of literature on the chosen topic. The five stages are explained below.

3.3. Stages of the scoping review framework

Stage 1: identifying the research question

Arksey and O'Malley (2005) suggest a refined process to developing the research question that aims to increase the familiarity with the literature around the searched area. After the initial literature search, the need to formulate a structured research question was desired. Therefore, "Population, Concept, and Context" format (PCC) was used to formulate the research question. PCC is recommended by Joanna

Briggs Institute (JBI 2020) to construct the study's title, and by incorporating its component, a well-structured research question will be developed (JBI 2020). In Table 4 the research question is explained based on using the PCC format. The answer to the research question using the published literature will help in providing a comprehensive understanding of the utilisation of wearable sensor technology biomechanical biofeedback capabilities in the management of lower limb OA.

Table 4 PCC Research Question Format

Item	Explanation
(P)	Population: Adults diagnosed with osteoarthritis.
(C)	Concept: Biomechanical biofeedback
(C)	Context: Wearable sensor technology attached to the lower extremity joints.
Research Question	
How has wearable sensor technology been used to provide biomechanical biofeedback for adults with lower limb (L.L.) osteoarthritis?	

Stage 2: Identifying relevant studies

Although scoping reviews aim to comprehensively address broad research questions, it is required to include certain parameters to help guiding the search. Therefore, at this stage, we included studies' eligibility criteria, databases used for the search, searching strategy, and searching terms.

Eligibility criteria

The current review has considered all study designs and published scientific articles that looked at OA in the lower limbs' joints (hip, knee, and ankle) in adults, males and females, and published in English language. More, Participants aged over 45 years old, as according to Versus Arthritis (2021), OA is a condition that found to appear starting from the age of 45, were included. Lastly, studies reported the use of any wearable sensor technology that provides a biomechanical biofeedback on any activity were included. Subsequently, studies that look at any other medical

conditions in the lower limbs, or OA in upper limbs or the spine, in patients who are under the age of 45, and in any other language were excluded. Furthermore, only the studies that were published from the year of 2000 until present were included. To justify this, the review published by Fong and Chan (2010) highlighted the early date when the accelerometers were used with human joints, which was in the 1990s by Willemse and Heyn (1991). However, Cooper et al. (2009) stated that not before the 2000s, the simplified systems using accelerometers and gyroscopes to estimate the orientation relative to the inertial frame were developed. Therefore, our scoping review considered the published studies starting from 2000 until the present time. For more clarity, the inclusion and exclusion criteria of the current review are stated in table (3.2.).

Table 5 Inclusion and Exclusion Criteria

Inclusion Criteria	**Exclusion Criteria**
Adults aged 45 and more.	Adults under the age of 45, adolescents, or children.
Hip, knee, or ankle osteoarthritis	Osteoarthritis that is located in other body regions.
All wearable technology and their accessories (e.g. body sensors linked to accessories like a smartphone).	Other types of technology that don't have the wearing feature.
Wearable technology that is attached to the human body in any way (e.g. directly attached to the body, or sensors attached to clothing).	Wearable technology that doesn't provide biofeedback data about biomechanical variables.
Wearable technology that provides biofeedback data about biomechanical variables.	Studies that are published in other languages.
English language studies	Studies that are not offered in full text.
Available in full text	Studies that are published before the year of 2000.

Databases

In this review study, the search was done using the following electronic databases:

Table 6 Searched Databases

Databases
Cochrane Library.
CINAHL EBSCO
MEDLINE EBSCO
SCOPUS.
OVID EMCARE.
Web of Science.

These scientific databases contain a vast number of peer-reviewed articles and medical and technology research (Aveyard 2019), which is necessary for any type of review study.

Search strategy

To identify studies and articles that have utilised wearable sensor technologies as a biomechanical biofeedback tool for adult with OA, an initial review was conducted to identify the appropriate key searching terms. The list of searching terms is presented in table (2.4). Because of the nature of scoping reviews, search terms should be general to cover the largest number of studies that are linked to the desired topic (Munn et al. 2018).

According to Bowling (2014) using different word forms (synonyms) is crucial to collect more structured and detailed information about the topic in question and allows providing more studies in the search, which will be utilised in our scoping review. In addition, Grewal et al. (2016) highlighted keywords that are driven from the research question can eliminate the possibility of obtaining irrelevant results, which is

also considered in the current review. According to Rees (2016), Boolean operators ('AND', 'OR', and 'NOT') can produce more relevant and productive outcomes in which they exclude or combine searching key terms leading to more focused results. Thus, in the current search, these were used.

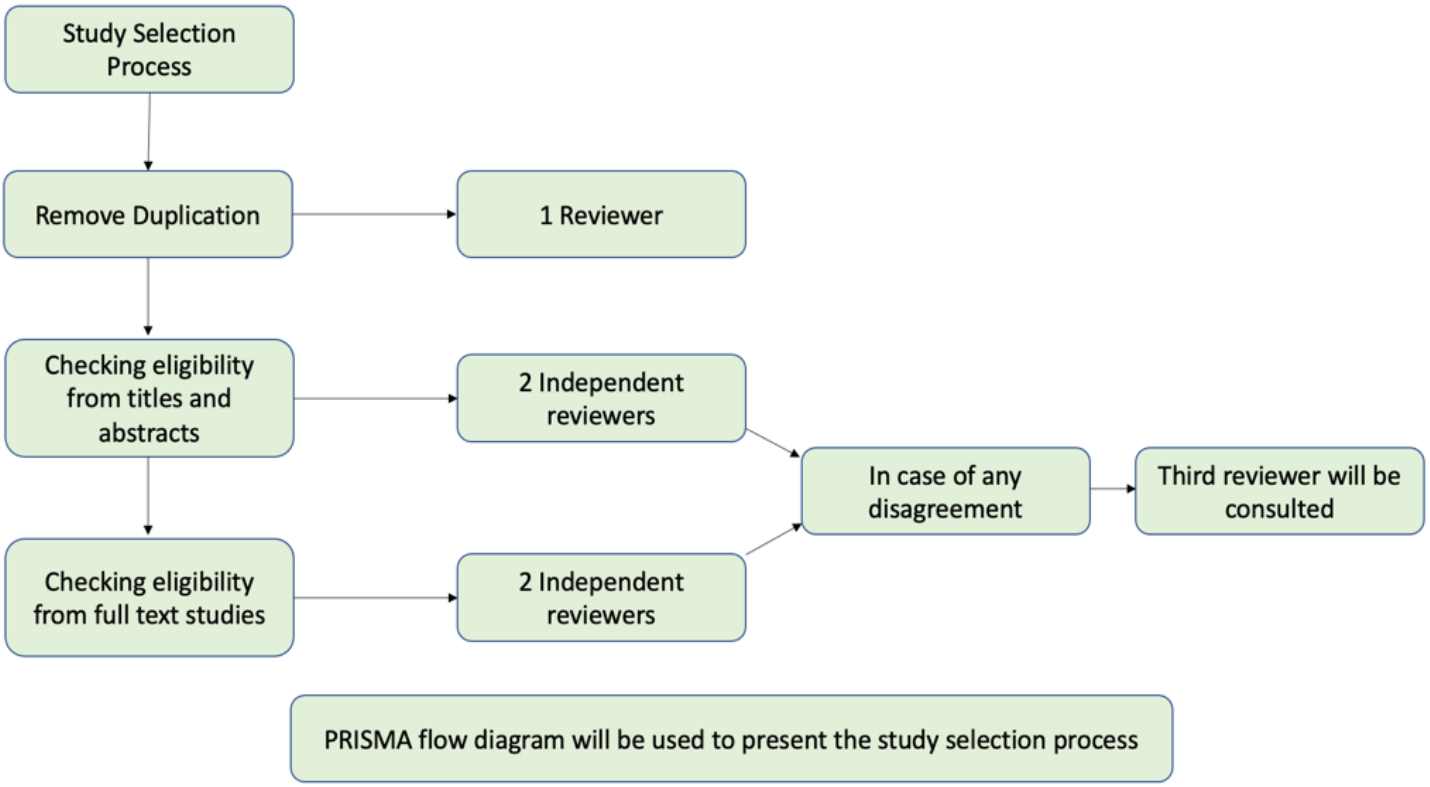
Table 7 Searching Key Terms

Key words categories	Key words combined with "AND" & "OR"
1- "Wearable" related key words	(weara*) OR (worn) OR (portab*) OR (attach*) OR (strap) OR (place*)
AND	
2- "Sensor" related key words	(sensin*) OR (senso*) OR (acceler*) OR (Gyro*) OR (imu) OR (inertial measurement unit)
AND	
3- "Biofeedback" related key words	(biofeedb*) OR (feedb*) OR (edu*) OR (patient edu*) OR (reedu*) OR (real-time) OR (haptic) OR (Vibra*) OR (Vibro*) OR (visual*) OR (touch*) OR (audio)
AND	
4- "Biomechanics" related key words	(biomech*) OR (mechan*) OR (qualit*) OR (move*) OR (perform*) OR (joint angle*) OR (kin*) OR (kinematic) OR (range of motion) OR (ROM) OR (joint range)
AND	
5- "Osteoarthritis" related key words	(Osteoarth*) OR (OA) OR (degene* disease) OR (degene* joint) OR (arthritis) OR (degen* arthritis)
AND	
6- "Site" related key words	(lower limb*) OR (lower extremit*) OR (knee) OR (hip) OR (ankle) OR (leg) OR (thigh) OR (foot)

Stage 3: Study selection

The first step after finishing the searching stage is to remove the duplicated studies, which was done by one reviewer (M.S.) using Mendeley reference manager. After that, all the titles and abstracts were reviewed independently by two reviewers (M.S. and A.F.) to check which study meets the eligibility criteria (2.1 eligibility). All the documents that met the eligibility criteria were included for full texts check. All full-text studies were reviewed for inclusion by two independent reviewers (M.S. and A.F.). Where differences arise, the reviewers consulted a third reviewer (M.A.) to reach a consensus. PRISMA flow diagram was used (Figure 2 in the results section), and in (Figure 1) the data selection process is highlighted.

Figure 1 Study Selection Process



Stage 4: Data Extraction

Data charting, or also called data extraction in systematic reviews, is identifying the important data and the key pieces of information from the selected articles. In addition, additional information can be added like (authors and year of publication). At this stage, the extracted data was presented in an agreed template using Microsoft word tables. For the qualitative research, the data extracted based on the recommendations from Cochrane handbook guidance for qualitative research data extraction (Appendix 3). The component of this sheet was created by (M.S.) and approved by (M.A. and K.B.). For the current review, the key information was linked to the utilisation of sensor technology as a biofeedback tool and the way biofeedback information was used in the management of lower limbs OA. (Please see Appendix 3 and 4 for the quantitative and qualitative data extraction templates, and data extraction definitions).

Table 8 Example of the data extraction template

No	Author(s)	Year of publication	Study location	Study design	Sample size (n)	Participants (Gender)	Population	Study Aims	Study settings
1	Ismailidis et al.	2020	Switzerland	Two-groups experimental design	n = 67 n = 22 patients. n = 45 asymptomatic controls.	A. Male= 12 Female= 10 B. Male= 16 Female= 29	Group A: Severe hip OA. Group B: Healthy.	To investigate the feasibility of using the RehaGait for gait analysis in patients with hip OA	University lab.

Stage 5: Framework formulation

The framework stage is a more practical step to the previous step of “data extraction”. It includes collecting, summarising, and reporting the results. In scoping reviews, presenting an overview of all the reviewed materials is essential. Therefore, it is paramount to have a framework or thematic construction to present a narrative account of existing literature (Arksey and O’Malley 2005).

Arksey and O’Malley (2005) suggested two approaches. The first is to produce tables and charts that maps the basic numerical analysis of extent, nature, and distribution of the studies included in the review. This includes presenting the geographical distribution of the studies, identifying the study populations, stating the range of interventions, research methods utilised, and intervention effectiveness.

The second approach is to organise the literature thematically. This stage involves presenting a summary table of key study characteristics, followed by a narrative overview highlighting each intervention’s design, sample size, participants, methods, outcomes, effectiveness, economic aspects, and research gaps. This approach enables comparison across interventions, identification of conflicting evidence, recognition of research gaps, and exploration of future directions.

In the current review, integration of both ways was considered based on the identified studies found after running the literature search. Additionally, a focus on highlighting the key information that answers the research question was prioritised.

3.4. Data synthesis

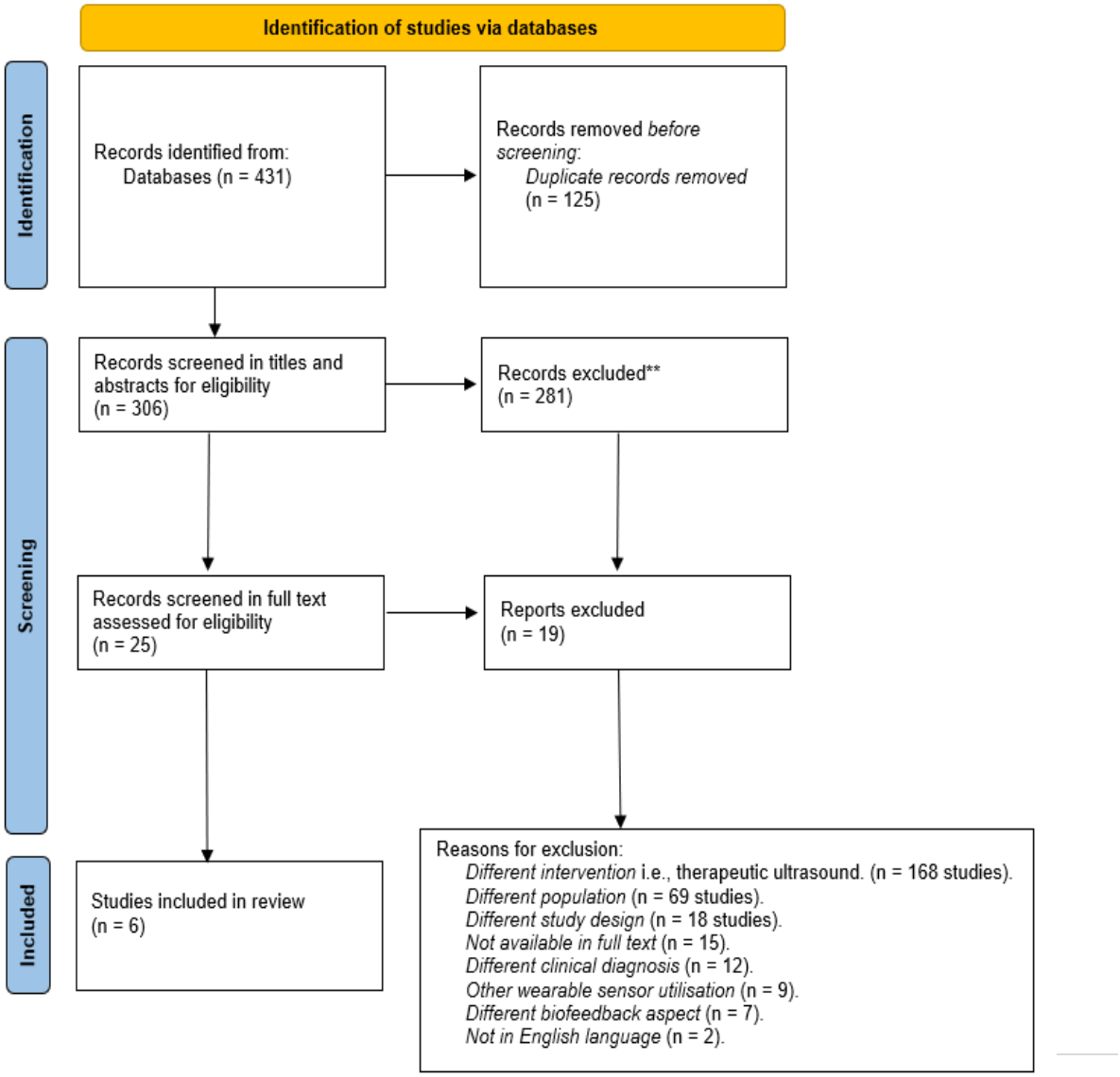
We used Microsoft Word to store the data taken from each study in tables and summarise it using visualisations like bar graphs, histograms, pie charts, and tables. We initially visualised the number of studies by year of publication, sample size, country, mean age, and gender of participants to aggregate general study and population characteristics. To answer “How has wearable sensor technology been used to provide biomechanical biofeedback for adults with lower limb osteoarthritis”, we collected the following metrics starting with the published study designs, the type of wearable sensors used, the functional task used to test the sensors, the location of the arthritis, the location of sensor placement, the type of biofeedback provided, the method of presenting the biofeedback, the biofeedback application from wearable sensors, the settings of each study, and the opinions of individuals with OA

and clinicians on using wearable sensors to provide biomechanical biofeedback. We also conducted an assessment that highlights the main findings and limitations of each included study.

3.5. Results

There were 431 records identified from the databases search. Of which, 125 were duplicated and were removed. 306 titles and abstracts were screened and assessed for eligibility. Of these, 25 articles were assessed in full text for eligibility, which resulted in identifying 19 articles that met the exclusion criteria. Thus, the article included in the current scoping review as only they demand suitable and met the inclusion criteria were 6 (Figure 2).

Figure 2 PRISMA Flowchart



3.5.1. Data extraction: general studies information

Table 9 Quantitative studies general information

No.	Author(s)	Year of publication	Study location	Study design	Sample size (n)	Participants (Gender)	Population	Study Settings
1	Ismailidis et al.	2020	Switzerland	Non-randomised controlled trial.	n = 67 n = 22 patients. n = 45 asymptomatic controls.	A. Male= 12 Female= 10 B. Male= 16 Female= 29	Group A: Severe hip OA. Group B: Healthy.	University laboratory.
2	Goślińska et al.	2020	Poland	Randomised controlled trial.	n = 81 n = 27 patients in the exercise group. n = 27 patients in manual therapy group. n = 27 asymptomatic control group.	Not clearly stated.	Group A+B: Knee OA patients. Group C: asymptomatic control group.	University clinic.
3	Angthong and Veljkovic	2019	Thailand.	Uncontrolled trial.	n = 52 patients, of which 24 arthritis patients.	Male= 15 Female= 37	Foot and ankle related conditions.	University laboratory.
4	Wang et al.	2020	Hong Kong	Non-randomised	n = 90. n = 78 Study group. n =	A. Male= 33. Female= 45.	Study group: Patients with	University, out of laboratory

				controlled trial.	12 Control group.	B. Male= 8. Female= 4.	MKOA. Control group: Healthy participants.	doorway.

n = Number OA = Osteoarthritis MKOA= Medial knee osteoarthritis.

Table 9 highlights the general information from each study. This table gathers the quantitative research included. (n= 3) studies were published in 2020 whereas (n) = 1 study was in 2019. the geographical distribution varies in which (n= 1) study was published in each Switzerland, Poland, Thailand, and Hong Kong. Only (n= 1) study was a randomised controlled trial. The highest number of participants was in Wang et al. (2020) study (n= 90). On the other hand, the lower number of participants was in Angthong and Veljkovic (2019) study (n= 52). All the studies included both male and female participants except the study by Goślińska et al. (2020) did not clarify any gender specification.

Table 10 Qualitative studies general information

n	Authors	Year of publication	Study location	Study settings	Theoretical background of the study	Sample size (n)	Sampling approach	Participant's characteristics
1	Papi et al.	2015	United Kingdom	University settings.	The usability and practicality of a new wearable sensor technology	n = 21 participants.	Poster advertisements	Diagnosed with OA through clinical assessment, imaging, or undergoing rehabilitation. Good

					based on patient's views.			understanding of written and spoken English.
2	Lin et al.	2019	United Kingdom	University settings.	Clinicians' views about the utilisation of new wearable technology (Flexifoot) with OA patients for successful implementation	n = 30 participants.	Telephone and email invitations.	Participants were clinicians: n = 11 physiotherapists. n = 11 orthopaedic surgeons. n = 5 general practitioners "GP". n = 3 podiatrists. Gender: n = 18 Male. n = 12 Female.

n = Number OA = Osteoarthritis

Table 10 illustrates the general information from each study. This table gathers the qualitative research included. Both studies were published in the UK and the most recent one was in 2019. Both studies were conducted in a university setting. Lin et al. (2019) study included the largest number of participants. (n= 1) study included knee OA patients whereas the other study included clinicians. The usability and practicality of a new wearable sensor technology based on patient's views was the theoretical background of Papi et al. (2015) study. On the other hand, Lin et al. (2019) looked at the clinicians 'views about the utilisation of new wearable technology with OA patients.

3.5.2. Age range across the studies

Ismailidis et al. (2020) reported a mean participant age of 66.1 years (SD = 8.9). Goślińska et al. (2020) included three groups with an overall average age of 64.7 years (SD = 6.2). Wang et al. (2020) reported a mean age of 59.7 years (SD = 7.1) for the OA group. Angthong and Veljkovic (2019) included participants with a mean age of 51.9 years (SD = 13.7). In studies where only age ranges were provided, estimated midpoints were used: Papi et al. (2015) involved participants aged 45–65, approximated at 55 years, and Lin et al. (2019) included clinicians aged 21–57, estimated at 39 years. Based on all extracted values (n = 8), the overall estimated mean age across the included studies was 58.2 years (SD = 9.4).

3.5.3. Types of commonly used wearable sensor technology

The type of used wearable sensors is illustrated across the six included studies. The number of inertial measurement units (IMUs) used overweight (83%) the number of other wearable sensors used (foot sensing insole= 16%).

3.5.4. Sites of sensor placement

Across the six studies, all of them (100%) placed sensors on the lower leg including below knee, shin, ankle, and foot regions. 33.3% of the studies utilised sensors placed on the thigh. Only 16.7% of the studies implemented pelvic sensors. The universal adoption of lower leg sensors demonstrates their fundamental importance in wearable gait analysis, whilst thigh and pelvic sensors appear to be used for specialised applications requiring additional kinematic information beyond the standard distal measurements.

3.5.5. The utilised testing tasks

Among the included studies, 33.3% were qualitative and did not incorporate structured testing tasks. Of the remaining quantitative studies, 25% utilised an active and passive knee flexion task, 25% employed a 10-metre walking test, and 50% implemented a 20-metre walking task. These findings indicate that walking-based assessments, particularly the 20-metre walk, were the most used testing protocols in quantitative evaluations.

3.5.6. The biofeedback applications with lower limb osteoarthritis

Half of the included studies (50%) delivered biofeedback focused on joint kinematics and spatiotemporal parameters. A further 16.7% applied biofeedback targeting joint proprioception, while another 16.7% focused on gait pattern feedback. The remaining 33.3% explored perspectives on biofeedback systems without implementing specific sensor-based feedback protocols, reflecting a qualitative approach to understanding user experiences and contextual factors

3.5.7. Types of provided feedback from wearable sensors

Figure 3 Types of Provided Feedback

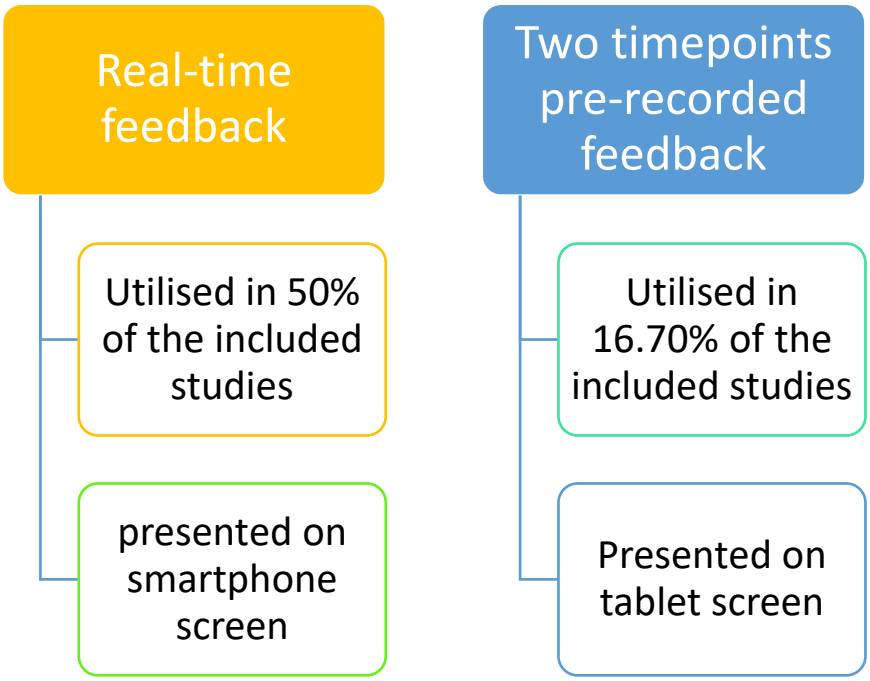


Figure 3 Real-time biofeedback delivery was the most common approach, reported in 50% of the included studies. Additionally, 16.7% of the studies employed a pre-recorded feedback system delivered at two timepoints. The remaining 33.3% explored user perspectives and system expectations without implementing a real-time or timepoint-based feedback mechanism.

3.5.8. Main interviews details

The included interview styles and their general characteristics are summarised as follows: 16.7% of the included studies conducted semi-structured interviews with individuals with OA, while 16.0% conducted focus-group interviews with clinicians.

3.5.9. Principle findings and quality assessment

Table 11 Included studies principle findings and quality assessment

No.	Author(s)	Outcome measures	Principal findings	Strengths	Limitations
1	Ismailidis et al. (2020)	Spatiotemporal measurements. Kinematic parameters.	**Spatiotemporal:** Patients with knee OA walked at slower speed compared to healthy controls. Patients had shorter stride length and longer stride duration compared to controls. **Kinematic parameters:** Patients with severe knee OA had significantly lower knee flexion during stance (4-24% of gait cycle, maximum difference: -6.8°) and swing (60-77%, maximum difference: -11.0°). Greater ankle dorsiflexion during stance (8-68%, maximum difference: +12.5°). At matched walking speed, no significant kinematic differences remained between groups. RehaGait® system provides feasible biofeedback for gait assessment.	Used validated inertial sensor system (RehaGait®). Included age-matched control group. Used Statistical Parametric Mapping (SPM) for comprehensive time-series analysis. Controlled for walking speed by testing controls at both normal and slow speeds. Objectively demonstrated that kinematic differences were due to walking speed rather than disease severity.	Sample size discrepancy between groups (patients n=23; controls n=28). Findings limited to one inertial sensor technology system. Study limited to laboratory settings. Gender imbalance (female n=13; male n=15 in patient group; female n=18; male n=10 in control group).
2	Goślińska et al. (2020)	Knee proprioception (joint position sense using Orthyo® system). Patient's function (WOMAC). Pain intensity (VAS).	**1-Knee proprioception:** Left knee showed significant difference between groups post-intervention (p=0.04). Exercise group: no significant change in proprioception pre-post (p=0.8) on left knee. Manual therapy group: participants showed significantly poorer joint position sense (JPS) post-treatment on left knee, indicating exercise is slightly better. No significant results for right knee proprioception. **2-Patient's function (WOMAC):** Both intervention groups showed significant functional improvement post-treatment (E: p<0.01; MT: p=0.01). No significant difference between groups post-treatment. **3-Pain level (VAS):** Both intervention groups showed significant pain reduction (p<0.01). No significant difference between groups post-treatment. Pain and function improved despite lack of JPS improvement, suggesting pain and function do not directly impact JPS. Orthyo® system provided accurate assessment of joint position sense.	Randomised controlled trial design. Used objective measurement (Orthyo® wireless sensors) for proprioception assessment. Included control group with no intervention. Used validated outcome measures (WOMAC, VAS). Assessed multiple parameters (proprioception, function, pain). Demonstrates feasibility of wearable sensors in clinical assessment.	Relatively small sample size (exercise group n=27; manual therapy group n=27; control group n=27). Sample size calculation method not clearly specified. Use of WOMAC and VAS are subjective self-assessment tools. Short intervention duration (10 days) for chronic condition management. Gender distribution not clearly reported for participants (gender not specified in groups).
3	Angthong and Veljkovic (2019)	Pain level (VAS). Gait parameters: walking distance, step count or length, cadence, speed. Health-related quality of life (SF-36).	Significant negative correlation between physical component summary (PCS) and maximal cadence (r=-0.308, p=0.025). Significant positive correlation between mean walking speed and mean cadence (r=0.776, p<0.001).	Validated wearable technology (Garmin foot pod). Used validated patient-reported outcome measures (VAS-FA, SF-36).	Sample size calculation method not clearly specified. Small sample size (n=52; 37 female, 15 male).

			Significant correlation between walking speed and mean step length (r=0.498, p<0.001). Significant negative correlation between mean cadence and mean step length (r=-0.491, p<0.001) and between maximal cadence and mean step length (r=-0.355, p=0.009). No correlation found between gait parameters and pain level. Cadence was the only objective spatiotemporal parameter significantly negatively correlated with subjectively reported PCS in health-related quality of life. Cadence is an essential parameter for compensatory gait mechanisms in foot-ankle condition patients.	Included diverse foot-ankle pathologies. Assessed both objective gait measures and subjective outcomes. Explored inter-metric relationships comprehensively. Age-matched participants (mean age 51.9 years).	Gender imbalance (71% female, 29% male). Limited generalisability due to heterogeneous foot-ankle conditions and single-site recruitment.
4	Wang et al. (2020)	Gait patterns (normal, toe-in, and toe-out). Knee adduction moment (KAM).	Toe-in gait reduced the first KAM peak. Toe-out gait reduced the second KAM peak. Both systems provided immediate (real-time) feedback on smartphone screen. Both systems minimised computational delay whilst providing sufficient accuracy. ANN model slightly more accurate than XGBoost model. Audio feedback system implemented. Provides viable solution for gait retraining outside laboratory.	Novel machine learning approach (ANN and XGBoost). Real-time feedback capability. High accuracy (R^2=0.956 for ANN; R^2=0.947 for XGBoost). Low-cost wearable sensors (IMU and plantar pressure sensors). Included diverse participant group (n=106; 78 knee OA patients, 28 healthy controls). Validated against laboratory-based measurements. Demonstrated clinical feasibility of wearable system. Gender distribution: 90 female, 16 male across all participants.	Systems relatively large and could affect smartphone battery life, potentially causing sudden shutdown. Both systems require stable internet connection, limiting practicality in some settings. Findings specific to one gait retraining strategy (foot progression angle modification only).
5	Papi et al. (2015)	N/A (qualitative study exploring patient preferences).	Patients showed positive response towards utilisation of wearable technology in rehabilitation context. Recognised benefits obtainable from using technology. Main determinants of acceptance: appearance and comfort during use. Wanted device to be small, light, discrete, not 'appear medical'. Preferred device in band form rather than integrated into leggings.	First qualitative study exploring patient preferences for wearable technology in knee OA. Used focus group methodology allowing in-depth exploration. Recruited from diverse socioeconomic backgrounds. Recruitment continued until data	Gender imbalance (19 female, 2 male). Participants unable to physically test the devices, limiting experiential feedback. Single geographical area (London), potentially limiting generalisability. Single-centre recruitment not clearly

			Supported use for exercise guidance, progress monitoring, and communication with clinicians. Wanted two operational modes: exercise guidance and everyday monitoring. Data should be available to both patients and clinicians.	saturation achieved (n=21; 4 focus groups). Aged 45-65 years, representing typical OA population.	stated.
6	Lin et al. (2019)	N/A (qualitative study exploring clinician preferences).	Clinicians thought wearable system may complement and improve current OA management methods. System recognised as useful for objective measures. Supported uses: assessing treatment efficacy, monitoring disease progression, feedback for patients and clinicians, monitoring activity levels/compliance, screening tool. Enhanced information exchange between clinicians and patients. Could motivate patients through goal setting. Main barriers: time, cost, patient compliance. Data should be secure, concise, and visually appealing. Duration of wear and data output frequency should depend on intended use. Identified potential uses beyond OA (Parkinson's disease, diabetic neuropathy, chronic pain, obesity).	First qualitative study specifically exploring clinicians' views on implementing instrumented insole for OA patients. Diverse clinician sample (11 physiotherapists, 11 orthopaedic surgeons, 5 general practitioners, 3 podiatrists; total n=30). In-depth semi-structured interviews allowing detailed exploration. Recruitment until data saturation achieved. Included multiple healthcare professional perspectives. Aged 21-57 years with 4 months to 28 years clinical experience. Analysed using inductive thematic analysis.	Clinicians unable to use device prior to interviews, limiting hands-on experiential feedback. Varied levels of experience and familiarity with wearable technologies among participants (18 male, 12 female). Majority recruited from London area (27/30), with 3 from other English cities, potentially limiting geographical generalisability. Prior knowledge of technology may introduce selection bias towards technology-positive participants.

Table 11 demonstrates the outcome measures, principal findings, and limitations from each of the included study in the revie

3.6. Discussion

This scoping review aimed to explore how wearable sensor technology has been used to deliver biomechanical biofeedback in the management of individuals with lower limb OA. This section discusses the finding from our search. Overall, there was a limited number of studies (n=6) that used wearable sensor technology with lower limbs OA and provided a biomechanical biofeedback. The section discusses four main areas: demographics, settings and functional tasks, biomechanical biofeedback applications, and movement measurement of wearable sensor technology. These findings highlight the current state of research in this field and identify key gaps that need to be addressed in future studies.

3.6.1. Demographics

In the current review, total of 313 participants were included across the six studies reviewed. The gender distribution showed that more females than males were involved. While this could be seen as a sampling imbalance, it reflects the higher prevalence of OA among females, as reported in a recent systematic review by Tschon et al. (2021). This gender pattern aligns with population trends in OA and therefore supports the generalisability of the findings.

Participants ranged in age from 45 to 66 years, with a mean age of 58.2 years, which corresponds with the typical age profile for OA. According to the OA Research Society International (OARSI 2022), OA is most commonly diagnosed after the age of 50. This supports the appropriateness of the included studies' sampling, as they focused on individuals diagnosed with OA, aligning with the age range most commonly affected and enhancing the clinical relevance of their findings.

Three broad participant categories were identified across the studies: individuals with OA, asymptomatic controls, and healthcare professionals. The majority of studies focused on individuals with knee OA, while fewer included participants with hip or ankle OA. This is consistent with the higher prevalence of knee OA compared to other lower limb joints (Tschon et al. 2021) and reflects current research interest in gait-related biomechanical changes in this population. Asymptomatic participants were primarily recruited as controls to compare joint kinematics and gait characteristics, providing baseline references for interpreting deviations in OA populations. Additionally, two studies involved healthcare professionals, including

physiotherapists and orthopaedic surgeons, to gather professional insights into the usability and relevance of wearable sensor feedback systems within clinical contexts.

Including these distinct participant groups helps to contextualise how biomechanical biofeedback has been used in different ways: from directly supporting self-management in people with OA to informing the design and clinical relevance of sensor-based interventions. This distinction directly supports the scoping review question by showing how wearable sensor technology is not only applied to monitor movement but also adapted according to the needs and roles of specific user groups.

3.6.2. Settings and functional tasks

In our scoping review, we found that the majority of included studies were conducted in laboratory environments, with only one study reporting the use of a home-based setting. None of the studies were implemented in routine clinical practice contexts such as outpatient physiotherapy clinics or rehabilitation services. This limited range of settings represents a significant constraint in how wearable sensors are currently applied for biomechanical biofeedback in OA populations.

This finding aligns with previous literature suggesting that, despite the portability and user-friendly nature of wearable sensor technologies, their potential to support real-world application remains underutilised. For instance, Patel et al. (2012) and Del Din et al. (2021) argued that these technologies are well-suited for deployment in home or clinical environments, where they could provide more accessible and scalable solutions. However, our review highlights that this potential is not yet being fully realised, echoing the conclusions drawn by Shull et al. (2014) and Dorschky et al. (2019), who noted that wearable sensors continue to be predominantly used in controlled, laboratory-based settings.

We found that delivering biofeedback exclusively in laboratory contexts may limit our understanding of how these technologies function in day-to-day rehabilitation. This interpretation is supported by Del Din et al. (2021), who highlighted that laboratory environments often fail to capture the variability and complexity of real-world movement. This is particularly relevant in the current study context for people with OA whose gait may be influenced by fluctuating pain, environmental factors, and task demands. Similarly, Shull et al. (2014) and Robbins et al. (2019) pointed out that

lab-based assessments may not accurately reflect the kinds of movements people typically perform in their daily lives. This raises questions about the external validity of study outcomes and their practical application in clinical settings or self-management programmes.

Our study also offers a distinct contribution when compared to prior reviews. For instance, Small et al. (2019) conducted a scoping review that mapped the use of wearable sensors in individuals with knee OA following arthroplasty. Although their review did not report on the settings in which the studies were conducted, it showed that wearable sensors were employed for various purposes such as detecting instability or measuring physical activity. Unlike our review, however, their focus was not on biofeedback. This contrast reinforces the uniqueness of our study, which specifically examined how wearable sensors have been used to deliver biomechanical feedback to individuals with OA.

Furthermore, in terms of functional tasks, we found that walking was the most commonly used task for biomechanical analysis, with protocols such as 10-metre or 20-metre walk tests frequently employed. While these variations did not appear to influence the main findings of the studies, the lack of standardisation complicates comparisons across studies. Roush et al. (2021) similarly observed that differences in walking protocols often stem from environmental constraints. This finding adds further weight to the argument for exploring more naturalistic environments, such as home or community settings, where movement can be assessed under conditions that better reflect everyday life.

Overall, our review highlights a notable gap between the technical suitability of wearable sensors for diverse settings and their current implementation, which remains predominantly confined to controlled environments. This discrepancy limits the broader utility of these technologies for supporting clinical decision-making or enabling self-management in real-world contexts. By extending future research into home and clinical environments, researchers can better capture the complexity of real-world movement and generate findings that are more representative of everyday rehabilitation needs. This is especially important for people living with OA, for whom context-specific factors can significantly influence the effectiveness and acceptability of biofeedback interventions.

3.6.3. Biomechanical biofeedback applications.

In our review, we found that inertial measurement units (IMUs) were the most commonly used type of wearable sensor across the six included studies. Sensor placement varied depending on the biomechanical parameters being assessed. For example, three studies positioned IMUs on the anterolateral thigh and lower leg to capture lower limb kinematics (Wang et al. 2020; Gośliński et al. 2020; Angthong and Veljkovic 2019). Similarly, foot-mounted sensors were used in studies by Lin et al. (2019) and Angthong and Veljkovic (2019) to monitor gait symmetry, while Ismailidis et al. (2020) placed sensors near the pelvic region, which is a location used less frequently, possibly due to practical challenges such as discomfort or difficulty securing the device.

These variations in placement are important to consider, as they directly influence both the accuracy of biomechanical data and the nature of feedback provided. This finding aligns with prior work by Shull et al. (2014), who emphasised the role of sensor location in capturing meaningful gait data. In our review, the biomechanical biofeedback delivered typically focused on spatiotemporal parameters, joint kinematics, and gait characteristics. Studies reported targeting stride length, gait symmetry, step count, and ROM as key feedback variables (Ismailidis et al. 2020; Wang et al. 2020; Angthong and Veljkovic 2019). One study (Gośliński et al. 2020) also addressed proprioceptive awareness by comparing joint movement perceptions before and after the intervention, offering a novel perspective on the use of feedback to enhance sensorimotor integration.

With respect to delivery methods, we observed that visual feedback was consistently used across all included studies. Participants typically received graphical representations of their performance via tablet or mobile interfaces, either in real-time or immediately after completing the activity. This is consistent with trends in musculoskeletal rehabilitation, where visual cues are commonly favoured for their simplicity and clarity (Silva-Batista et al 2023). However, in contrast to studies in neurological rehabilitation, where haptic and auditory feedback have been effectively employed to guide motor retraining (Shull et al. 2014; Riener et al. 2006), none of the studies in our review reported using such modalities. This suggests that the application of biofeedback in lower limb OA may currently prioritise user comprehension and ease of delivery over multi-sensory integration.

Notably, we also found that none of the studies described physiotherapists actively using biofeedback data to inform exercise prescription or adjust clinical interventions. The primary emphasis was placed on how participants interpreted and responded to the feedback themselves. While this user-focused approach may support autonomy and engagement, it highlights a current gap in clinician involvement. Unlike models in other rehabilitation domains where therapists integrate sensor feedback into clinical decision-making (e.g. Dobkin and Dorsch 2011), the studies in our review positioned feedback as a self-managed resource rather than a collaborative clinical tool.

Overall, these findings contribute directly to the aims of our review by illustrating the current applications of wearable sensor technology for biomechanical biofeedback in lower limb OA. While there is promise in the use of IMUs and visual feedback to enhance movement awareness, the lack of sensory diversity and clinical integration limits the full potential of these tools. Future research should explore more interactive and clinician-informed feedback models, as well as alternative modalities such as haptic or auditory cues, to expand the functionality and reach of sensor-based rehabilitation in this population.

3.6.4. Movement measurement of wearable sensor technology

In our study, we found that spatiotemporal (ST) parameters and joint ROM were detected by wearable sensors, which is similar to Small et al. (2019) scoping review. However, Small et al. (2019) review identified the use of wearable sensors with knee OA patients who underwent an arthroplasty whereas in our review we found that ST and ROM can be detected by wearable sensors with individuals with hip OA condition. Further, in the current review, we looked at the biomechanical information that can be shared with individuals with hip OA as a biofeedback about their condition, unlike small and colleagues' study that just identified wearable sensors as a tool that can collect ST and ROM data. Similar to Niswander et al. (2020) study, we looked at the location of wearable sensor placement. This review supports Niswander et al. (2020) study as knowing the appropriate sensor locations could assist in discovering anatomical regions that are less prone to mistake when monitoring the angular kinematics of joints. By doing so, we can demonstrate that the use of wearable sensors in clinical settings for rehabilitation assessment and diagnosis can be more reliable.

Kobsar et al. (2020) scoping review summarised the expanding body of evidence on the use of wearable inertial sensors for gait analysis in patients with OA of the lower extremities. Kobsar et al. highlighted the importance of having more research to improve the diagnosis and the management of lower limb. OA. The authors found that ST parameters, joint angles, and knee adduction moment (KAM) were the most reported data that are collected from wearable sensors. However, there is a lack of illustrating how to use wearable sensors in more meaningful approach for individuals with OA. Thus, the current study differs in that providing biomechanical biofeedback about ST and ROM is a keyway to bring wearable sensors towards clinical and diagnostic insight. The current review demonstrates that data about knee adduction moment can help identifying the different gait patterns of individuals with knee OA, which can be provided as a biomechanical biofeedback that can help in gait training/re-training. Moreover, we found that the use of wearable sensors for detecting knee ROM can be used with physiotherapy treatment as usual to help in increasing joint deep sense (proprioception). Lastly, we included qualitative studies in the current review that revealed both OA sufferers and clinicians, who are involved in treating individuals with OA, favoured having the use of this technology.

3.7. Implications

The findings of this scoping review offer several important implications for both clinical practice and self-management strategies in individuals with lower limb OA. As wearable sensor technologies become more accessible, their use to deliver biomechanical biofeedback presents new opportunities to support functional assessment, patient education, and engagement with physiotherapy.

First, the reviewed studies demonstrate that wearable sensors can provide biomechanical biofeedback on parameters such as spatiotemporal gait metrics, joint ROM (kinematics), and proprioceptive awareness (e.g. Goślińska et al. 2020; Wang et al. 2020). Sharing these metrics with individuals who have OA can enhance their self-awareness and understanding of movement deficits. This type of feedback enables patients to visualize how their joint functions, how they were affected by OA, and track changes over time, potentially increasing their motivation to participate in rehabilitation and supporting self-monitoring outside of clinical settings (Shull et al. 2014 and Dobkin and Dorsch 2011).

Second, biomechanical biofeedback can be used to explain compensatory movement strategies or altered gait patterns, particularly in individuals who develop adaptations to pain, instability, or joint stiffness. For example, studies in this review illustrated how wearable sensors were used to monitor asymmetrical gait, reduced stance time, or limited joint excursion (Ismailidis et al. 2020; Wang et al. 2020). Providing visual representations of these movement characteristics allows users to gain insight into how OA affects their everyday mobility, and it can offer a valuable basis for physiotherapists to educate patients on the rationale behind specific exercises or movement corrections (Del Din et al. 2021).

Additionally, the application of wearable sensors is not limited to assessment alone. The review findings indicate that they can support monitoring and treatment, particularly when used across different time points to compare baseline and post-intervention performance. For instance, Goślińska et al. (2020) reported on using sensor-based measures of knee joint ROM before and after standard physiotherapy. These changes were used to provide post-treatment feedback to the researchers, helping to reinforce perceived progress and guide future therapeutic targets. This type of feedback loop may enhance the continuity of care between sessions and increase patient confidence in their rehabilitation plan.

Finally, wearable sensor biofeedback may be best integrated into care alongside physiotherapy treatment, rather than in isolation. None of the reviewed studies implemented biofeedback as a standalone intervention. Instead, feedback was typically offered before or after structured rehabilitation activities or assessments, suggesting that its value lies in complementing, not replacing, traditional care. As such, physiotherapists may consider using wearable biofeedback tools to inform clinical decision-making, track performance trends, or personalise treatments and goal setting, particularly in patients managing their condition long-term.

3.8. Recommendations

This scoping review identified several key areas where future research and development could enhance the use of wearable sensor technologies for biomechanical biofeedback in the management of lower limb OA. These recommendations are grounded in the synthesis of findings from the six included studies.

First, there is a clear need to develop a structured intervention toolkit that incorporates wearable sensors to capture and deliver biomechanical biofeedback relevant to physiotherapy. Several studies in the review (e.g. Ismailidis et al. 2020; Wang et al. 2020) demonstrated how gait-related data and joint kinematics could be used to monitor movement changes. However, there was no consistent platform or system for integrating this feedback into clinical practice. A standardised toolkit could support physiotherapists in tailoring exercise prescriptions based on real-time or session-based biomechanical data, improving both the relevance and personalisation of care (Del Din et al. 2021).

Second, the review highlights the potential value of creating a biomechanical reporting system to share feedback with patients alongside conventional physiotherapy. Goślińska et al. (2020) and Wang et al. (2020) demonstrated the use of visual feedback post-intervention, which participants used to reflect on their movement progress. Building on these findings, a clinical report format, similar to existing PROMs summary tools (Pila et al. 2023; Stern et al. 2022), could be co-designed with clinicians and patients to support education, adherence, and shared decision-making.

Another important finding from the review is that nearly all included studies were conducted in laboratory settings, with only one study collecting data outside of the lab. Given the portability of wearable technology, future research should explore applications in clinics, homes, and free-living environments, where users typically engage with rehabilitation activities. This would improve the ecological validity of future interventions and support the broader adoption of wearable biofeedback systems (Dobkin and Dorsch 2011 and Small et al. 2019).

In addition to design and implementation improvements, methodological advancements are needed. Future studies should aim for larger sample sizes,

guided by appropriate power calculations, to ensure that findings are robust and generalisable. Most of the studies in this review were limited by small sample sizes, which constrains the strength of their conclusions. Extended intervention durations should also be considered to evaluate how wearable biofeedback systems perform over time and whether sustained use improves outcomes in OA populations.

Technological improvements are also recommended. Several studies relied on devices that had limited battery life or required stable internet connections, constraints that may limit the functionality of these systems in community or home-based settings. Therefore, future research should explore longer battery life, offline-compatible systems, and energy-efficient designs, particularly for interventions intended to be used outside of controlled environments (Shull et al. 2014).

Lastly, while many studies reported movement outcomes, few captured user experiences or perceptions of using biofeedback tools. Future work should incorporate qualitative interviews with individuals who receive or interact with biomechanical feedback. This would allow researchers to better understand the acceptability, usability, and motivational impacts of sensor-based interventions, aligning with patient-centred care principles (Sekhon et al. 2017).

Together, these recommendations reflect the current gaps identified through this review and point to practical, technical, and methodological directions for advancing the field of wearable biofeedback in lower limb OA management.

3.9. Limitations

This scoping review was conducted systematically using recognised frameworks for evidence mapping (Arksey and O'Malley 2005), but certain limitations should be acknowledged. The number of included studies (n = 6) was relatively small, which reflects the emerging nature of research on wearable sensor-based biomechanical biofeedback in lower limb OA. As such, the findings should be viewed as an initial overview of current practice rather than a comprehensive evidence base.

All included studies met the eligibility criteria and aligned with the review's specific focus on interventions that delivered biomechanical biofeedback using wearable sensors. This focus necessarily excluded studies where wearable sensors were used only for diagnostic or assessment purposes without providing feedback to users. While appropriate for the review objective, this may have limited the inclusion of broader technological innovations in sensor use.

Overall, these limitations reflect the early stage of the field rather than methodological shortcomings. The findings remain valuable in identifying current

applications, highlighting knowledge gaps, and informing future research directions aimed at advancing biofeedback-supported rehabilitation in OA care.

3.10. Conclusion

This scoping review demonstrates that wearable sensor technology is a promising tool for managing lower limb OA by capturing and analysing gait-related movement data. The included studies showed that biofeedback was primarily delivered on spatiotemporal parameters, joint angles, and gait patterns, often during or following walking tasks (Ismailidis et al. 2020; Wang et al. 2020; Angthong and Veljkovic 2019). In addition, one study used wearable sensors before and after physiotherapy to provide feedback on knee proprioception (Goślińska et al. 2020), highlighting their potential for tracking joint function and post-treatment improvements.

However, the current evidence base reveals that wearable sensor systems have primarily been applied in laboratory settings, with limited translation into clinical or real-world rehabilitation contexts. Their use has also been largely restricted to assessment and monitoring, rather than being integrated as an active component of physiotherapy interventions. At present, there is little evidence of these tools being used to provide real-time or session-based biofeedback aimed at guiding patient movement or supporting therapeutic behaviour change.

Future research should explore how wearable sensor technology can be systematically embedded into physiotherapy practice, particularly in home or clinic-based environments. This includes developing structured biofeedback protocols that are meaningful to patients and actionable by clinicians, for example, by informing tailored exercise prescription or supporting patient education. In doing so, biomechanical biofeedback could move beyond assessment alone and become a more impactful tool in supporting person-centred OA management.

Chapter 4

Synthesis of Literature Review and Scoping Review Findings

4.1 Introduction

This chapter synthesises the key findings from the narrative literature review (Chapter 2) and scoping review (Chapter 3) to provide a comprehensive understanding of digital health interventions and biomechanical biofeedback applications for CKP management. Together, these chapters illuminate how digital technologies have advanced pain management, while also exposing critical limitations that justify the development of a more integrated and personalised approach.

The literature review examined 18 studies that focused on digital health interventions for CKP, particularly those involving mobile apps and web-based platforms designed to support home exercise. These studies consistently demonstrated potential benefits, including reductions in pain, improvements in function, and enhanced quality of life. For instance, Yamamoto et al. (2022) reported significant pain reductions following a 12-week mobile application-based exercise programme, while Thiengwittayaporn et al. (2023) observed improved ROM and quality of life using an app-based intervention compared to educational handouts. Broader findings across the literature highlighted how digital tools support muscle strength, joint stability (Zeng et al. 2021), and mental wellbeing (Hallgren et al. 2021), confirming their growing role in extending physiotherapy into home and community settings.

4.2 Current state of digital health interventions

Despite promising outcomes, the implementation and usability of digital tools varied considerably. SUS scores ranged from below average to good (e.g., 57.8 in Shewchuk et al. 2021 and 77.5 in Joseph et al. 2022), reflecting mixed user experiences. Usability concerns were typically linked to missing features such as exercise tracking, reminders, and feedback functions, elements frequently requested by participants to maintain motivation and monitor progress.

Some digital interventions also aimed to enhance communication between users and healthcare professionals. Notably, Pila et al. (2023) and Stern et al. (2022) developed online platforms that generated personalised reports based on patient-reported outcome measures (PROMs) to assist in surgical decision-making. While participants appreciated receiving individualised feedback that helped them understand their health status and engage in treatment decisions, they also expressed frustration with the lack of clear explanations and the absence of objective clinical data. The reliance solely on PROMs made it difficult to interpret functional limitations in concrete terms, signalling a need for reports that include more actionable, objective insights into joint and movement health.

These concerns were echoed and extended in the scoping review, which explored the use of biomechanical biofeedback through wearable sensor technologies. Six studies were identified, most of which used inertial measurement units to monitor spatiotemporal and kinematic gait parameters. Although these systems successfully captured objective movement data, their application remained largely restricted to laboratory environments. Feedback was generally limited to visual formats, and the data collected were seldom used to personalise exercise prescriptions or guide clinical decision-making. Importantly, none of the studies demonstrated physiotherapists applying this biomechanical feedback in real-world therapeutic planning.

4.3 Key research gaps

Taken together, the insight form both the narrative literature review and the scoping review point to four significant research gaps as follows,

1-Lack of personalisation

Interventions typically delivered standardised exercise programmes without accounting for individual movement limitations or functional needs. This was apparent across digital health interventions (e.g., Yamamoto et al. 2022; Joseph et al. 2023; Weber et al. 2024) as well as biomechanical feedback studies. In contrast, Davergne et al. (2023) showed that personalisation could enhance user engagement and align interventions more closely with participant expectations.

2-Underuse of objective movement assessments:

Despite the availability of wearable sensors, the data they generated were rarely used to inform exercise prescription or monitor functional progress. This underutilisation of objective data represents a missed opportunity to create more precise and responsive interventions.

3-Inconsistent support for adherence and engagement:

While some interventions achieved relatively high adherence (e.g., Yamamoto et al. 2022: 82.4%), others experienced significant drops over time (e.g., Nelligan et al. 2021: from 97% to 61%). Several features known to support sustained use, reminders, logging systems, video demonstrations, feedback reports, and personalised adjustments, were included across studies, but rarely all in one place. Interventions typically offered different combinations of these features without a comprehensive and integrated toolkit seeking for gathering the benefits of those features together.

4-Limited integration of feedback into clinical practice:

Most interventions either offered basic completion metrics or relied on PROMs. Even in studies collecting biomechanical data, such feedback was simplified and disconnected from therapeutic workflows. To our knowledge, no evidence was found of physiotherapists using biomechanical biofeedback to prescribed exercises or evaluate progress, suggesting a disconnection between available data and its clinical utility.

4.4 Positioning within the medical research council framework

These gaps present a clear opportunity to unify the strengths of digital health and biomechanical technologies. While the literature review highlighted the promise of digital delivery for exercise-based rehabilitation, and the scoping review confirmed the technical capability of biomechanical data capture, to our knowledge, no study combined both real-world, user-focused system. The work by Pila et al. (2023) and Stern et al. (2022) further reinforced the value of digital reporting but called attention to the need for deeper integration of objective data.

To guide the development of an integrated solution that addresses the identified research gaps, this study conceptually introduces a DBBT. This toolkit was designed to combine biomechanical assessment, personalised exercise prescription, and digital engagement features for individuals with CKP. To structure and evaluate the development process, the study was positioned within the UK Medical Research Council (MRC) framework, which provides comprehensive guidance on the design and evaluation of complex health interventions (Shahsavari et al. 2020).

The DBBT incorporates the Xsens sensor system, MotionCloud software, and the Kinduct platform, all developed by Movella company. MotionCloud is an established system that receives raw gait data from Xsens Analyze software post movement data collection, processes it, and generates individual gait reports. The Kinduct online platform and mobile application had been previously developed and utilised with athletes but had not been applied in symptomatic cohorts such as individuals with CKP. For this project, the existing Kinduct system was adapted and integrated with the biomechanical assessment components through the regular communication and meetings with the research and development team.

In the context of this PhD project, a bespoke Cardiff University version of the toolkit was adapted through an ongoing collaboration between Movella and the Cardiff University SPIN research group, of which the researcher (M.S.) is a member. This version was specifically modified for use in the PhD following presentation of evidence from a scoping review (chapter 3), which identified a gap in the literature regarding the use of wearable sensor technology gait reports as a biomechanical biofeedback tool for individuals with lower limb OA. The findings of this review were used to justify progression and adaptation of the Cardiff-specific version, ensuring the toolkit was suitable for a symptomatic population. M.S. was actively involved throughout the adaptation process, providing input and guidance based on physiotherapy expertise, and liaising with the development team on how the toolkit should function in the context of participant use. Specific modifications were implemented, including the integration of PROMs relevant to individuals with CKP, and refinement of exercise video demonstrations to ensure they were short and clear. These alterations were finalised prior to study protocol development and ethical approval. Following completion of the bespoke version, the researcher

received training in its operation, which ensured preparedness for the delivery of the DBBT and subsequent data collection.

According to the MRC framework, the DBBT is currently in the stage of the development phase. While it has been conceptually designed and refined based on evidence and user needs, it has not yet undergone formal feasibility testing or full clinical evaluation, which are core components of the subsequent MRC phases (Figure 4). Therefore, the current study represents an important step within the development phase, evaluating the acceptability and usability of the DBBT from the perspective of its intended users before progression to feasibility testing.

4.5. PhD thesis aim

To evaluate the acceptability and usability of a digital biomechanical biofeedback toolkit (DBBT) for the physiotherapy management of individuals with chronic knee pain.

4.6. Research question

Is a digital biomechanical biofeedback toolkit (DBBT) acceptable and usable to individuals with chronic knee pain?

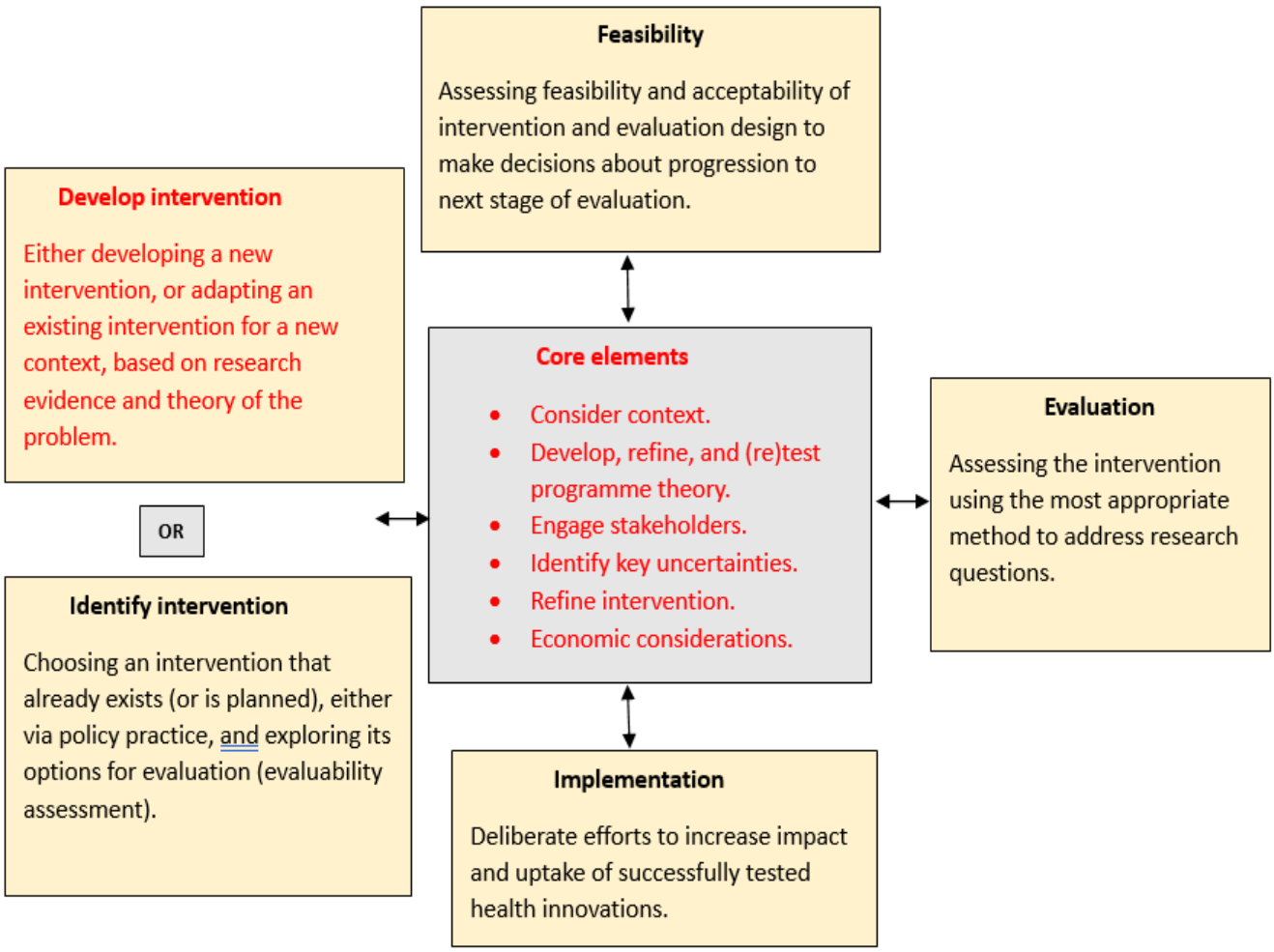
4.7. Objectives

(1) To explore the acceptability and usability of the DBBT among individuals with CKP.

(2) To observe changes in biomechanical parameters, including kinematics and spatiotemporal measures, before and after the use of the DBBT

(3) To observe perceived changes in PROMs responses over the duration of the study.

Figure 4 MRC Framework



Chapter 5

Methodology chapter

5.1. Introduction

This chapter outlines the methodology employed to evaluate the acceptability and usability of a DBBT for the physiotherapy management of individuals with chronic knee pain. The research question guiding this project is: “Is a digital biomechanical biofeedback toolkit (DBBT) acceptable and usable to individuals with chronic knee pain?”
This question responds to a literature gaps identified in earlier chapters (Chapter 4: Synthesis of the Literature Review and Scoping Review) which highlighted the absence of early-stage evaluation for such digital interventions in musculoskeletal care.

Moreover, given the dual focus on acceptability and usability evaluation, a mixed methods design underpinned by a pragmatic research philosophy was chosen. This approach facilitates a comprehensive understanding of how participants interact with and perceive the DBBT, integrating both quantitative and qualitative data (Bishop 2015; Munn et al. 2018). Additionally, the study employed a pre-post design, not with the aim of detecting between-groups clinical significance, but to enable structured data collection at two timepoints, which supports baseline measurement and helps assess whether participants share similar characteristics and are representative of the target population, and further allow participants to actually engage with the DBBT before evaluating the acceptability and the usability.

5.1.1. Chapter structure

This chapter is structured as follows:

Section 1: Research Philosophy and Methodology
Describes the philosophical underpinnings of the study and provides justification for adopting a mixed methods design grounded in pragmatism.

Section 2: Research Design
Outlines the overall study design, including the use of a pre-post structure.

Section 3: Materials and methods

The materials and methods sections include several areas as follows:

1- Intervention Description
   Defines the components of the DBBT using the Template for Intervention Description and Replication (TIDieR) to ensure clarity and replicability.

2- Acceptability and Usability Outcome Measures
   Details the outcome measures used to assess Acceptability and Usability, including variables, definitions, data collection tools, justification of measurement validity and reliability, data management and data analysis.

3- Study Setting and Participant Recruitment
   Provides an overview of the study population, inclusion and exclusion criteria, sampling strategy, recruitment process, piloting, and research procedure.

4- Ethical Considerations
   Summarises the ethical approvals, consent procedures, and measures taken to protect participant welfare.

5.2. Research philosophy and methodology

In academic research, research philosophy guides the processes of data collection, interpretation, and implementation; and it represents the fundamental assumptions researchers hold about reality and how it can be explored thereby influencing methodological decisions and the interpretation of results (Crotty 1998). Research philosophy generally addresses two key dimensions: ontology, which examines the nature of reality, and epistemology, which explores the nature of knowledge and how it can be acquired (Guba and Lincoln 1994). Various philosophical paradigms such as positivism, interpretivism, and pragmatism offer distinct perspectives on these dimensions, shaping how researchers approach complex challenges (Creswell and Creswell 2018).

Ontology considers whether reality exists independently of human perception or is socially constructed. Realist ontologies assert that reality is objective, external, and measurable, a perspective often associated with positivist research (Bryman 2016).

In contrast, relativist ontologies suggest that reality is subjective and shaped by social interactions, aligning more closely with interpretivism (Guba and Lincoln 1994). On the other hand, epistemology concerns how knowledge is obtained. Positivist epistemology assumes that knowledge can be discovered through systematic observation and objective measurement, while interpretivist epistemology prioritises understanding meaning through human experience (Saunders et al. 2018).

Given the complexity of the current study, that include various data sources, adopting a single ontological or epistemological viewpoint may be limiting. For this, this study adopts pragmatism, a philosophy that rejects rigid divisions between positivism and interpretivism in favour of a flexible, problem-centred approach (Tashakkori and Teddlie 2010). Pragmatism acknowledges both objective elements that can be measured and personal experiences that can be understood, avoiding adherence to a single ontological stance (Feilzer 2010).

In this project, pragmatism aligns with the primary goal of evaluating the acceptability and usability of the DBBT with CKP population. This philosophy allows for the exploration of participants' qualitative insights alongside quantitative data. The epistemological foundation of pragmatism is similarly pluralistic. It maintains that knowledge is acquired through both practical experience and empirical observation (Morgan 2007). Unlike positivism, which seeks universal truths, or interpretivism, which focuses on expressed meaning, pragmatism views knowledge as dynamic and shaped by its practical applications (Biesta 2010). Furthermore, in terms of methodology, pragmatism is widely recognised in the academic literature as a philosophical paradigm that aligns closely with mixed methods research (Brierley 2017). The research by Byrne (2023) explains that mixed methods methodology is not just combining the two, quantitative and qualitative, methods into one frame. Instead, it has a deeper meaning of combining different types of data sources, and different types of analysis to develop an integrative outcome, which aligns with pragmatism. Therefore, using both quantitative and qualitative methods in this study should be interdependent and both should serve the study purpose to finally answer the research question and meet the research aim.

Furthermore, mixed methods designs are distinguished by their temporal structure and approach to data integration (Creswell and Clark 2018). Sequential designs comprise distinct phases wherein initial data collection and analysis directly shape subsequent data collection (Morse and Niehaus 2009), with sequential explanatory designs commencing with quantitative inquiry followed by qualitative exploration, and sequential exploratory designs reversing this order (Creswell et al. 2003). Whilst offering iterative refinement, sequential approaches require extended timeframes, multiple participant contacts, and risk attrition (Creswell and Clark 2018). Conversely, embedded designs involve concurrent collection of qualitative and quantitative data within a single phase, with integration occurring at interpretation rather than one dataset informing collection of another (Fetters et al. 2013; Morse and Niehaus 2009). This proves advantageous when research questions require holistic interpretation of complementary datasets within constrained timeframes, particularly in intervention studies where contextual understanding must accompany outcome measurement (Schoonenboom and Johnson 2017).

This study employed an embedded design wherein qualitative semi-structured interviews served as primary data for acceptability evaluation guided by the theoretical framework of acceptability (Sekhon et al. 2017), and the system usability scale and adherence rates served as secondary data to evaluate the usability. Lastly, kinematic, spatiotemporal, and participant-reported outcome measures provided supplementary contextual data, all collected concurrently. This approach was justified for three reasons. Firstly, the research question focused on evaluating acceptability and usability, requiring comprehensive understanding through complementary datasets rather than iterative hypothesis generation, quantitative measures contextualised experiential accounts without necessitating sequential phases (Morse and Niehaus 2009). Secondly, participants attended laboratory facilities twice within doctoral timeframes, and sequential phases would have required additional visits, increasing burden and risking attrition (Creswell and Clark 2018). The embedded design maximised efficiency whilst maintaining rigour appropriate for developmental evaluation (Schoonenboom and Johnson 2017). Finally, the approach aligned with pragmatic philosophy, which emphasises addressing research questions through appropriate methodological combinations rather than rigid sequential structures (Morgan 2007), proving particularly valuable in

digital health research where user experience and usage patterns may diverge (Yardley et al. 2015). A sequential design would have been methodologically unnecessary for this early-phase developmental evaluation.

5.3. Research design

In the current study, the pre-post experimental design is utilised as it aids in the early development and evaluation of the (DBBT). The study design aims to collect descriptive data to support the refinement and adaptation of the intervention prior to feasibility or pilot testing, rather than to assess effectiveness (O'Cathain et al. 2019; Skivington et al. 2021).

Several benefits from pre-post design occur during the developmental phase of the DBBT. The initial stage of this research process involves collecting baseline data which supports the development of detailed participant characteristic profiles prior to intervention exposure (Craig et al. 2008). This leads to gain the ability to determine the intervention's implementation context which informs its suitability for the targeted population group (Skivington et al. 2021).

The post-intervention phase facilitates the collection of outcome data following participants' exposure to the intervention. While the objective is not to identify statistically significant changes, post-intervention observations provide valuable insights into acceptability and usability, particularly in relation to user responses and usage patterns (Bashi et al. 2020). Descriptive analysis of participant interactions with the DBBT further supports understanding of user experience, which is central to evaluating both acceptability and usability. Detailed outcomes are discussed later in this chapter.

5.4. Research outcome measures

Presented in this section are the primary, secondary, and supplementary outcome measures, which are addressed in connection to the research question and the study aim.

Primary outcome

- Acceptability outcome through semi-structured interviews following the theoretical framework of acceptability.

Secondary outcomes

- Usability outcomes through the utilisation of system usability scale (SUS) and quantifying adherence rates to using the DBBT mobile application, namely, Kinduct Athlete.

Supplementary outcomes

- Kinematics and spatiotemporal parameters through using wearable sensor technology, and participants reported outcomes (PROMs) submitted using Kinduct Athlete application.

5.5. Materials and methods

This section starts with a detailed and completed items of the template for intervention description and replication (TIDieR). After that, each of the study outcome measures is explored in terms of its relevance to the research objectives, the methods of data collection, how the data were managed, and the approaches used for analysis. Given the distinct nature of the primary and secondary outcomes, the data sources and analytical strategies are organised under their respective headings to ensure clarity and alignment with the overarching evaluation approach. Additionally, the details of the study settings, participants inclusion and exclusion criteria, recruitment, sample size, piloting, and study procedure are explained in this section.

5.5.1. The template for intervention description and replication (TIDieR)

The template for intervention description and replication (TIDieR) was developed by Hoffmann et al. in 2014 as a checklist and guide to improve the reporting of complex interventions in research studies. It consists of several items that provide a structured framework for describing interventions, including their rationale, materials, procedures, providers, delivery, modifications, and fidelity. The TIDieR checklist is designed to enhance the transparency and reproducibility of interventions, allowing clinicians, researchers, and other stakeholders to better understand and evaluate the details of complex interventions. The development process for TIDieR template involved a literature review, a Delphi survey of an international panel of experts, and a face-to-face panel meeting to ensure comprehensive and consensus-based

content. The TIDieR template and guide are a valuable resource for improving the quality of intervention reporting across various study designs, ultimately facilitating the implementation and assessment of interventions in both clinical and research settings. Since the current project research question asks, ‘Is a digital biomechanical biofeedback toolkit (DBBT) acceptable and usable to individuals with chronic knee pain?’, It is important first to have a clear understanding of the DBBT, which justifies the decision of using TIDieR template.

5.5.1.1. *The template for intervention description and replication items*

In this section, TIDieR items are presented, and each item will include a brief description on what it is, followed by the actual implementation in relation to the DBBT.

Item (1) Brief name and components

This item aims to provide a phrase, name, or an abbreviation to describe the intervention, which for the current study was the DBBT. The DBBT name describes that the current intervention includes components as follows, (1) Xsens wearable sensor technology: This component collects gait data using MVNX Analyze software. (2) MotionCloud online website: This platform processes the gait data and generates comprehensive gait reports. (3) Kinduct online digital platform: This tool creates participant profiles that include personalised exercise programmes, sets up reminders, and enables researchers to track and monitor participants' exercise completion and self-reported outcomes submissions. (4) Kinduct athlete mobile application: Participants use this app from home to receive reminders, log completed exercises, watch video demonstrations of the exercises, and fill out and submit self-reported outcomes. Thus, the DBBT stands for the major components of the developed intervention.

Item (2) Why

In this item, a description of the rational, goal, or theory of the essential elements of the intervention should be highlighted. The management of CKP requires new digital interventions due to its growth and the mechanically driven nature of the disease (Tunen et al. 2018). Biomechanical biofeedback is crucial in these interventions as it can address joint movement limitations, malalignments, movement patterns and loading which leads to more insight on individuals’ movement patterns (Tunen et al.

2018). Implementing biomechanical biofeedback, then, can optimise personalised exercise prescription by providing feedback on those elements leading to targeted and effective exercise programmes (Munsch et al. 2020). Furthermore, the adoption of biomechanical biofeedback could serve as a powerful means of engaging individuals with CKP in their treatment by promoting active participation and improving their understanding of safe movement patterns. This, in turn, may enhance exercise adherence and support self-management by helping individuals feel more confident and less fearful about exacerbating their symptoms during physical activity (Gool et al. 2005). Therefore, the integration of biomechanical biofeedback in new digital interventions for chronic knee conditions is essential not only for optimising exercise prescription, but also for improving exercise adherence, and enhancing self-management.

In the context of the current intervention, the DBBT was developed to offer physiotherapists and individuals with CKP with several options that include:

1. Personalised Exercise Prescription
   Objective biomechanical, or movement, data that can be used in the form of a report to personalise the exercise prescription by physiotherapists.

2. Engagement in Condition Management
   Allows individuals with CKP to engage in their condition management process via receiving a biomechanical biofeedback report, which would increase their movement understandability and is part of the patient education approach.

3. Identification of Limitations and Patterns
   Used by physiotherapists to identify lower limb joint limitations and movement patterns, which would influence their clinical decision making when creating their treatment plan.

4. Tracking and Monitoring
   Helps in tracking, monitoring, and reassessing individuals with CKP.

5. Pain Information for Reassessment
   Provides both physios and individuals with CKP with pain information that can be used as an important part of the reassessment, follow-ups, and self-monitoring.

6. Emphasis on Self-Management Approach
   Emphasises the self-management approach for individuals with CKP to help them become part of the treatment journey.

Item (3) Why (materials)

Item three focuses on describing any physical or information materials used in the intervention including (1) materials used in the intervention, (2) provided to participants, (3) used in the intervention delivery, or (4) used in the training of using the intervention for both the provider and the recipient. In the current project, the provider is the researcher (M.S.), and the participants are the study group (individuals with CKP). The researcher used Xsens MVN wearable sensors to collect gait data. Also, an online digital platform (namely Kinduct), where participants profiles were created, exercises were prescribed, and PROMs questionnaires were administered. Additionally, (M.S.) used MotionCloud, which is a website that is linked to the digital platform, and it analyses the collected data then provides a gait report. On the other hand, the study group received participants' information sheet (PIS) that has the required details to take part in the intervention (Appendix 5), and they used a mobile application, namely, Kinduct Athlete that presented their personalised exercise programmes, provided an option to log each exercise upon completion, receive auto remainders, watch exercise videos, and fill in PROMs questionnaires.

Item (4) What (procedure)

A description of each procedure, activity, or process used in the intervention should be highlighted in this section. It is important to highlight that this section is mainly explaining the procedure of using the DBBT, and not the whole PhD project, because the PhD project included more details which are presented in the data collection section later in this chapter.

For the DBBT procedure, since the intervention requires placement of Xsens MVN wearable sensors, the placement guide tutorials from Movella Xsens website and the Xsens manual guidelines (Xsens Technologies B.V. 2021; https://tutorial.movella.com/) were first used to correctly place each sensor in its right

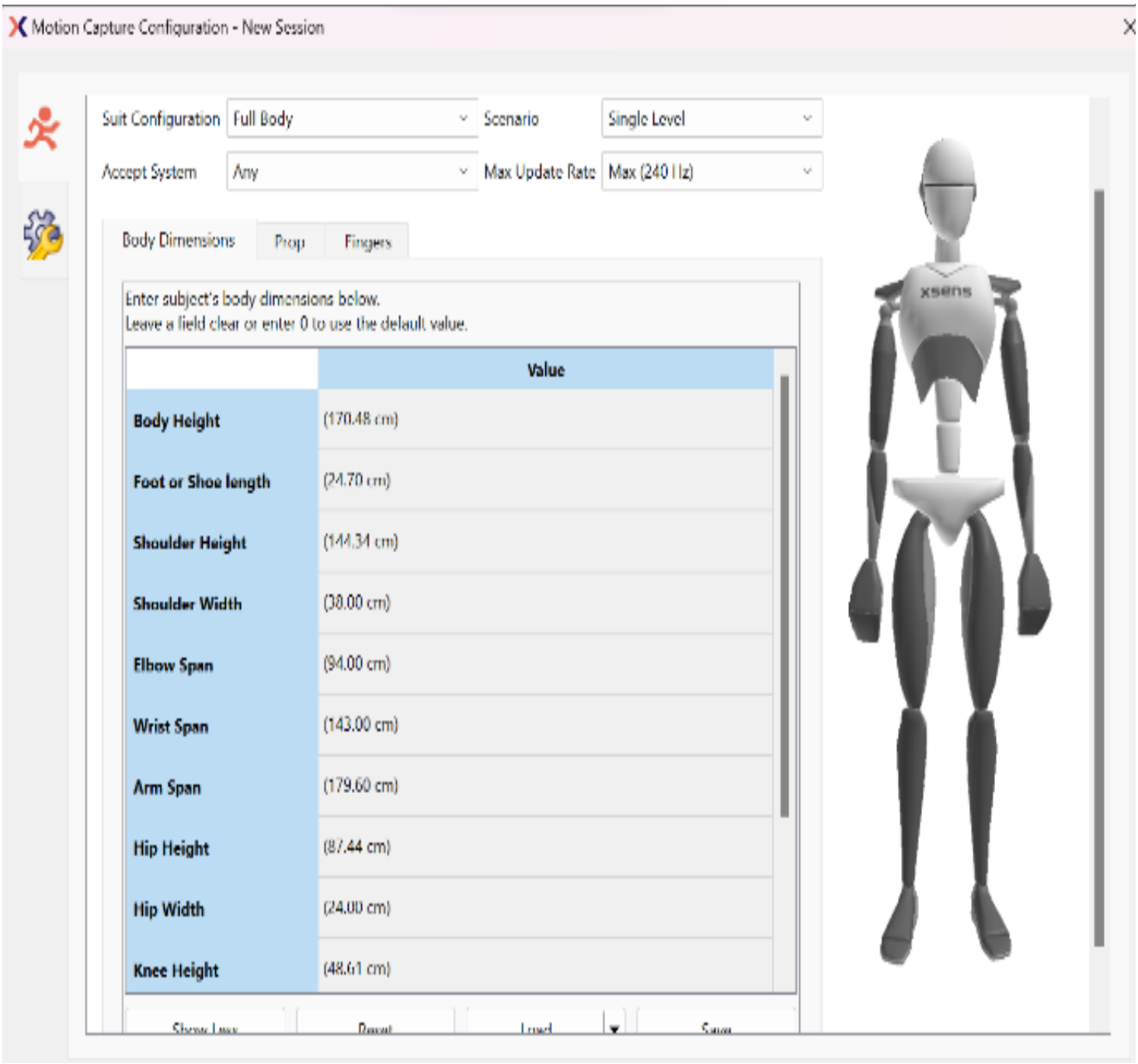
place. I am also including the steps of using the Xsens MVN sensors in this section. Overall, the procedure can be divided into six main steps.

The first step was the preparation and sensor placement step, followed by the calibration step. The third step was collecting movement data, and the fourth step was sending the data to the motion cloud for gait report generation. For the fifth step, it was the researcher (M.S.) interpretation of the gait report to the participants. Lastly, the sixth step is the exercise prescription step. In addition, the current project was designed to be completed on two lab visits. For this, the steps from 1 to 6 were done with each participant on the first lab visit whereas the steps from 1 to 5 were done with participants who came for the second lab visit. Below, each step is further explained.

Step (1) Preparation and sensor placement

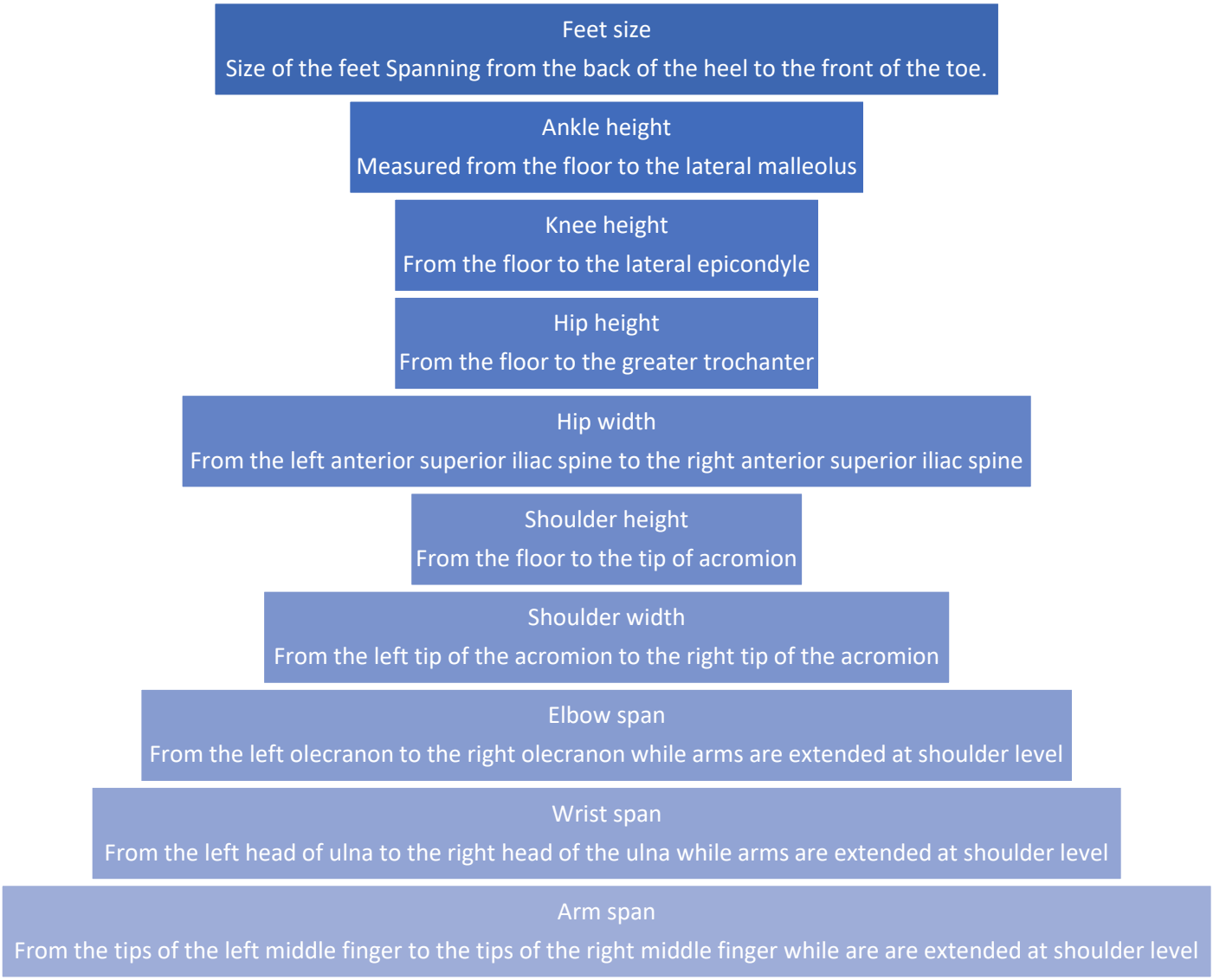
With the arrival of each participant, they were asked to fill PROMs including WOMAC, TSK, PHQ-9, NPRS, and SES6G, through Kinduct mobile application. Then, participants were asked to wear sportswear (shorts and shirts) to facilitate sensor placements (screen-off area was provided). Following this step, participants' body dimensions were collected including body height, shoulder height and width, arm span, hip height and width, knee height, ankle height, and foot length. This was done using a measuring tape by the researcher (M.S.) from standing position. The body dimensions are crucial because they were inserted into the MVNX Analyze software to create a body configuration model (Avatar) so quantification of the body segments can be achieved (Roetenberg et al. 2007). (see Figure 5).

Figure 5 *Body Dimensions and Body Configuration Model (Avatar).*



Furthermore, the detailed procedure on how the researcher (M.S.) has measured the body dimensions using the measuring tape is highlighted in figure 6 below,

Figure 6 Body Measurement Using the Measuring Tape



A further need is that the researcher must be able to correctly identify the MVN sensors before they are placed. This is because each sensor has a unique identifier that indicates its exact location (for example, if the sensor is labelled "Rt lower knee," it indicates that it should be positioned below the right knee). Additionally, the top of the sensor must be differentiated from the bottom, and the front must be differentiated from the back in order to properly place the sensor. When each sensor

is positioned appropriately on each body's segment, it is possible to achieve the greatest possible ROM for the joints and to ensure that there are minimal skin motion artefacts. For the placement of the full set of wearable sensors, a head band, vest, gloves and straps were used. In total, there were 17 sensors that were attached (MVN Analyze; Awinda; Xsens Technologies, Enschede, The Netherlands), and they are listed in the table below (12).

Table 12 MVN Xsens Sensors List

MVN Xsens sensor list	Head sensor	Right shoulder sensor	Right upper arm sensor	Right lower arm sensor	Right hand sensor	Right upper leg sensor	Right lower leg sensor	Right foot sensor	Pelvic sensor
	Sternum sensor	Left shoulder sensor	Left upper arm sensor	Left lower arm sensor	Left hand sensor	Left upper leg sensor	Left lower leg sensor	Left foot sensor	

Additionally, the figure below (Figure 7) highlights the final look of participants after all sensors are placed (*a permission was gained from the participant to use his picture). Also, it is important to highlight that in order for sensors to be secured from falling while participants performing their movement activity, an additional elastic tape was used.

Figure 7 Xsens Full Outfit

Step (2) Calibration

In order to coordinate sensors with aligned body segments, segment calibration was carried out. Also, performing excellent calibration is essential to provide sufficient and superior results (Xsens Technologies B.V. 2021). In the current study, a complete dynamic calibration based on the specified instructions from the Xsens guidelines was carried out (Xsens Technologies B.V. 2021). The following is a description of the calibrating process.

First, participants were told to hold the upright neutral position, often known as static N-pose, for about 20 seconds while keeping both of their arms and legs pointing downward. The individuals were then instructed to walk at their usual pace and way. Lastly, the subject was told go back to the starting point and to hold the N-pose position constantly until the calibration procedure was finished. As a result, the calibrated sensors were represented by the MVNX Analyze software, which also displayed the calibration quality as good, acceptable, poor, or fail. Participants were instructed to move around freely and slowly for about 30 seconds after the calibration was performed to confirm the appropriate movement detection. following this step, the data collection step started.

Step (3) Data collection

In this step, the data collection is explained in relation to the DBBT only. It is important to highlight that the data collection in this project included more elements such as collecting the system usability scale data and data from semi-structured interviews, which are explained in the data collection section of this chapter. Moreover, walking (gait) outside of the lab is the task that was performed by all participants in the current project. This is because this task is the main task in the DBBT intervention, and by walking in a free environment, the gait report that is used in this intervention was generated.

After the first two steps have finished (preparation and sensor placement, and calibration), participants were asked to walk in the corridor of the building, where the lab is located, for a minimum of 10 - 15 steady walking steps (Xsesn MVN Gait Report Guide 2021). However, in the current project, we allowed participants to walk for up to 25 walking steps to ensure that the collected data are proper for analysis and for gait report generation.

Step (4) MotionCloud for gait report generation

After participants have completed the walking task from outside of the lab, the data was saved in an MVNX type file. Then, this file was processed at an HD level (HD processing) using the MVNX Analyze software. When the file HD processing was completed, the file was sent for gait report generation (sent from the MVNX Analyze software to the MotionCloud website [https://www.xsensmotion.cloud]). The motionCloud generated the gait report that included general walking data (e.g., speed and number of steps) (Figure 8), spatial parameters like step length, and temporal parameters such as gait cycle duration (Figure 9 and 10). Also, the kinematic data (joint angles) that were used for exercise prescription, were presented in the gait report including hip, knee, and ankle joint waveforms from three planes (sagittal, frontal, and transversal) (Figure 11).

Figure 8 General Gait Parameters from the Gait Report

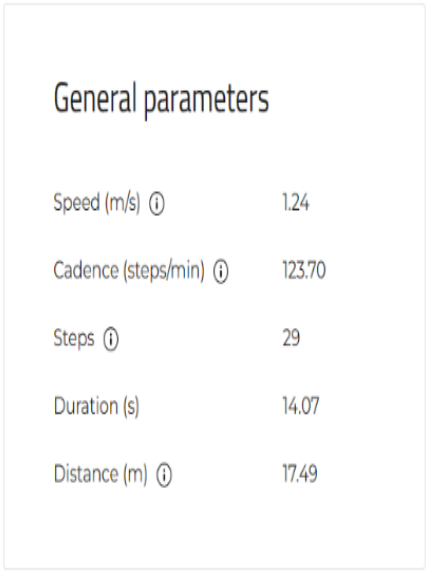
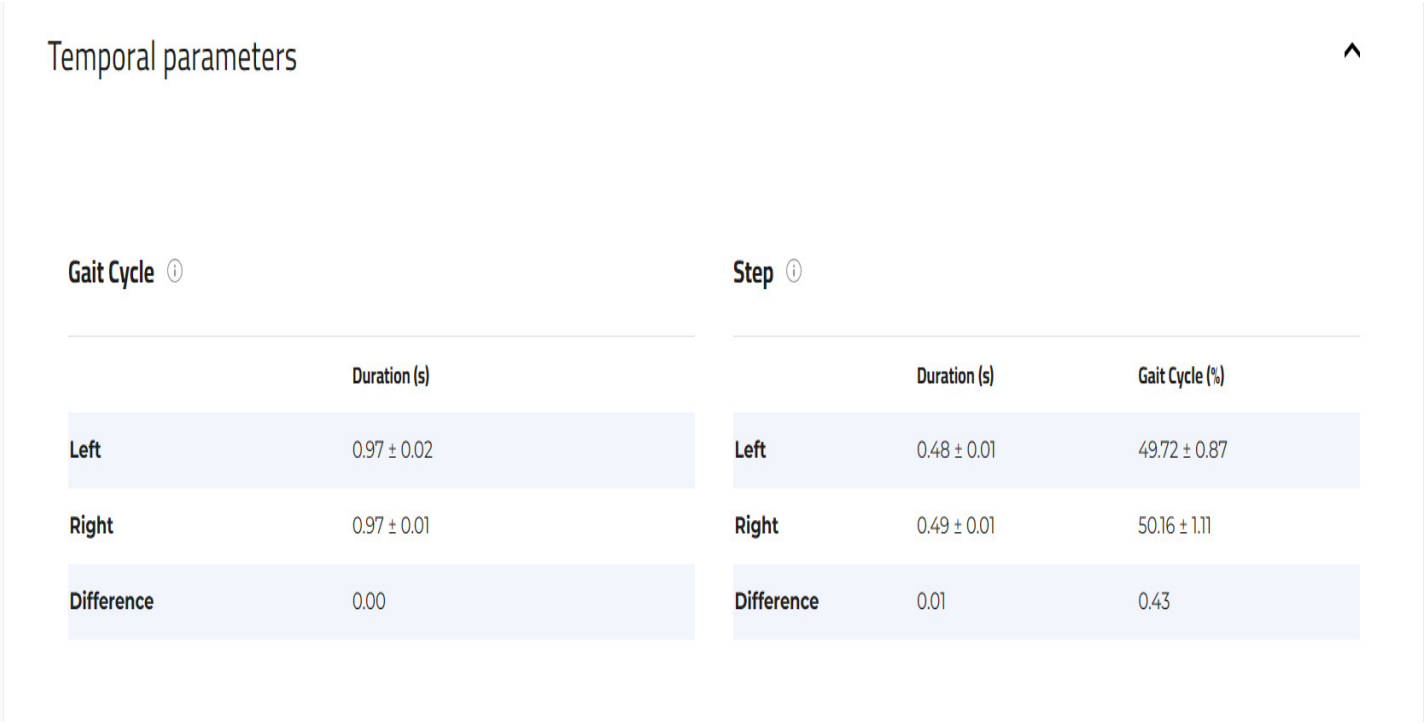


Figure 9 *Temporal Parameters from the Gait Report*



Temporal parameters

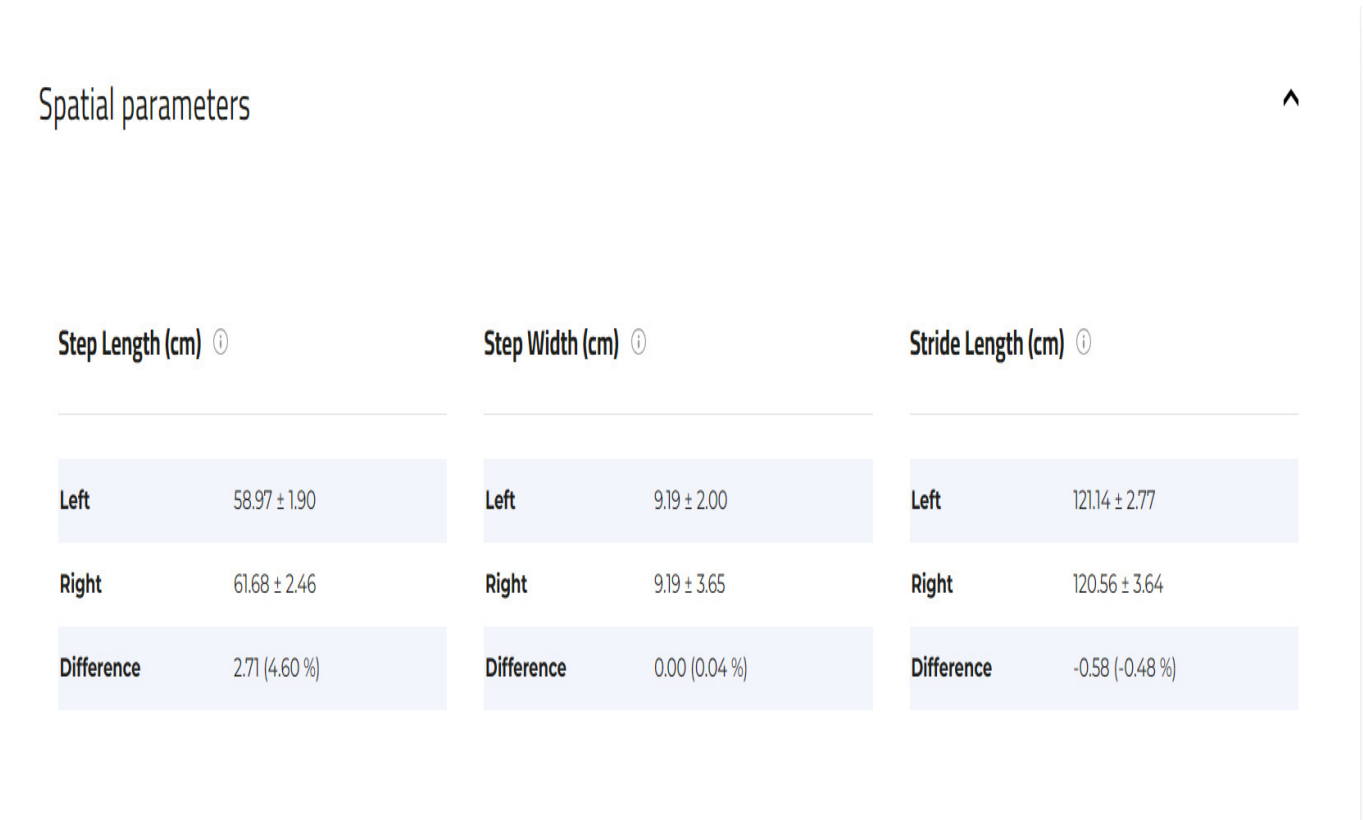
Gait Cycle

	Duration (s)
Left	0.97 ± 0.02
Right	0.97 ± 0.01
Difference	0.00

Step

	Duration (s)	Gait Cycle (%)
Left	0.48 ± 0.01	49.72 ± 0.87
Right	0.49 ± 0.01	50.16 ± 1.11
Difference	0.01	0.43

Figure 10 *Spatial Parameters from the Gait Report*



Spatial parameters

Step Length (cm)

Left	58.97 ± 1.90
Right	61.68 ± 2.46
Difference	2.71 (4.60 %)

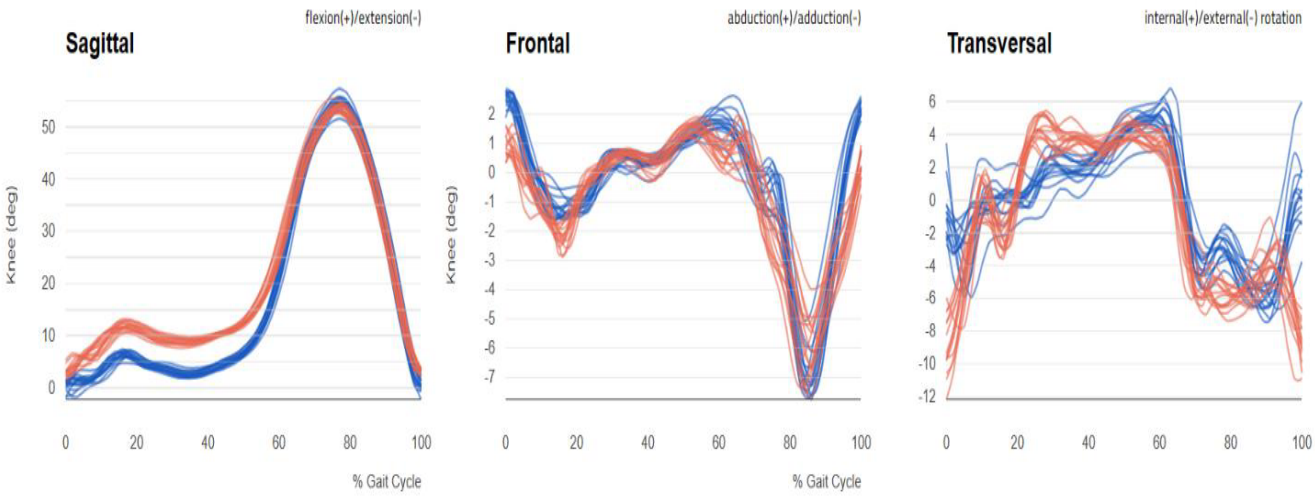
Step Width (cm)

Left	9.19 ± 2.00
Right	9.19 ± 3.65
Difference	0.00 (0.04 %)

Stride Length (cm)

Left	121.14 ± 2.77
Right	120.56 ± 3.64
Difference	-0.58 (-0.48 %)

Figure 11 *Joint Angle Waveforms from the Gait Report*



Step (5 and 6) Researcher gait report interpretation and exercise prescription

The researcher's interpretation of the gait report is an important step as it is when the biomechanical biofeedback was provided for each participant and the exercise is being prescribed based on the report's findings. In this section, those details are highlighted. Screenshots from an actual individual with CKP are used to facilitate the understanding of the use of the gait report. It is worth noting that the template of standard terminology for interpretation of kinematic waveforms from a sensor-based clinical movement analysis toolkit, developed by Button et al. (2022), was utilised to standardise the terminology when identifying movement compensations to facilitate providing the biomechanical biofeedback (Appendix 6). Furthermore, during delivery of the gait report, care was taken to ensure that participants clearly understood technical terminology such as "hip abduction." Each term was explained using simple language and related to the participant's own gait pattern, with the corresponding waveform demonstrated phase by phase. For instance, hip abduction was clarified as the leg moving outwards to the side of the body during a particular walking phase, and the movement was demonstrated to aid understanding. By relating explanations to individual data and observable movements, participants were able to grasp the meaning of biomechanical terms and engage meaningfully with the feedback provided.

Figure 12 and 13 is an example of an individual with chronic left knee pain. The report shows that the first knee flexion curve (circled in figure 12) is reduced

compared to the right side, identified from the sagittal view. Additionally, the reduced first knee flexion curve occurs in the gait stance phase, which indicate that the knee joint is limited in flexion when initiating movement causing a knee extension movement pattern. This pattern indicates that the participant is compensating using a different joint, which in this case was the hip joint. The participant had their knee extending in the beginning of the movement and they are abducting their hip to be able to progress in motion (see Figure 13)

Figure 12 ***Reduced Left Knee Joint Angle***

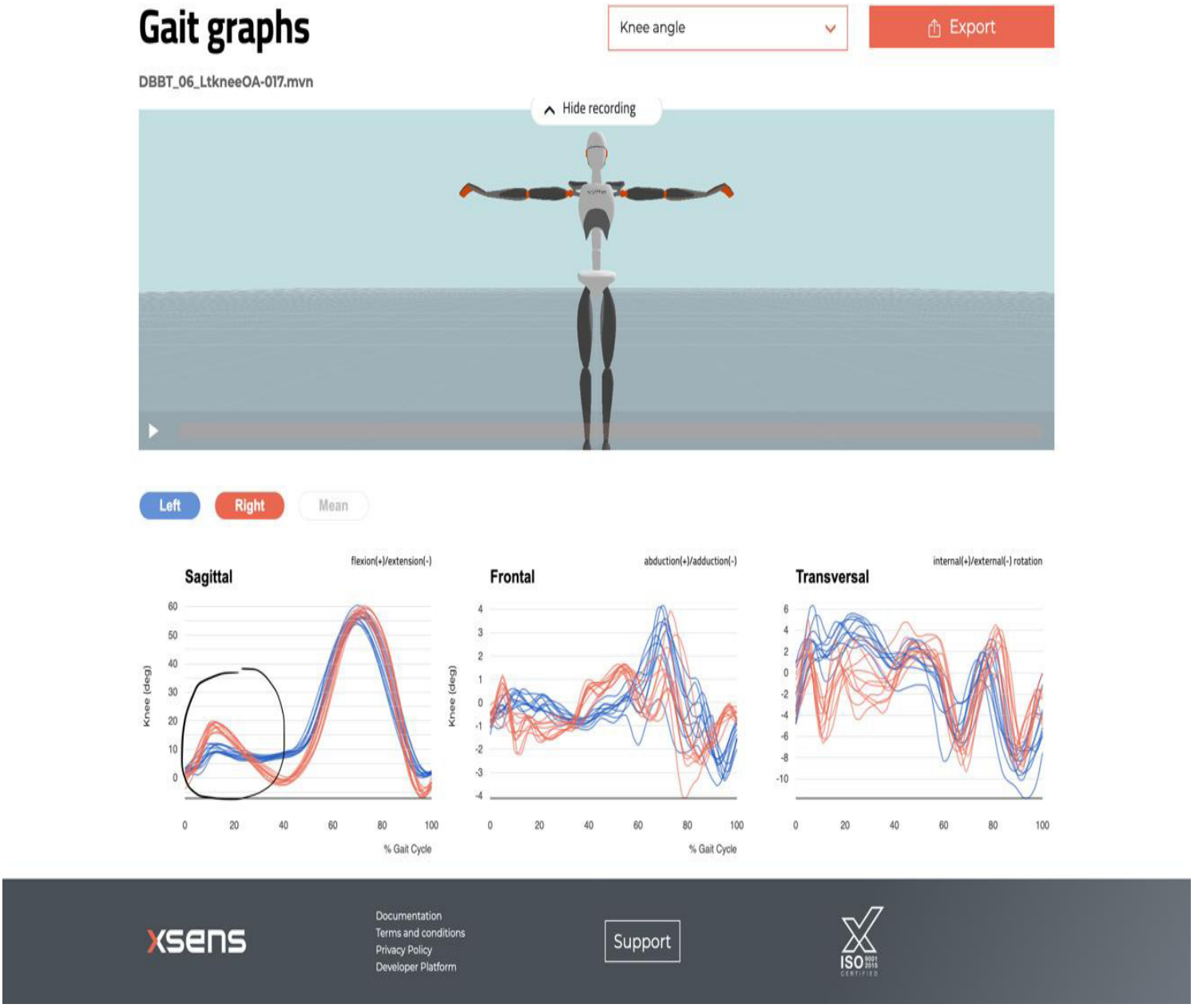
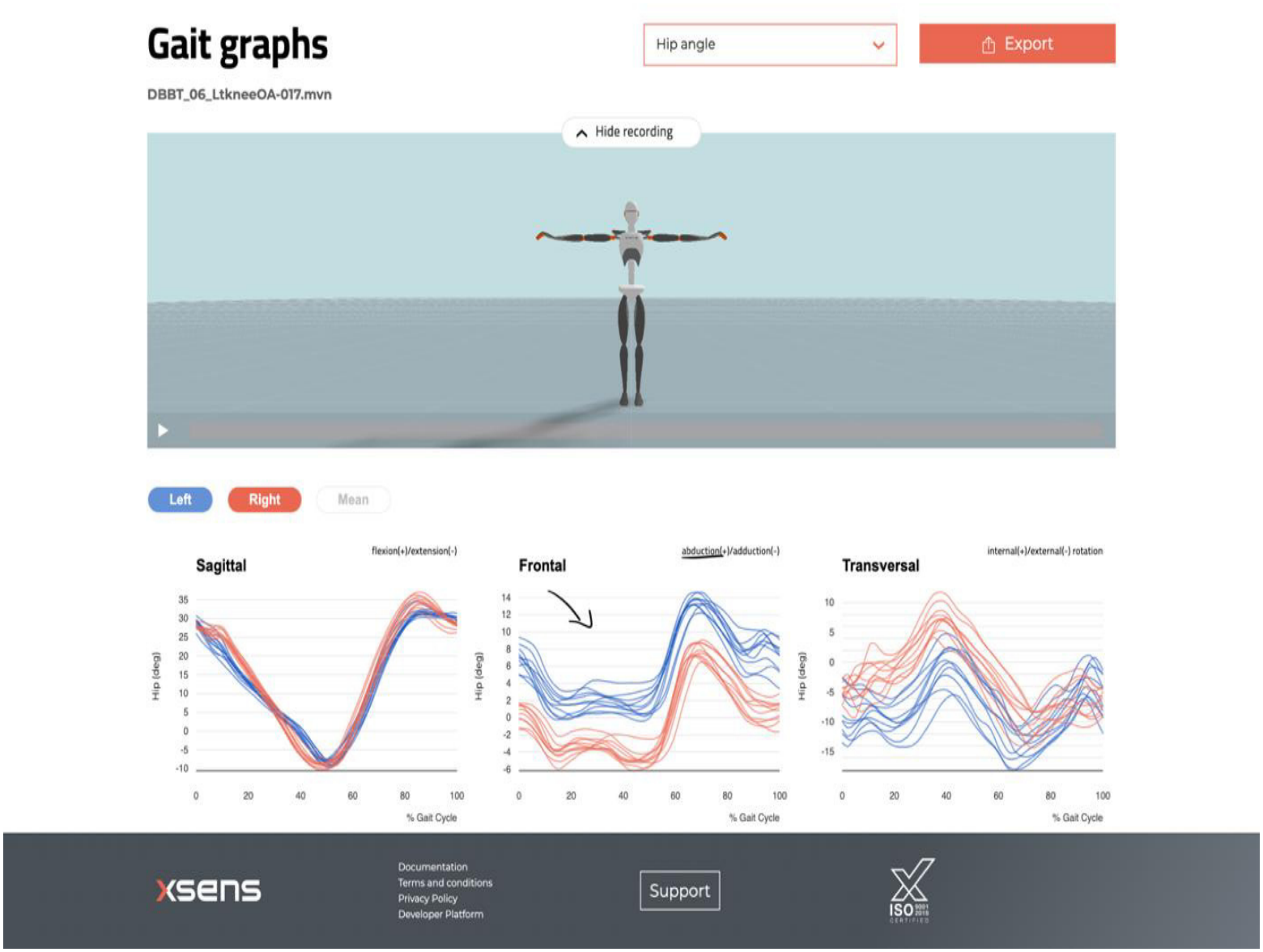


Figure 13 Increased Hip Abduction



After discussing and interpretating the gait report and providing the biomechanical biofeedback to the participant, the researcher used those findings to prescribe the exercise programme. It is worth noting that the selection of the exercises also involved the participants' decision, as they actively engaged in this process. Considering those findings, for instance, the type of exercise that the researcher decided to prescribe was hamstring strengthening exercises, to help increasing the knee ROM. The exercise prescription principle (FITT) provides more details on how the exercises were decided to be personalised and this principle is highlighted below in Item 8.

Item (5) Who

Item five aims to illustrate who provided the intervention with a description of their expertise, background, and any specific training they received. The intervention was provided by the PhD researcher (M.S.), who is a qualified orthopedic and sports physiotherapist in Saudi Arabia and has an experience in assessing and treating individuals with CKP. (M.S.) also received training in utilising Xsens wearable sensor technology and had training on using the Kinduct digital platform and MotionCloud online website that were used for feedback sharing, PROMs assessment and exercise prescription. Also, the researcher created participants information sheet (PIS) that has the required details for everyone who decided to take part in the intervention. Additionally, training on how to create participants' profiles, using a mobile application, sending auto reminders and notifications, and how to create the individualised exercise programmes using the digital platform were received from the system developing company (Movella Xsens). Lastly, the researcher received background knowledge, by utilising the template for standard terminology for interpretating kinematic waveform (Button et al. 2022), on how to share and provide biofeedback after collecting the biomechanical data from the study group.

Item (6) How (describe the mode of delivery)

In this part, the mode of delivery of the intervention is explained. The intervention was first delivered face-to-face. This was when individuals with CKP arrived at the university lab and wearable sensors were placed on them for collecting movement data. Then, the data was sent to the MotionCloud to generate the gait report, which was shared and discussed face-to-face. Additionally, the exercise programme plan and exercise options were discussed with all participants face-to-face. Also, participants' education on how to use the mobile app was done face-to-face. The second mode was using the mobile app at home from the participants side, and the researcher was using the online digital platform for monitoring and tracking participants' PROMs submission and exercise completion log.

Item (7) Where

This item highlights the locations where the intervention was used and illustrate participants recruitment. All participants were recruited from Cardiff communities (people who live, work, or study in Cardiff) and they were required to come to Cardiff university's laboratory where the DBBT was initially used. However, the movement data were collected from an out of lab environment (the building's corridor). Individuals with CKP used the mobile application from home, gym, office, and local parks. During the time when participants used the intervention, the researcher monitored them using the online digital platform from the university lab, university office, and from home. Lastly, participants were required to use the intervention for two weeks and come back to the university lab for the second project timepoint.

Item (8) When and how much

Item (8) focuses on describing the number of times the intervention was delivered and over what period of time. Also, providing details on the number of sessions, schedule, duration, and intensity or dose should be highlighted. The study group used the intervention for two weeks from home. All participants received a personalised exercise programme of 14 days and scheduling to fill in four PROMs that can be accessed from the mobile application. Participants received auto reminders to complete the PROMs and perform the exercises. In terms of the exercise dose, the exercise programme was created first after analysing and discussing the gait report; then using F.I.T.T. principle for exercise prescription. F.I.T.T. principle is an evident way for prescribing safe, personalised, and well-structured exercise programme with better results in the adherence with the exercises (Burnet et al. 2020). F.I.T.T. is explained as follows, (F) is the frequency 'number of sessions per week', (I) is the intensity 'level of exertion or effort expended during exercise', (T) is the timing 'duration of exercise sessions', and (T) is the type of the exercise 'e.g., strengthening, aerobic, stretching …etc'. For the DBBT, F.I.T.T. principal was used with each participant individually after discussing their lifestyle, exercise routine (if applicable), exercise preference (if applicable) in addition to the researcher's observation on participant's fitness levels to prescribe a tailored programme. However, in the table (5.4) below, an overview, example, of using F.I.T.T. is presented.

Table 13 Example of using F.I.T.T. principal for exercise prescription

F.I.T.T principal	Prescription
Frequency	7 sessions per week.
Intensity	Mild impact exercise (exercise using an elastic band or body weight).
Time	30 - 45 minutes for each session.
Type	Multi-joint, lower limb-focused resistance training, incorporating quadriceps, hamstrings, glutes, and calves.

Item (9) Tailoring

In this section, an illustration of when and how tailoring has happened if the intervention was planned to be personalised. The personalisation in the DBBT took place with exercise prescription. This was done by using the gait report. The researcher (M.S.) used the report's details to identify any joint motion limitation or compensation. Then, the researcher used F.I.T.T. principle, which was discussed earlier, to tailor the exercise programme based on individuals need.

Item (10) Modification

If the intervention was modified during the intervention course, what, why, when, and how, should be explained here. The only modification that took place in the DBBT was related to the timeframe. Evaluating the DBBT was originally planned to be in two weeks. However, the timeframe was changed with participants who were not able to come in two weeks' time yet were still willing to complete the project. Those participants were offered an extension of their exercise programme, and the researcher used the online digital platform to add more training sessions.

Following the comprehensive description of the DBBT using the TIDieR template, the next section presents the study outcomes. These outcomes reflect how the DBBT was experienced by participants, focusing primarily on its acceptability, followed by its usability.

5.5.2. Acceptability outcomes

Acceptability has been defined as a “multi-faceted construct that reflects the extent to which people delivering or receiving a healthcare intervention consider it to be appropriate, based on anticipated or experiential cognitive and emotional responses to the intervention” (Sekhon et al. 2017.*p4*). In the present study, the theoretical framework of acceptability (TFA) was used to guide the evaluation of the acceptability of the DBBT. The TFA offers a structured and comprehensive approach to exploring individuals’ responses to healthcare interventions and was particularly well suited to this project especially that the DBBT is characterised by a multidimensional nature, combining biomechanical biofeedback, personalisation, and self-management features.

The framework encompasses seven key components that reflect cognitive, emotional, and behavioural aspects of intervention experience, each of which is stated and defined below.

- **Affective attitude:** How an individual feels about taking part in an intervention.
- **Burden:** The perceived effort required to participate in the intervention.
- **Ethicality:** The extent to which the intervention aligns with the participant’s values.
- **Intervention coherence:** How well the participant understands the intervention and how it works.
- **Opportunity cost:** The extent to which participants must give up other benefits or resources to engage in the intervention.
- **Perceived effectiveness**: The degree to which the intervention is seen as likely to achieve its purpose.
- **Self-efficacy:** The participant’s confidence in performing the behaviours required by the intervention.

In addition to these components, the TFA identifies three phases of acceptability depending on the timing of the evaluation:

- Prospective (before participation),
- Concurrent (during participation), and
- Retrospective (after participation).

The current study focused on retrospective acceptability, as acceptability evaluation was conducted after participants had completed their full experience with the DBBT. Moreover, the primary evaluation of acceptability was conducted through qualitative semi-structured interviews designed around the seven TFA constructs. However, to enhance the interpretive depth of the findings, the study also incorporated supplementary data including kinematic parameters, spatiotemporal parameters, and participant-reported outcome measures (PROMs). These measures were not analysed as standalone outcomes but rather served to support and contextualise participants' narratives. The details of all collected data and their utilisation is explained below.

5.5.2.1. Data collection

5.5.2.1.1. Semi-structured interviews

Semi-structured interviews facilitate in-depth exploration of individual experiences through one-to-one interactions guided by predetermined topics whilst permitting flexibility to pursue emergent themes (DiCicco-Bloom and Crabtree 2006). This approach enables detailed probing of personal perspectives, accommodates sensitive disclosures, and allows participants to articulate experiences without influence from others (Kallio et al. 2016). The method proves particularly valuable when exploring heterogeneous experiences or when confidentiality concerns exist (Holloway and Galvin 2016). Semi-structured interviews served as the primary qualitative method to evaluate the acceptability of the DBBT. Interviews were conducted at the end of the intervention period, immediately following each participant's final laboratory visit, and followed a flexible yet predetermined schedule of open-ended questions. The interview guide (appendix 7) was created based on the seven constructs of the theoretical framework of acceptability: affective attitude, burden, ethicality, intervention coherence, opportunity cost, perceived effectiveness, and self-efficacy. Questions were designed to elicit reflections that could be meaningfully mapped onto one or more of these domains, ensuring theoretical alignment while allowing participants to express their views in their own terms.

Focus groups generate data through facilitated discussions among multiple participants, typically six to twelve individuals sharing relevant characteristics (Kitzinger 1995). The group dynamic enables participants to respond to, challenge and elaborate upon each other's perspectives, revealing shared understandings and contested viewpoints through social interaction (Morgan 1996). This approach efficiently captures multiple perspectives simultaneously and proves valuable when examining socially constructed meanings or community norms (Barbour 2007). However, focus groups require careful facilitation to ensure balanced participation and may be less suitable when topics are highly personal or when participant experiences differ substantially (Smithson 2000).

The present research employed semi-structured interviews rather than focus groups for three primary reasons. First, participants completed their two-week intervention at different times determined by individual schedules, with interviews conducted immediately following each participant's final laboratory visit. Coordinating focus groups would have required either delaying acceptability evaluation until multiple participants finished simultaneously or grouping participants who completed weeks apart (Barbour 2007). Second, the highly individualised nature of the DBBT meant each participant received different biomechanical feedback and personalised exercise programmes based on their unique gait patterns and movement limitations. This heterogeneity would have made collective discussion challenging, as participants might have struggled to relate to others' substantially different experiences (Morgan 1996; Kallio et al. 2016). Third, the theoretical framework of acceptability (Sekhon et al. 2017) required systematic exploration of its seven constructs with each participant. Semi-structured interviews facilitated comprehensive coverage of all constructs whilst allowing participants to elaborate on salient aspects of their experience, a balance difficult to maintain in focus groups where discussion dynamics might emphasise certain topics whilst marginalising others (DiCicco-Bloom and Crabtree 2006).

5.5.2.1.2. Kinematic and spatiotemporal parameters

To support the interpretation of the interview findings, kinematic and spatiotemporal gait data were collected using wearable sensor technology. At two timepoints (baseline and follow-up).

The kinematic data included hip, knee, and ankle joint angles and ROM from frontal and sagittal views, which were used to assess movement characteristics relevant to participants' perceptions of joint function and control.

The spatiotemporal data included the following parameters:

- Speed (m/s)
- Cadence (steps/min)
- Distance (m)
- Number of steps
- Duration (s)
- Affected-side step length (cm)
- Non-affected-side step length (cm)

These parameters offered additional insight into functional mobility and were intended to help explain aspects of TFA reported during interviews. These data were not used to measure clinical outcomes but rather to provide supportive context for the acceptability evaluation.

5.5.2.1.3. Participant-reported outcome measures (PROMs)

PROMs were also collected to further support and contextualise the evaluation of acceptability. Participants completed these measures via the Kinduct mobile application, which facilitated remote data collection. Five PROMs were used in total:

- Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC)
- Numerical Pain Rating Scale (NPRS)
- Tampa Scale of Kinesiophobia (TSK)
- Patient Health Questionnaire-9 (PHQ-9)

- Self-efficacy for managing chronic disease 6-item scale (SES6G) Scale

Each participant completed the PROMs four times throughout the 14-day intervention. However, for analysis purposes, only the first and final submissions, corresponding to the research design (pre and post design) were used. These self-reported outcomes offered additional insight into perceived changes in pain, function, emotional wellbeing, fear of movement, and self-management confidence, all of which are relevant to the interpretation of TFA components.

5.5.2.1.4. Instruments validity and reliability

As stated earlier, in the acceptability evaluation, multiple instruments were utilised. Thus, it is important to clarify the validity and reliability of these tools to ensure that the findings are trustworthy, accurately reflect participants' experiences, and provide a sound basis for interpreting the acceptability of the DBBT (Sullivan 2011). For this, the validity and reliability in addition to more details regarding instruments definitions and scoring systems are explained below.

1-Semi-structured interviews questions

The development of the semi-structured interview questions was anchored in the theoretical and conceptual framework of acceptability (Sekhon et al. 2017), ensuring coverage of its seven components while tailoring items to reflect the features of the DBBT and participants' individual experiences. This theoretical grounding strengthened the content validity of the questions by directly linking them to established domains of acceptability. The process was further supported through expert review, with supervisors and doctoral fellows contributing iterative feedback. Two physiotherapist fellows had expertise in the specific research area of digital health interventions, while another two possessed experience in qualitative research and semi-structured interviews, providing a complementary perspective that enhanced both conceptual alignment and methodological rigour (Creswell and Poth, 2018; Kallio et al., 2016).

The piloting stage offered an additional means of assessing the validity of the interview schedule. Three individuals with CKP who assisted in piloting the study were interviewed and asked to comment on the clarity and suitability of the questions; no issues were identified, thereby supporting their face validity. Language

and reflexivity were also carefully considered throughout the process. Technical or leading terminology was deliberately avoided, with questions phrased in lay-friendly language and structured in an open-ended format to encourage participants' own perspectives. In consultation with supervisors, prompts were added to selected items to provide additional clarification where necessary, without undermining the openness of responses. Collectively, these stages ensured that the interview questions were theoretically informed, peer-validated, piloted for clarity, and reflexively designed to minimise bias and maximise accessibility. The validity process therefore strengthened confidence that the interviews generated robust and meaningful data for analysis.

2-Xsens MVN wearable sensors

MVN Xsens wearable sensors (Xsens MVN Awanda system version 2019.0, Xsens Technologies, Enschede, The Netherlands) can be described as an inertial sensor-based motion capture system that utilises 17 inertial sensors placed over the full body (Guo and Xiong 2017). These sensors are situated in the head, chest, pelvic, upper and lower limbs to perform motion capture and tracking of the body with a wireless communicated suit (Muro-de-la-Herran et al. 2014). The system generates a wide range of data, including kinematic data and spatiotemporal parameters during gait (Karatsidis et al. 2016; Faber et al. 2016).

The Xsens MVN wearable sensor system demonstrates strong validity and reliability for analysing lower limb gait kinematics and spatiotemporal parameters, as evidenced by peer-reviewed studies. Spatiotemporal metrics such as step time, stride length, and stance/swing phases show excellent agreement with gold-standard optical systems, with cross-correlation values exceeding 0.90 in controlled settings (Kobsar et al. 2020; Heuvelmanset al. 2023). Sagittal plane joint angles (hip, knee, and ankle flexion/extension) exhibit high concurrent validity, with root mean square errors (RMSE) below 5.8° compared to Vicon motion capture (Al-Amri et al. 2018). For example, Al-Amri et al. (2018) reported mean differences of 1.4°– 5.9° for sagittal angles during walking, supporting the system's accuracy for clinical gait assessment.

Further, reliability is robust for within-day measurements, particularly in the sagittal plane, with intraclass correlation coefficients (ICCs) >0.88 for joint angles during running and walking tasks (van der Kruk et al. 2023). However, frontal and

transverse plane kinematics (e.g., ankle eversion, hip abduction) show variable reliability (ICCs 0.38–0.83), necessitating cautious interpretation in these planes (Kobsar et al. 2020). Additionally, Kobsar et al. (2020) confirms that Xsens' inertial measurement units (IMUs) provide quality data for spatiotemporal parameters and kinematics but recommend protocol standardisation for longitudinal studies. In clinical populations, the system's sensitivity to detect meaningful differences (e.g., 6.7° knee flexion asymmetry in OA patients) further validates its utility for functional movement analysis (Karatsidis et al. 2018). These findings collectively affirm that Xsens technology is a valid and reliable tool for gait analysis.

3-The western Ontario and McMaster universities osteoarthritis index - WOMAC

WOMAC is used for assessing the impact of knee pain and disability in individuals with OA (Jinks et al. 2002). It consists of 24 questions that cover three dimensions: pain (5 questions), stiffness (2 questions), and physical function (17 questions) (Clement et al. 2018). The questions are answered using a Likert scale, with options ranging from none (0) to extreme (4) (Bellamy et al. 1988). After answering the questions, the scores are summed for each dimension, with a higher score indicating more severe pain, stiffness, or functional limitation (Clement et al. 2018). The highest possible total score is 96 (Solmaz et al. 2013) and the average cut-point is as follows, 0–20 = mild symptoms; 21–40 = moderate symptoms; 41 and above= indication of severe symptoms (Kapstad et al. (2008).

WOMAC has been validated and adapted for use in various populations, including the Arabic, Thai, and Italian populations, demonstrating its cross-cultural applicability and validity (Guermazi et al. 2004; Kuptniratsaikul and Rattanachaiyanont 2007). Its reliability has been tested through psychometric evaluations, showing high internal consistency and test-retest reliability (Kuptniratsaikul and Rattanachaiyanont 2007 and Salaffi et al. 2003). Additionally, WOMAC has been used in numerous clinical studies and research, indicating its widespread acceptance and reliability as an outcome measure for OA (Alghadir et al. 2016; McConnell et al. 2001; Davies et al. 1999). Despite its widespread use, there is no universally accepted online version of the WOMAC. However, there are some studies that have utilised electronic formats

for data collection (Theiler et al. 2004; Bellamy et al. 2011). Thus, in the current study, a similar approach was utilised.

4-Tampa scale for kinesiophobia - TSK

TSK is a used tool to assess fear of movement and re-injury in patients with musculoskeletal pain (Woby et al. 2005). It consists of 11 items with higher scores indicating greater kinesiophobia (Woby et al. 2005). The questions in TSK are typically answered using a Likert scale, where respondents rate their agreement with each item (French et al. 2007). The scoring system for TSK ranges from 17 to 68, with higher scores indicating higher levels of kinesiophobia indicating avoidance of physical activities and potentially hinder the rehabilitation process (Roelofs et al. 2007). The average cut-points of the TSK are, 37 or above = high fear of movement (Vlaeyen et al. 1995).

The TSK has been validated in various populations, including patients with chronic musculoskeletal pain, demonstrating its applicability across different patient groups (Tkachuk and Harris 2012). The reliability of TSK has been tested in various studies, and it has been found to have good internal consistency and test-retest reliability, indicating its stability over time (Lundberg et al. 2009). Paper and computer versions of TSK have been found to be comparable, providing a convenient and accessible means of administering the scale to patients (Koho et al. 2014). For this study, an electronic version was used as part of the assessments offered by the DBBT.

5-The patient health questionnaire-9 - PHQ-9

The PHQ-9 is a tool used for screening, diagnosing, monitoring, and measuring the severity of depression. It consists of nine questions that are based on the nine DSM-IV criteria for major depressive disorder as outlined in the Diagnostic and Statistical Manual of Mental Disorders (Kroenke et al. 2001). The questions are designed to be easy to understand and answer, using a Likert scale to rate the frequency of symptoms over the past two weeks (Kroenke et al. 2001). The scoring system for PHQ-9 ranges from 0 to 27, with higher scores indicating more severe depressive symptoms (Kroenke et al. 2001). A score of 10 or above is generally considered indicative of moderate to severe depression, while a score of 20 or above suggests severe depression (Kroenke et al. 2001). The PHQ-9 has been validated in various populations, including primary care and mental health settings, and has shown good

psychometric properties (Spitzer et al. 1999; Kroenke et al. 2001). Its reliability has been tested and has been found to have a clinically relevant range for measuring the severity of depression (Kroenke et al. 2001). An online version of the PHQ-9 is available, which has been used in automated healthcare databases and has been validated against other measures of depression severity (Gilbody et al. 2007). Therefore, the online version is suitable for being implemented in the DBBT intervention.

6-Numerical pain rating scale - NPRS

NPRS is a measurement tool that assesses pain intensity on a scale from 0 to 100, with 0 representing "no pain" and 100 representing "worst pain imaginable" or "pain as bad as you can imagine" (Hjermstad et al. 2011). Individuals select the whole number that best reflects their pain intensity (Krebs et al. 2007). The cut-points in the NPRS have been identified as follows: 0–4 (no pain), 5–44 (mild pain), 45–74 (moderate pain), and 75–100 (severe pain) (Jensen et al. 2003). The NPRS has been validated as one of the most widely used tools for evaluating pain intensity in adults and children over 10 years old (Hjermstad et al. 2011). Its reliability has been tested in various clinical settings, including chronic pain conditions and rheumatic diseases (Hjermstad et al. 2011). The NPRS is considered a simple, fast, and patient-friendly method for measuring pain intensity, taking less than a minute to complete and being easy to administer and score, and it can be administered both verbally and in writing, making it versatile for different clinical contexts (Hjermstad et al. 2011).

7-Self-efficacy for managing chronic disease 6-item scale - SES6G

SES6G is a validated instrument designed to assess an individual's perceived self-efficacy in managing chronic conditions (Melin et al. 2023). This behaviour-specific assessment focuses on an individual's judgement of their capabilities in handling various aspects of their chronic disease (Lorig et al. 2001). The scale consists of six items that evaluate an individual's confidence in managing daily activities, symptoms, medications and treatments, emotions, and social interactions. Each item is rated using a Likert scale ranging from 1 to 10, with higher scores indicating greater confidence in chronic disease management (Lorig et al. 2001). Thus, a higher overall score reflects a greater level of perceived self-efficacy in coping with the challenges

associated with chronic illness. The SES6G has been validated across various cultural and linguistic contexts, including Turkish and European Portuguese versions, demonstrating its applicability across diverse populations (İncirkuş and Nahcivan 2020; Marconcin et al. 2021). Furthermore, multiple studies have confirmed its reliability and validity as a measure of self-efficacy in chronic disease management across different populations and languages (Freund et al. 2013).

5.5.2.1.5. Data management and data analysis

After explaining the data collection and data sources for evaluating the DBBT's acceptability, this section will present how those data were managed and analysed.

5.5.2.1.5.1 Interviews data management and analysis

Following the completion of each semi-structured interview, audio recordings were securely stored and subsequently transcribed verbatim to ensure an accurate representation of participants' responses. Transcripts were then organised and labelled systematically for ease of reference and analysis. All identifiable information was removed during transcription to maintain confidentiality. The anonymised transcripts were stored in a secure, password-protected digital repository, accessible only to the research team. Further details on the organisation and handling of these transcripts are described within the data analysis procedures outlined next.

The analysis was based on the six steps of Braun and Clarke (2006) for reflexive thematic analysis. Barun and Clarke (2006) highlighted that when conducting a reflexive thematic analysis, the following six steps should be followed,

(1) Familiarisation with the data.
(2) Generating initial codes.
(3) Generate themes 'searching for themes among codes.
(4) Review themes
(5) Defining and naming themes.
(6) Write up 'producing the final report'

However, in later publications by Braun and Clarke (Braun and Clarke 2012; Braun and Clarke 2014; and Braun and Clarke 2020), the authors highlighted several theoretical assumptions that should be taken into consideration when conducting a reflexive thematic analysis prior to following the six analysis steps. The aim from those theoretical assumptions is not only to pinpoint the location of their analysis on

each of these assumptions, but also to explain why the analysis is positioned in the way that it is, and why this conceptualisation is suitable for addressing the research question. The theoretical assumptions identified by Braun and Clarke are as follows:

(1) Essentialist versus constructionist epistemologies.
(2) Experiential versus critical orientation.
(3) Inductive versus deductive analysis.
(4) Semantic versus latent coding.

Each of those theoretical assumptions was considered in the current project in relation to answering the research question.

1-Reflexive thematic analysis theoretical assumptions

- Essentialist versus constructionist epistemologies.

By following essentialism, the researcher assumes that language is simply an expression of our expressed meanings and experiences, leading to a unidirectional explanation of the relationship between language and communicated experience (Widdicombe and Woofitt 1995). On the other hand, a constructionist perspective would often take a bidirectional approach to the link between language and experience, seeing language as implicit in the social production and reproduction of both experience and meaning (Byrne 2022). In the current study, the essentialist approach was applied in the reflexive thematic analysis of the interviews. This is because interviews in this project are used for acceptability evaluation based on the TFA, which requires the grasping of the essential expressions from the participants that are in line with the TFA components.

- Experiential versus critical orientation.

Examining how a particular phenomenon is experienced by participants is typically prioritised within an experiential perspective, which aims to understand the content of individuals' experiences. In contrast, a critical perspective seeks to uncover the underlying structures and sociocultural mechanisms that shape meaning systems, offering interpretations beyond what individuals overtly express (Braun and Clarke, 2012). In the current project, the interviews were designed to give participants the opportunity to express their own views and experiences. As such, the experiential orientation was deemed most appropriate. More importantly, the research question,

in relation to acceptability evaluation, focused on exploring how individuals with CKP experienced using the DBBT, rather than examining the broader sociocultural influences on these attitudes. Therefore, the experiential approach was selected to guide the acceptability evaluation.

- Inductive versus deductive analysis.

In the reflexive thematic analysis of the semi-structured interviews, a theory-driven or deductive technique aims to generate codes in accordance with a predetermined conceptual framework or codebook. Conversely, a researcher using an inductive or "data-driven" approach might want to create codes that are just indicative of the data's content and lack of any conceptual framework or preconceived theories (Byrne 2022). In the current project, the creation of the interview questions, and the reflexive thematic analysis were based and guided by TFA. For this, the deductive analysis is the most suitable approach when analysing the interviews and answering the research question.

- Semantic versus latent coding.

Semantic codes are discovered based on the data's explicit or surface meanings. The researcher does not go beyond what a respondent has stated or written. Latent coding, on the other hand, looks for hidden meanings or underlying assumptions, ideas, or ideologies in the data rather than just describing them. When coding is latent, the analysis becomes considerably more interpretive than descriptive of the participants' experiences (Braun and Clarke 2006). Gevin the nature of the current project utilising mixed-methods methodology and early-stage development phase of the DBBT, the description of the true experience is appropriate for this purpose rather than trying to uncover the hidden meaning on what led participants to have such experience. Thus, sematic coding was utilised in the current reflexive thematic analysis.

Following the discussion of the theoretical assumptions that underpin the present reflexive thematic analysis, the next section outlines Braun and Clarke's (2006) six-phase process for conducting thematic analysis. These steps were carefully reviewed and implemented by the researcher (M.S.) to ensure that the analysis was both rigorous and systematic. This structured approach reflects a clear commitment

to established qualitative research standards and enhances the trustworthiness of the findings.

2-Steps of the reflexive thematic analysis

This section presents a detailed account of the thematic analysis conducted to evaluate the acceptability of the DBBT. A deductive approach was adopted, guided by Braun and Clarke's (2006) reflexive thematic analysis framework and informed by the TFA proposed by Sekhon et al. (2017). NVivo 12 software was used to support the organisation and analysis of the qualitative data (see Appendix 8). Additionally, the following steps also incorporate details of interview data management, as outlined earlier.

Step (1) Familiarisation with the data

The analysis began with importing the audio recordings from a digital voice recorder to a password-protected and encrypted laptop in the format of WAV. Additionally, each audio file had a pseudonymised name and it was retained throughout the remaining analysis steps and in the final analysis report. It was done to protect the privacy of participants. These audio recordings were then loaded into a Word document for transcription for each participant's interview. When they were being transcribed, the researcher (M.S.) listened to the recordings and read the transcripts to ensure clarity and consistency between what was said and what was written. Such textual transcription provided an unprecedented insight into what the participants thought and felt about the DBBT. When the transcripts were completed, they were forwarded to the supervisor (K.B) to check for precision, so that the transcription accurately captured the voices of the participants. This familiarisation phase was essential because it made the data approachable so that one could draw subtle conclusions about what participants have experienced.

Step (2) Generating initial codes

Once the transcripts were verified to be accurate, they were loaded into (NVivo.12) software for coding. The coding was guided by following the TFA (Sekhon et al. 2017). This framework outlined a systematic way to identify essential aspects of acceptability that made it possible to classify respondents' responses. Initial codes were developed to document particular dimensions of the participant's experience, like perceived challenges and ease of use. This codification method was iterative,

with the researcher (M.S.) constantly re-entering the data to reword codes when something new was found.

Step (3) Searching for themes among codes

After producing a list of initial codes, the investigator (M.S.) identified sixteen themes, which included a total of twenty-nine subthemes. This stage was all about discovering patterns and connections between the themes, subthemes, and the TFA constructs. Each theme was aptly titled to reflect its content and importance. This theme-level organisation was crucial to pulling together the data and enabling a greater grasp of the experience of the participants.

Step (4) Reviewing themes

When reviewing, the themes were evaluated to ensure that they described the coded data properly. This included verifying that the themes corresponded with the original interview transcripts, making sure they conveyed the essence of participants' experiences. The researcher (M.S.) coded the extracts of individual transcripts and had the extracts reviewed by the supervisor (K.B.) and two PhD fellows (S.A.) and (M.G.) who are qualitative researchers and experienced in analysing interview data. Thus, ensuring that the codes were correctly allocated and corresponded to the raw data. This process adds legitimacy and trustworthiness to qualitative research, as pointed out by Fereday and Muir-Cochrane (2006).

Step (5) Defining and naming themes

After themes were defined, each theme was titled and named appropriately to communicate its message effectively. This was the second step, explaining what each theme stood for in terms of the TFA by offering comprehensive descriptions that highlighted their importance. For instance, a theme of "Impression on the toolkit and its features" captured factors that participants categorised as technological innovation and treatment personalisation. Thus, this theme and its subthemes were connected to the 'Affective Attitude' component of the theoretical and conceptual framework of acceptability. The researcher (M.S.) provided clear names for each theme to make it easy for the reader to grasp what the analysis is essentially about.

Step (6) Producing the final report

The final step was to translate the findings into a report that summarised the themes in a structured format. The report was meant to blend participants' voices with

analysis and provide sample quotes to illustrate each theme. By connecting the themes with the TFA, the report aimed to convey a holistic picture of how acceptable the DBBT was. The final report not only summarised the outcomes of the reflexive thematic analysis but also contributed to the broader discourse on managing CKP through innovative digital solutions.

3-Collaborative review

The researcher (M.S) had a collaborative review process to make the reflexive thematic analysis more rigorous and credible. Two PhD fellows (S.A. and M.G.) were invited to read through the original codes and themes, creating a constructive dialogue about the analysis. Their suggestions were critical to catching any biases or errors within the codes. Further, the supervisor (K.B.) reviewed the final report, making sure that the analysis was robust, and the conclusions were supported by data. Such teamwork enhanced the integrity of the analysis and created an atmosphere of openness and rigour in the research. Lastly, an example of a participant interview transcript is presented in appendix (9).

5.5.2.1.5.2. Kinematic data

Management and analysis

This study examined lower limb joint angles (hip, knee, and ankle) in both the sagittal and frontal planes. These kinematic data were extracted from Excel files exported from the MotionCloud digital platform, which provided joint angle and spatiotemporal parameters for each participant.

To process these data, a custom MATLAB (R2023b) script was developed. This script automated the extraction of gait cycle indices (0–100%) and segmented the data into the stance (0–60%) and swing (61–100%) phases. For each phase and full gait cycle, the script calculated key metrics, including maximum joint angles (flexion, extension, abduction, and adduction), joint angles at initial contact (index 0), and ROM. The script also identified the affected and non-affected limbs for each participant based on labels embedded in the MotionCloud export, ensuring consistent comparison between sides.

The numerical joint angle data were summarised using descriptive statistics (mean and standard deviation) for each timepoint and limb side. Additionally, MATLAB was used to generate waveform plots that visualised average joint angle

trends across the full gait cycle. These visualisations presented the mean and standard deviation of joint angles for the group as a whole, across both timepoints, limb sides (affected vs non-affected), and planes of motion (sagittal and frontal). The full MATLAB code used in this analysis is provided in Appendix (10).

5.5.2.1.5.3. Spatiotemporal parameters

Management and analysis

The general gait parameters were first extracted from the Motioncloud digital website as an Excel file. The Excel file includes three sheets. The 'Parameters' sheet was the one that included the general gait parameter. All the gait parameters were extracted from each individual and then posted into another Excel sheet that combined all the required data from all participants, organised in columns. The data from the second Excel sheet was then imported into the (IBM SPSS Statistics 29.0.1.1). Each gait parameter was defined as a variable in the IBM SPSS software as follows, (1) Speed in meter per second, (2) Cadence in steps per minutes, (3) Distance in meters, (4) number of steps, (5) duration in seconds, (6) Affected side step length in centimetre, and (7) Non-affected side step length in centimetre. After this step, the descriptive analysis was run in the IBM SPSS software to present the mean and standard deviation from two timepoints.

5.5.2.1.5.4. Participants self-reported outcomes.

The self-reported measures included the measurement of pain, stiffness, physical function, depression severity, fear of movement and re-injury, confidence in managing chronic disease, and pain intensity. This was done by administering several questionnaires and scales as follows:

- **WOMAC**

Measures

pain, stiffness, and physical function

- **PHQ-9.**

Measures

Depression severity.

- **SES6G**.

Measures

Confidence in managing chronic disease.

- **TSK for kinesiophobia.**

Measures

Fear of movement and re-injury.

- **NPRS**.

Measures

pain intensity.

Management

The data were first saved in Kinduct digital online platform after being filled by each participant using Kinduct mobile application. Then, the scores were extracted from the digital website and inserted into an Excel sheet. Two Excel sheets were created (one for each timepoint). The data, then, were exported from the Excel sheet and inserted into (IBM SPSS Statistics 29.0.1.1). In the IBM SPSS software, the variables were defined based on the name of the questionnaire or scale. Following this, the test for descriptive analysis of the mean and standard deviation was run for the two timepoints.

5.5.3. Usability outcomes

Usability refers to the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a particular context (ISO 2018). In digital health, usability is crucial for promoting user engagement, maintaining adherence, and ultimately determining intervention

success. It encompasses the ease of use, navigation, comprehensibility, and the ability to integrate the system into daily routines (Zahabi et al. 2015; Maramba et al. 2019).

In this study, Usability was assessed through participant-reported experiences alongside system-recorded usage data, offering a comprehensive view of how the DBBT was used and perceived in practice. While the system usability scale (SUS) captured participants' perceptions of usability, system usage patterns including exercise logging and PROMs submissions offered behavioural indicators of engagement.

Additionally, while usability and acceptability are conceptually distinct, the qualitative interview data collected for the acceptability evaluation also offered valuable insights into participants' usability experiences. For instance, participants shared which system features they found intuitive or challenging, and what elements helped or hindered their engagement. These qualitative perspectives are explored further in the discussion chapter to contextualise and enrich the interpretation of usability results.

5.5.3.1. Usability data collection

Usability data were collected through two primary sources:
(1) the System Usability Scale (SUS), and
(2) system-generated adherence monitoring via the Kinduct mobile application.

The SUS questionnaire was administered at the end of the 14-day intervention period. This timing ensured that participants had sufficient exposure to all features of the DBBT, allowing them to reflect comprehensively on their experience when completing the usability ratings.

Adherence data were captured directly by the Kinduct system and included two protocol-defined tasks:

- **Exercise logging**: Participants were instructed to log one prescribed exercise session per day over a two-week period, resulting in a total of 14 expected sessions per participant. Adherence was calculated by comparing the number of logged sessions to the expected total and expressed as a percentage.

- **PROMs submission**: Participants were expected to complete four entries of Patient-Reported Outcome Measures (PROMs) over the course of the intervention. Adherence was calculated by comparing the number of completed submissions to the expected total and expressed as a percentage.

This dual-source data collection approach enabled an evaluation of the system's usability by aligning real-world usage patterns with participants' reported experiences.

5.5.3.1.1. Instruments validity and reliability

1-System usability scale

The System Usability Scale (SUS) is a widely used, standardised questionnaire designed to measure the perceived usability of various systems, including software, hardware, and digital health applications (Brooke 1996). It consists of 10 Likert-scale items, alternating between positively and negatively worded statements, which participants rate on a scale from 1 (strongly disagree) to 5 (strongly agree) (Bangor et al. 2009). The SUS scoring system involves a specific calculation process, where odd-numbered item scores are subtracted by 1, even-numbered item scores are subtracted from 5, and the sum of these adjusted scores is multiplied by 2.5 to yield a final score ranging from 0 to 100 (Lewis and Sauro 2018).

The SUS has demonstrated high reliability, with a Cronbach's alpha of 0.91, indicating excellent internal consistency (Bangor et al. 2008). Its validity has been supported through various studies, showing sensitivity to interface differences and changes, as well as concurrent validity with other usability measures (Sauro and Lewis 2011). In the context of digital health applications, research has confirmed the SUS's suitability for evaluating usability, with a meta-analysis supporting the widely accepted benchmark mean SUS score of 68 (SD 12.5) for these applications (Bangor et al. 2009). The SUS has been successfully applied to assess the usability of various digital health products, providing a quick and effective method for gathering quantitative data on user experience (Zhou et al. 2017). Its brevity, reliability, and versatility make it a valuable tool for researchers and practitioners in the digital health field, offering insights into the perceived usability of health-related apps and systems (Peres et al. 2013).

5.5.3.1.2. Data management and data analysis

5.5.3.1.2.1. System usability scale.

Management and analysis

The system usability scale is a 5-point Likert scale with a total score of 100. It includes 10-question with each answer is equivalent to a number of points, which are presented below:

Strongly disagree = 1 point.

Disagree = 2 points.

Neutral = 3 points.

Agree = 4 points.

Strongly agree = 5 points.

The answers of each participant were inserted into the (IBM SPSS Statistics 29.0.1.1) (Appendix 11) software and the variable on SPSS were defined by each question, and under each question, the point from each participant were inserted. Further, the frequency of the answers in line to the percentage of the number of participants answering each question were calculated. In order to calculate the score, the following equation was first applied for each participant:

$$\mathrm{X} = \text{the sum of points for odd numbered questions} - 5$$

$$\mathrm{Y} = 25 - \text{the sum of the points from even numbered questions}$$

$$\text{SUS score} = (\mathrm{X} + \mathrm{Y}) \times 2.5$$

Then, the descriptive mean and standard deviation of the score from each question were measured. The total mean score was then multiplied by 2.5 to report the system usability scale final score.

5.5.3.1.2.2. Adherence rates

Management and analysis

Kinduct Athlete mobile application was used by participants to submit PROMs and log exercise sessions allowing the researcher (M.S.) to track the total number of completed entries. For PROMs, a total of 100 PROMs were expected across the 25

participants. Adherence rate was calculated as the percentage of submitted PROMs using the following equation:

$$\text{Percentage} = \frac{\text{Number of submitted PROMs}}{\text{Total number of PROMs administred}} \text{ X } 100$$

Moreover, the total number of the prescribed exercise sessions for (n = 25) participants was 350. The adherence rate calculation was done by calculating the percentage of the total number of logged exercise sessions out of the 350 total number of the prescribed exercise sessions following this equation:

$$\text{Percentage} = \frac{\text{Number of logged exercise sessions}}{\text{Total number of prescribed exercise sessions}} \text{ X } 100$$

5.5.4. Study settings and population

This study took place in the University lab (lab no. 2.25b) that is located in the Cardigan House, Heath Campus, Cardiff University. More, the gait analysis procedure was performed in a corridor of the same building demonstrating an out-of-lab environment. Additionally, study subjects were still part of the study when they went home. This is because all participants were asked to use Kinduct mobile application from home prior coming to the second study timepoint. The targeted population were individuals who are suffering from CKP (≥3 months). Although the population is detected in the current study, the term CKP remains broad. Thus, Table 6.1 below specify the inclusion and exclusion criteria of the eligible participants.

Table 14 Participants inclusion and exclusion criteria

Inclusion Criteria	Exclusion criteria (any of the following)
Adults aged 18 and above.	Musculoskeletal pain whereby the knee is not the main source of pain.
Self-reported knee osteoarthritis, as it represents the most common cause of	Contraindication to exercise (e.g., high risk of falling)

chronic knee pain and ensures recruitment of individuals with degenerative joint-related symptom (Hsu et al. 2023).	
Have activity related joint pain.	Pain caused by malignancy, fractures, or inflammatory arthritis.
Self-reported knee pain on most days of the week for the past 3 months as this aligns with definitions of chronic knee pain (i.e., pain persisting or recurring for more than 3 months) ensuring the population meets a chronic pain threshold (Vanneste et al. 2024).	Having received surgery for their knee pain in the last 12 months, as postoperative recovery and gait parameters may not stabilise within this period (Zhou et al. 2015)
Average pain severity in the past week of 4 or greater on a 10-point numeric pain rating scale, because threshold of ≥4 on 0–10 scale indicates at least moderate pain and ensures participants have sufficient symptom severity for intervention evaluation (McAlindon et al. 2015).	Having commenced another new treatment for knee pain, including intra-articular injection, during the preceding 24 weeks, because such treatments may continue to influence gait, function and PROMs from 8 to 24 weeks (Testa et al. 2024).
Able to understand written and spoken English.	Concurrent ongoing physiotherapy (other than study interventions) to prevent confounding effects on function, gait outcomes, and PROMs scores (Bennell et al. 2017).
Able to provide written informed consent.	Previous knee arthroplasty in either knee as prosthetic joints alter natural activities biomechanics, pain profiles,

Willing to avoid commencing other new interventions for knee pain during the duration of the study.	and PROMs scores (Seymour et al. 2024).

5.5.5. Recruitment

Invitation flyers were created and distributed via the university's exclusive social media application, "Viva Engage" (Appendix 12). The flyers were also shared throughout the university campus, including the student union. In addition, local communities such as clinics, gyms, and religious centres were contacted to assist in distributing the flyers and to deliver talks about the study and its significance. The invitation was posted on Facebook pages for the Cardiff community, Cardiff University students, and Cardiff accommodation. Finally, participants who agreed to take part in the study were approached and encouraged to share the study invitations further. For participants to book their lab appointment, a QR code, that is found in the flyer, was generated. Once the QR code was scanned, google forms page turns on. Participants filled their demographic information (age, duration of knee pain, reason for knee pain, emails …etc.) and submit the form. The researcher (M.S.) was notified when the form was submitted and directly send them a welcoming email that has the available time and dates for their participation along with the location of the lab, participant information sheet (PIS), and the consent form to sign. When participants chose their preferred time and date, the researcher (M.S) send them an email invitation and sets up a one-day reminder before their actual appointment. Thank you, Amazon vouchers, of £20 were provided upon their participation to acknowledge their participation.

5.5.6. Sample size and sampling strategy

A total of 25 participants with CKP who satisfied the predefined inclusion criteria were recruited to assess the acceptability and usability of the DBBT. Recruitment was conducted using a convenience sampling strategy, a method frequently employed in clinical and applied health research when participants are selected based on their accessibility, willingness to participate, and availability to the researcher (Etikan et al. 2016).

The adoption of convenience sampling in this study was guided by pragmatic considerations, particularly the logistical challenges associated with recruiting individuals with CKP from hospital settings. While this approach does not offer the randomisation required for statistical generalisability, it is widely recognised as appropriate in evaluative research, especially in digital health intervention studies where the primary aim is to foster in-depth user engagement and support the iterative refinement of the intervention (Patton 2015 and Yardley et al. 2016).

Moreover, this sampling strategy is especially suitable when the research objective is to gather detailed feedback from end users and evaluate an intervention's real-world acceptability and usability (Nielsen 2000; Kushniruk and Patel 2004). In this context, the strategy enabled the collection of rich, user-centred data that are critical for informing subsequent optimisation of the DBBT.

5.5.7. Piloting

To ensure the clarity and smooth data collection procedures, both the data collection session and the semi-structured interviews were piloted with three participants prior to formal recruitment. Each pilot session followed the full study protocol, including the use of biomechanical biofeedback tools and the delivery of the interview schedule.

Following each session, detailed notes were taken to document participants' impressions, the duration of the procedures, and any challenges encountered. This process informed minor refinements to the flow of the session, question phrasing, and overall structure, ensuring consistency and clarity during the main study. The piloting phase was instrumental in shaping an efficient and participant-friendly data collection approach that was subsequently applied across the full sample.

5.5.8. Procedure

This section provides details of the procedure that the researcher (M.S.) went through with each participant upon their arrival to the university lab for their participation. The procedure mentioned earlier in the TIDieR template is related to the DBBT, whereas in this section, the procedure covers the whole data collection process.

5.5.8.1. First timepoint (baseline)

When participants arrived, they were welcomed and asked to wear their shorts in a screened-off changing room. Then, they were asked to use Kinduct Athlete app to fill PROMs, namely, WOMAC, TSK, PHQ-9, NPRS, and SES6G.

After that, the researcher took participants CKP history and talked them through the data collection session and introduced the Xsens wearable sensor technology for them. Following this step, participants body dimensions, hight, and weight were collected. This is important to be inserted into Xsens Analyze software to create an avatar for each participant. The body dimensions are measured using the guide from Xsens website. The used sensors in the study are the MVN Xsens motion detection sensors. Placing of sensors were done following the evident sensor placement protocols (Xsens Technologies B.V. 2021; https://tutorial.movella.com/).

Prior to starting sensor placement, a check for connection was run and once confirmed, the placement proceeds. The MVN sensors were worn using a head band, vest, gloves, and straps. The levels of the straps were identified from the Xsens guide videos on their website and their text guide. Once this step was completed, a system calibration started. Walking outside the lab was introduced to the participants showing the start and end point and ensuring there is no obstacles that could affect their performance. Additionally, the researcher keeps a diary throughout this process and note any observation from the data collection session.

After completing the data collection session, the researcher started helping out participants to remove the wearable sensors. Then, sends the walking data through the MotionCloud system via Kinduct Analyze software for processing and generating the gait report.

All of the participants were introduced to the Kinduct mobile app, the researcher (M.S.) shared a short simulation of their experience with the application when they use it at home. Furthermore, when the gait report was ready, the researcher provided the biomechanical biofeedback about how their movement was. The researcher explains the key findings around participants' movement patterns and explains which exercises they might need to focus on. When participants understand how they were moving, they were allowed to ask any question or ask for any clarification. Then, they were asked about their second appointment, which was booked at the same time.

After participants were sent home, the researcher (M.S.) used Kinduct digital online platform to start prescribing the exercises from the exercise library based on the findings from the gait report. Additionally, the researcher sat up PROMs so participants could fill them from home using the app. Finally, the researcher sat reminders for participants to be sent to them. Lastly, it is important to highlight that the period when participants use the mobile application from home was two weeks. Moreover, the researcher (M.S.) engaged in detailed discussions with each participant regarding their exercise habits, fitness levels, and gym attendance. Exercise plans were then created through a collaborative process that combined the findings from the gait report with participants' individual needs and preferences. Using the Kinduct exercise library, the researcher (M.S.) demonstrated each proposed exercise to the participant during this session, explaining how it targeted specific movement limitations identified in their gait analysis. Participants were asked to confirm whether they felt able to perform each exercise. If a participant expressed difficulty or concern about a particular exercise, the researcher (M.S.) identified an alternative exercise from the library that addressed the same therapeutic aim but was more suitable for that individual. This process ensured that all prescribed exercises were both appropriate and practically feasible for each participant.

Once the exercise selection was finalised through this collaborative discussion, a complete two-week programme was designed for each participant using the Kinduct platform, with built-in progression and pre-scheduled reminders. The entire package was then uploaded to the participant's individual profile, which automatically synchronised with their Kinduct mobile application. This ensured that participants received their full exercise programme and associated daily reminders in advance, providing a structured and continuous plan for the entire two-week intervention period. Progression was incorporated within the programme design, such that exercise intensity increased systematically over time (for example, from 10 repetitions at initiation to 20 by the end of the programme, depending on exercise type).

Flexibility and participant safety were also built into the programme. The researcher (M.S.) retained the ability to add, remove, or modify exercises during the two-week period if required. Participants were informed that they should contact the researcher (M.S.) if they experienced any difficulty or pain with a prescribed exercise during the

home-based period. In such cases, the researcher (M.S.) would replace the problematic exercise with a suitable alternative selected from the Kinduct exercise library, which occurred once during the study period.

Support was provided through active monitoring of adherence. The researcher (M.S.) reviewed participants' exercise logs on a daily basis using the Kinduct platform and additionally checked completion on the final day prior to follow-up. This enabled the researcher (M.S.) to identify missed or incomplete sessions, which were subsequently discussed during the interview to explore barriers to adherence. This structured support ensured that exercise programmes were relevant, progressively challenging, adaptable to individual needs, and continuously monitored throughout the intervention period.

5.5.8.2. Second timepoint (follow-up)

For the second lab visit, participants went through the same process from the first visit. However, they were asked to fill SUS and participate in a semi-structured interview. The interviews were semi structured and face-to-face conducted by the researcher. Open-ended questions were used. Participants were aware of the audio recording of the interview. Moreover, for participants who could not attend for the second lab visit, the researcher organised an online interview to provide an opportunity to participate in the acceptability and usability evaluation. To facilitate the steps, the following flowchart summarises the process in points (Figure 14).

Figure 14 Study procedure flowchart

Timepoint 1: Baseline – Laboratory Visit

Initial Setup & Assessment

- Welcome and changing room preparation
- Complete PROMs via Kinduct app: WOMAC, TSK, PHQ-9, NPRS, SES6G
- Take CKP history and explain session
- Introduce Xsens technology
- Collect body dimensions, height, weight for avatar creation
- Check sensor connections and place MVN Xsens sensors
  - Equipment: headband, vest, gloves, straps
- Perform system calibration

Data Collection & Analysis

- Show walking path outside laboratory (ensure no obstacles)
- Participant performs walking task
  - Researcher observes and keeps diary notes
- Remove wearable sensors
- Send data through MotionCloud via Kinduct Analyse for gait report
- Provide biomechanical biofeedback session:
  - Explain gait report findings
  - Discuss movement patterns
  - Identify exercises to focus on
  - Answer questions

Exercise Programme Design

- Discuss with participant:
  - Exercise habits and fitness levels
  - Gym attendance and preferences
  - Individual needs and concerns
- Demonstrate exercises from Kinduct library:
  - Show how each targets movement limitations
  - Confirm ability to perform
  - Identify alternatives if needed
- Design 2-week personalised programme:
  - Based on gait findings and preferences
  - Include progression (e.g., 10 to 20 reps)
  - Set up reminders
  - Upload to Kinduct profile
- Provide app training and schedule follow-up appointment

Important Notes:

Researcher informed participants they could contact them if experiencing difficulty or pain. Researcher retained ability to modify exercises during intervention. One modification occurred during study.

2-Week Home-Based Intervention Period

- Participant completes personalised exercise programme at home using Kinduct mobile app
  - Progressive exercise intensity over 2 weeks
  - Daily reminders received via app
  - Exercise completion logged in app
- Researcher actively monitors adherence
  - Daily review of exercise logs via Kinduct platform
  - Check completion on final day prior to follow-up
  - Identify missed or incomplete sessions
- Provide ongoing support
  - Available for participant contact if issues arise
  - Modify exercises if needed

Timepoint 2: Follow-up – Laboratory Visit or Online

Repeat Assessments

- Same procedure as baseline:
- Changing room preparation
- Complete PROMs via Kinduct app
  - WOMAC, TSK, PHQ-9, NPRS, SES6G
- Xsens sensor placement and calibration
- Walking data collection
- Sensor removal and data processing

Evaluations

- Complete System Usability Scale (SUS) questionnaire
- Participate in semi-structured interview:
  - Face-to-face or online (if unable to attend laboratory)
  - Open-ended questions
  - Audio recorded (with participant awareness)

Alternative Option:

For participants unable to attend second laboratory visit, online interview organised for acceptability and usability evaluation

5.6. Ethical considerations

Before conducting the study, ethical approval was obtained from Cardiff University's research review ethics committee to ensure that participants are treated fairly and safely (O'Leary 2017) (Appendix 13). In accordance with Cardiff University's data privacy policy and data protection act (DPA 2018), the researcher ensured that the study data is protected and used solely for the purposes of the proposed study (DPA 2018). All data from this study were kept in a password-protected file that only the researcher (M.S.) and the supervisors (K.B.) and (M.A.) had access to. Furthermore, according to Cardiff University's record management policy and retention schedules, all data from this planned study were stored for five years before being destroyed (Cardiff University 2019). Participants in this study can be assured that the researcher adhered to the provisions of the Data Protection Act (DPA 2018).

For the lab study, after invitations were distributed, all participants who showed interest in taking part in the current study received a copy of the participant information sheet (Appendix 5) with an emphasis on replying with any question or details that they need to further discuss regarding the study. Once participants were confident to participate, the consent form (Appendix 14) and a timetable of the available time and dates were sent. Furthermore, Although the current study is based on voluntary participation, participants were encouraged to decide if they will take part within 5 working days. However, the researcher ensured that no pressure is applied on them that could affect their decision. Lastly, based on the time and the date that each participant has chosen, a reminder was sent 24 hours before they take part in the study.

By the arrival of each participant, the research (M.S.) explained the whole procedure. This explanation was in line to what participants have included on the participant information sheet. The researcher (M.S.) collected the data after creating a file for each participant that include the needed relative information for the study (names, email address, mobile number, age, height, weight, raw data, and processed data). To preserve confidentiality, the researcher (M.S.) informed all participants that their names will be changed into codes using their initials, and the file will be renamed using numbers (e.g. first participant's file will be named "participant 1", etc…). Using numbers and codes that only can be identified by the researcher is a good strategy to ensure that participant's privacy and confidentiality are protected (Gerrish et al. 2008). Moreover, the same codes were used with data processing and data analysis. All data from this study were kept in a password-protected file in an encrypted computer that only the researcher (M.S.) and the supervisors (K.B.) and (M.A.) have access to, which participants were informed about.

The researcher made certain that participation in the study is entirely voluntary, and that all participants have the right to withdraw at any time and without explanation. Furthermore, all potential risks associated with the experiment's functional task and wearable sensor placement were clarified, because there are some potential dangers in this experiment, such as skin irritation from the sensors, fatiguability and dehydration from the functional activity. However, the researcher did his best to reduce any risk from the study. For instance, for skin irritation from the sensors, participants were informed to wear sportswear to reduce any itchiness caused by the straps of the sensors. Fatiguability and dehydration were delt with by offering breaks, rest intervals, and water to all participants, only if needed and requested by the participant.

More, the researcher frequently asked participants about their feelings and condition. This feedback helped in deciding whether the participant can continue or stop as the safety of all participants comes first. Further, there was a potential for participants of having distress and feeling uncomfortable during the interview, which was dealt with by providing a break and drinking water. Also, they were encouraged to feel free to ask for any clarifications that they think they need, or to withdraw from the study without providing any explanation. The risk assessment in the current project also took place according to Cardiff University Operational Safety Health and

Environment Unit (2011), which indicated that the current project has a low risk of severity.

Additionally, because this study looked at recruiting participants with CKP, vulnerability issues were considered. Thus, the researcher was accompanied with an assistant researcher throughout the whole study duration. The location that the study took place in was private and secure place and all COVID-19 restrictions were applied. Finally, participants' dignity and privacy were completely respected and protected.

For the interview data, after the end of the second timepoint, the researcher (M.S.) asked participants to start a face-to-face interview about the acceptability of using the digital toolkit. The researcher followed the developed interview guide (Appendix 7) and also asked the research assistant to leave the room to prepare a quiet and comfortable environment for the participant. It is important to consider the wellbeing of participants who will be interviewed. Thus, verbal consents were gained from participants prior the interview. Additionally, the researcher (M.S.) provided clarification about the reason of commencing the interview and to remind participants that their participation is completely voluntary. Also, participants were encouraged to ask about any clarification that they need, and that they can withdraw without providing any clarification. Furthermore, confidentiality was an important aspect with interviews (Whiting 2008). The researcher made sure that the interviewees identity will remain confidential. The researcher intended to use the same anonymising strategy used in the experimental part since the interview was conducted just after the experiment was finished. This helped in storing each participant data in the same file and at the same place. Because the interviews were done by the researcher without any assistant, the researcher ensured that recordings wouldn’t be passed to others except the supervisors.

Chapter 6

Results

6.1. Introduction

The current project aimed to evaluate the acceptability and usability of a DBBT for the physiotherapy management of individuals with CKP. Hence, an exploration of the acceptability and usability of the DBBT was conducted. This chapter starts with highlighting the current study's recruitment process and participants' demographics including gender distribution, mean age, weight, height, and body mass index (BMI).

The chapter then presents the acceptability findings derived from the thematic analysis of qualitative interviews conducted with participants, highlighting key themes that reflect their perspectives and experiences towards the DBBT acceptability. Following this, the usability findings including mean system usability scale (SUS) score and adherence rates to exercise logging and participant-reported outcome measures (PROMs) submissions tasks, are then presented.

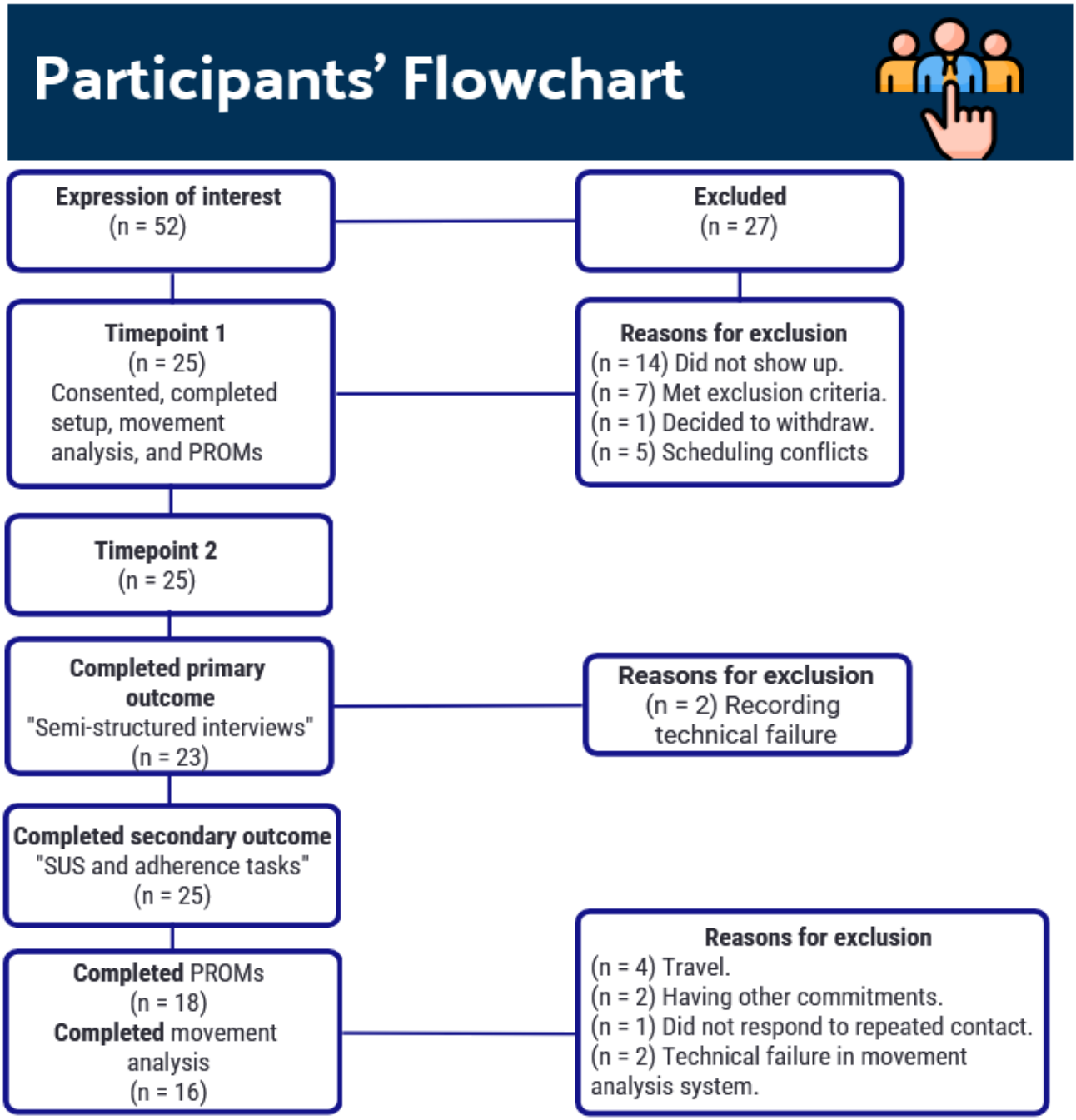
Lastly, the supplementary data are presented to further complement and contextualise participants' acceptability and usability evaluation. These data include joint kinematics (mean hip, knee, and ankle joints maximum, minimum, and initial contact angles, and ROM, from sagittal and frontal planes), spatiotemporal parameters (mean speed, cadence, distance, number of steps, duration, and step length), and mean PROMs scores (including WOMAC, TSK, PHQ-9, NPRS, and SES6G). All supplementary data were collected from two timepoints.

6.2. Participant recruitment

A total of 25 participants took part in the study. All participants completed the consent process, movement analysis, and patient-reported outcome measures (PROMs) at timepoint one. At timepoint two, 23 participants completed the primary outcome measure, which was the semi-structured interview. Two interviews were not recorded due to technical issues. All 25 participants completed the secondary outcome measure, the System Usability Scale (SUS). 18 participants also returned for the second movement analysis and completed PROMs. Seven participants did not

return due to travel, other commitments, or lack of response. Of the 18 movement datasets, two were excluded because of technical problems, resulting in 16 valid

Figure 15 Participants' Flowchart



datasets included in the final analysis.

All analysis is based on (N = 25) participants who completed the primary outcome.

6.3. Participants characteristics

In the current study, the total number of participants (N = 25). Of which, there were (N = 14, 56%) males, and (N = 11, 44%) were females. However, in terms of knee condition, females with knee OA (N = 7, 28%) outnumbered males with the same condition (N = 6, 24%). Conversely, males complaining of CKP (N = 8, 32%) outnumbered females with similar complaint (N = 4, 16%). Furthermore, the table below (Table 15) highlights the anthropometric characteristics of the study population. The age's mean and (SD) = 37 ± (16.03) and the BMI's mean and (SD) = 26 ± (2.9).

Table 15 Participants' Characteristics

Variable	Mean ± (SD)	Range
Age yrs	37 ± (16.03)	19 – 71
Weight in kg	76.5 ± (14.21)	59 – 112
Height in cm	171 ± (11.12)	152 191
BMI kg/m^2	26 ± (2.9)	20.5 – 32.7

(yrs) = Years. (kg) = Kilogram. (cm) = Centimeter. (BMI) = body mass index. (m^2 = meter square)

6.4. Acceptability findings

6.4.1. Reflexive thematic analysis

The thematic analysis of the semi-structured interview that took place in the current project to evaluate the DBBT acceptability is presented in this section. The theoretical and conceptual framework of acceptability (TFA) was used; thus, the analysis was conducted deductively according to the TFA constructs (components).

Table 15 Summary of the identified themes and subthemes from the thematic analysis in relation to the TFA

TFA Construct & Broad Themes		Subthemes	Supporting Quotes
Affective Attitude	**Impression about the toolkit and its features.**	Technological innovation and advancement.	"At the beginning I haven't thought that it would look like this. But then when I know what the purpose of everything is, it all made sense. I feel it is a successful way to make a physiotherapy assessment and I appreciate the technology that you used"
		Visual Feedback and Representation	"Well the technology is is interesting, I personally found it impressive you know by seeing myself moving as an avatar then seeing the the the report showing and and detecting um the way I walked, was interesting really, yeah."
		Personalising treatment Approach	"No problems using it, I felt it is quite advanced. I have used training apps before but this one was a bit different as it was based on my own movement and my own needs. So that was like a wow to to to mm and and positive impression was immediately after knowing

			exactly what the toolkit is about."
Burden	**Risks and Challenges in Using the Toolkit**	Perceived Safety and Low Risk	"So using the toolkit was not risky at all especially that all the steps were taken under a well trained physio and you were keen in giving the instruction and so so that I can't think of any risks"
		Exercise-Related Challenges	"Risks uh. There was there were no risks at all. But about challenges, challenges. Yeah, it was challenging at the first time when I was doing it. [...] it was challenging because of the of the levels of the of the exercises. [...] I personally uh I don't exercise much. Just walk. So yeah, it was a bit challenging, like a muscle sore […]"
Ethicality	**Participants Value the Technology**	Clarity and Encouragement	"Everything was clear and encouraging, and I had a good experience overall. And I appreciate my time spent here"
		Increased Self-awareness	"If nothing else, they'll learn a great deal about about what the what, what's what is wrong exactly, and what, what, what can be done to manage the the situation"
		Hope for Improvement	"I was very happy to come and try this technology with a a chronic condition, which made me feel like there is a hope to improve and

			and and well done with your project and thank you very much"
Intervention Coherence	**A. Understanding How the Toolkit Works**	A.1. Gait Analysis and Visualisation	"[…] my understanding is that it. It allowed you to sort of plot sort of these sort of graphs and sort of show me the differences between like my left and my right sort of hip or ankle or knee. And then that sort of pointed that out to me."
		A.2. Connecting Assessment to Exercise Prescription	"[…] compiled sort of evidence and data to show how I was walking. And the specific points in my gait that may differ from as opposed perfect gait. And then I was prescribed a set of specific physio exercises in order to combat those specific [...]"
		A.3. Holistic Approach to Movement Analysis	"Uh, yes, I think I understand now that how I how I move, how I walk and that the problem or the there's a relation between the ankle and the knee when it comes to the to my problem. And also I feel the exercises now are more tailored and targeting my my problem which helps actually cure my problem."
		A.4. Technology as a Tool	"I think that by using technology like this that provides accurate information on on how we use our joints and indicates that that this could be why I feel pain and see that through a report is something

		for Insight	good. And yeah the suit and sensors looked cool huh and they all made sense of course with your help and explanations."
	B. **Biomechanical Biofeedback Improvement and Suggestions for Enhancing the Gait Report**	B.1. Clarity and Comprehension of the Gait Report	"It was very clear it was very, very clear explanation was very good. Yeah, it was."
		B.2. Visual Learning and Representation	"Maybe I'm quite a visual learner, so maybe like a an example of maybe what I was doing wrong because you can't always visualise it to yourself because it's so natural at that point. So maybe seeing yourself doing it and it was hard, but maybe seeing someone else doing what you're doing."
		B.3. Technical Language and Explanations	"One other thing is well for me. It would be useful or interesting. Like, I don't know anatomy very well. So when it says I'm meant to be doing it, you know, hip abductor or hip abductor, even just the obviously I can Google these things. But I clicked to a little wiki page that just explains or has some like, you know, would be really useful."
			"When you're comparing the before and. The after you could sort of merge them. So there were the graphs specifically about the. My hip and tail that. There was a specific word for it that the abduction

		B.4. Data Presentation and Comparison	of my hip and we had two graphs. The abduction of my hip before and after, yeah. And maybe there's a way to sort of put them onto the same graph."
		B.5. Accessibility and Retention of Information	"I think regarding improving the biofeedback, probably maybe add some text to the charts provided. So that in case I forgot or I wanted to explain my condition to someone, I can do that."

Opportunity Costs	**Thoughts About Using the Technology in the Future**	Widespread Implementation and Integration of the toolkit into healthcare settings	"I think it will be important and I think it will spread all over the world because from my experience with with it, I think it was great. I've I've been with the physiotherapist before and this is really different because when I went to to a physiotherapist before the, I think the problem was the exercises weren't clear and there's no real follow up"
		Motivation Factors for	"Yes, yes, it is motivating in term of following an exercise

Perceived Effectiveness	**Performance Enhancement Factors**	Using the Toolkit	programme especially that it has a start and end date so I knew that I should be doing those exercises within this timeframe."
		The Toolkit Monitoring Feature	"Right, I guess that monitoring my own progress when I submit the completed my daily tasks was something nice. It also felt great when I had a look and found myself completed all the exercises that I was asked to do."
		Engagement with the toolkit	"the engagement Um I thought of the videos and the reminders mainly as the engaging parts where I received a reminder to do my exercises and watch the videos so there was that that interaction with the phone and meself."
		Personalisation feature of the toolkit	"[…] Starting from the you introducing the sensors in the beginning ending up with having a report and as I mentioned a personalised programme adding a lot, the app where you can see your exercises and watch the videos, so I believe that personalisation is something that is is clear in this experience."

		Reported benefits after using the toolkit	"I would also like to thank you because after using this toolkit because I feel now my knee is stronger and I felt this especially when I am walking and climbing stairs."
Self-efficacy	**A. Confidence in Using the Mobile Application**	A.1. User-Friendliness and Intuitiveness	"Very confident; it was uh you call it user-friendly, innit, yeah I was very confident. and intuitive."
		A.2. Familiarity with Technology	"Perhaps it was. It was all fine. It's all very, very intuitive, very easy to use. I didn't. Yeah, it was. It was fine. I mean, I mean, I assume if you were somebody wasn't familiar with with the technology might be might be difficult. But for me it was very similar to those of other apps I've used. So for different stuff."
		A.3. Initial Learning Curve	"Uh, it's not. Uh. It's not about confidence. I think it's about trying to familiarise myself first with with the application. I think this is this happens with all applications. In general you have to familiarise yourself, you have to go and and check and see the components. Check well, what is this for and. What if I did this? What if I press this button and so it's? It's more of a familiarisation thing, so in general it was, it was great."

	B. Adherence to using the mobile application for logging the exercises	B.1. Reasons for not logging exercise completion in the app	"Although the app and the toolkit was motivating, but sometimes you just can't help it when you're busy and you lack time in some cases."
	C. User Satisfaction	C.1. Positive Overall Experience	"OK, actually it was. It was an interesting experience. It was great to see maybe where it's going as well. And it was a good experience in general, actually enjoyed being part of it."
		C.2. Quality of Guidance and Support	"No other than it was meticulous. It was well done. The you know the the the data collection itself was was a simple process the you know the person conducting it was was was great, made me feel comfortable in in the session and and then the information that I got at the end was extremely relevant and very easy for me to access the app. There. So it was. It was a really smooth process."

6.4.2. Thematic analysis final report.

The final report that was produced after the completion of the thematic analysis is presented in the section.

6.4.2.1. Theoretical and conceptual framework of acceptability component: Opportunity costs

Definition: The extent to which benefits, profits, or values must be given up engaging in an intervention

Theme 1: Thoughts about using the technology in the future

The theme "**Thoughts about using the technology in the future**" emerged from the analysis of interview data, reflecting participants' perspectives on the potential future applications and benefits of the biomechanical biofeedback toolkit. This theme encompasses information that highlight different aspects of participants' expectations and hopes for the technology's future use.

Subtheme 1.1: Widespread implementation and integration of the toolkit into healthcare settings

Participants expressed a strong belief that the technology should be widely implemented in healthcare settings, including hospitals, clinics, and physiotherapy services. The enthusiasm for widespread implementation stems from participants' positive experiences with the toolkit and their recognition of its potential benefits for both patients and healthcare providers. Many participants saw the technology as a significant improvement over traditional physiotherapy methods and believed it could enhance the quality of care provided. An example of this is **Sumaia** who articulated this sentiment

"I think it will be important and I think it will spread all over the world because from my experience with with it, I think it was great. I've I've been with the physiotherapist before and this is really different because when I went to to a physiotherapist before the, I think the problem was the exercises weren't clear and there's no real follow up"

This quote highlights the perceived advantages of the toolkit over traditional physiotherapy, particularly in terms of clarity and follow-up. The participant's belief

that the technology will spread all over the world underscores the perceived value and potential impact of the toolkit on a global scale. The desire for widespread implementation also reflects participants' recognition of the technology's potential to standardise and improve care across different healthcare settings. By integrating the toolkit into various healthcare environments, participants envisioned a future where personalised, technology-assisted rehabilitation would be more readily available and accessible to a broader population.

Furthermore, participants expressed excitement about the potential for future improvements and technological advancements in the toolkit. Many participants saw the current version of the toolkit as a promising starting point and were eager to see how it might evolve with further development. They envisioned various enhancements that could make the technology even more effective and user-friendly in the future. For instance, what **Rebecca** shared regarding her vision for future improvements.

"And and this this toolkit actually helps me with the with everything that I need and actually can help even the physiotherapist maybe to attract the the patients advancement. It would be also great if this goes to goes to a level of of 3D maybe. 3D videos or you know with new technologies, so this will be. This will be the future I think"

This quote illustrates the participant's enthusiasm for potential technological advancements, such as the integration of 3D videos. It also highlights the belief that these improvements could further enhance the toolkit's effectiveness for both patients and physiotherapists. The anticipation of future improvements suggests that participants see the current toolkit as part of an evolving technological landscape in healthcare. This perspective indicates a willingness to embrace ongoing innovations and a belief in the potential for technology to continually enhance rehabilitation practices.

Furthermore, participants recognised the potential of the technology for remote monitoring and telemedicine applications, particularly in light of recent experiences with the COVID-19 pandemic. The ability to use the toolkit remotely was seen as a significant advantage, especially in situations where in-person visits to healthcare providers might be challenging or impossible. Participants appreciated the potential

for continuous monitoring and support without the need for frequent clinic visits. **Kailey**, here, has highlighted this aspect

"It's crucial for future use in hospitals and clinics, especially during times like the pandemic when remote monitoring was necessary."

This quote underscores the perceived importance of the technology in facilitating remote care, particularly during extraordinary circumstances like a pandemic. The participant's use of the word "crucial" emphasises the belief that such technology could play a vital role in ensuring continuity of care in challenging times. The potential for remote monitoring was also seen as a way to increase accessibility to specialised care, potentially benefiting patients who might have difficulty attending regular in-person appointments due to geographical, physical, or time constraints. Additionally, participants valued the potential of the technology to empower patients and facilitate self-management of their conditions.

The toolkit was seen as a means to provide patients with greater understanding and control over their rehabilitation process. Participants appreciated how the technology could help them become more familiar with their condition and learn effective management strategies. **Jonathan** has expressed this sentiment

"Yep, definitely. I think it's not just for knee pain, but for any sort of, you know, body pain. It would be good to include sort of a initial assessment before prescribing any. I would also say that becoming familiar with your own condition and learn what you should do to get better is something that this technology offers which I I would say is important to give patients the comfort in in managing their own condition."

This quote highlights the perceived value of the technology in promoting patient education and self-management. The participant's emphasis on becoming familiar with his own condition and gaining comfort in managing his own condition underscores the empowering potential of the toolkit. The ability to self-manage and monitor progress was seen as particularly beneficial for maintaining long-term engagement with rehabilitation exercises. Participants appreciated the potential for the technology to provide ongoing guidance and motivation, even outside of clinical settings.

Moreover, participants expressed hope for the integration of the technology into existing healthcare systems and practices. Many saw the potential for the toolkit to

complement and enhance current physiotherapy and rehabilitation practices. They envisioned a future where the technology could be prescribed by healthcare providers as part of a comprehensive treatment plan. **Haidi** is an example of such perspective

"I would love to see this developed technology and I would I would actually think that it would be great if it was, you know, could always prescribe it. So that you know, you could almost go to GP and just they could prescribe you a course like this or and. It's I don't know. What good looks like, but whatever that was, I think that would be really good because especially if you caught it early."

This quote illustrates the desire for the technology to be integrated into standard healthcare practices, with the possibility of being prescribed by general practitioners. The participant's emphasis on early intervention highlights the perceived preventive potential of the technology when integrated into routine healthcare. The idea of integrating the toolkit into existing healthcare systems also reflects a desire for a more holistic and technology-enhanced approach to patient care. Participants saw the potential for the technology to bridge gaps in current practices and provide more comprehensive, personalised care. More, participants consistently expressed a willingness to recommend the technology to others and a desire to continue using it themselves. The positive experiences reported by participants led many to state that they would recommend the toolkit to others with similar conditions. This willingness to recommend suggests a high level of satisfaction with the technology and confidence in its effectiveness. **Huda**, for instance, enthusiastically stated this.

"[…] I will recommend it for all, for all of the people who are who have a problem like mine. The knee pain or any joint problem, of course, for especially for this thing and for the technology in in general. Yeah, of course it's it helps in different ways and I recommend it."

This quote not only demonstrates the participant's willingness to recommend the technology but also highlights their belief in its broad applicability to various joint problems. The enthusiasm expressed in this recommendation suggests that the participant found significant value in the toolkit and believes it could benefit others facing similar challenges. Furthermore, many participants expressed a desire to continue using the technology beyond the study period. This interest in long-term

use indicates that participants saw ongoing value in the toolkit and believed it could contribute to their continued rehabilitation and management of their condition. The combination of willingness to recommend and desire for continued use strongly supports the overall theme that participants valued the technology. It suggests that the toolkit not only met immediate needs but also created a lasting positive impression on participants, potentially influencing their future approaches to managing their health conditions.

In conclusion, the theme "Thoughts about using the technology in the future" reveals a generally positive outlook on the future applications of the biomechanical biofeedback toolkit. Participants envisioned widespread implementation, continuous technological improvements, applications in remote monitoring and telemedicine, enhanced patient empowerment and self-management, and integration with existing healthcare systems. These perspectives highlight the perceived value and potential impact of the technology on future rehabilitation practices and patient care. The enthusiasm and optimism expressed by participants suggest that there is significant support for the continued development and implementation of such technology in healthcare settings.

6.4.2.2. Theoretical and conceptual framework of acceptability component: Burden

Definition: The perceived amount of effort that is required to participate in the intervention

Theme 1: Risks and challenges in using the toolkit

The overarching theme that emerged from the participant interviews was a general perception of low risk associated with the toolkit, coupled with some challenges primarily related to the exercise programme rather than the technology itself. This theme can be further divided into two subthemes that highlight different aspects of the participants' experiences.

Subtheme 1: Perceived safety and low risk

Participants consistently reported that they did not perceive any significant risks associated with using the toolkit. This perception of safety was often attributed to the professional guidance and supervision provided during the process. For example, **John** explicitly stated

"So using the toolkit was not risky at all especially that all the steps were taken under a well trained physio and you were keen in giving the instruction and so so that I can't think of any risks"

This quote highlights the importance of professional supervision in ensuring participant safety and comfort with the toolkit. The presence of a trained physiotherapist appears to have significantly mitigated any potential risk concerns. Another participant, **Jeremy**, echoed this sentiment

"Umm the risks, I don't think that there was any risks with using the toolkit."

This widespread perception of low risk suggests that the toolkit was designed and implemented in a way that prioritised user safety, which is crucial for any health-related intervention.

Subtheme 2: Exercise-related challenges

While participants generally didn't perceive risks, some reported challenges related to the exercise programme itself. These challenges were often associated with the physical demands of the exercises rather than the technology or toolkit. **Hannah** described her experience as she highlighted at the beginning, exercises were a bit challenging.

"Risks uh. There was there were no risks at all. But about challenges, challenges. Yeah, it was challenging at the first time when I was doing it. [...] it was challenging because of the of the levels of the of the exercises. [...] I personally uh I don't exercise much. Just walk. So yeah, it was a bit challenging, like a muscle sore […]"

This feedback highlights that for some participants, particularly those who were not regularly physically active, the exercises themselves posed a challenge. It's important to note that these challenges were seen as part of the process rather than a risk or negative aspect of the toolkit. Moreover, **Tom** also noted the initial difficulty with certain exercises.

"[…] They sometimes the the the very first exercise of the day. I was a bit stiff. That's that. And that's natural. But once I got through the first couple of motions, particularly the first exercise, [...] that one was particularly the the earlier exercises were quite hard for me to to. Yeah, to get my full range."

This quote suggests that while some exercises were initially challenging, participants recognised this as a normal part of the process and were able to adapt over time. Furthermore, exercise intensity was reported as a challenge when it is associated with pain or discomfort during exercise. **Tom** highlighting the need for clear guidance on distinguishing between normal exercise-related discomfort and potentially harmful pain

"So some of the exercises there was a a degree of pain […], pain was something quizzed about quite a bit. Yeah, […] I I didn't feel that there was a distinction between, you know, the pain that associates with exercise, you know, you get sore muscles I I don't mind that and the pain that you would associate with doing yourself a damage"

This feedback suggests that clearer communication about expected levels of discomfort and when to be concerned could enhance the user experience and safety. Another challenge that was reported by some participants was related to the environment or available equipment, which affected the ability to perform certain exercises as prescribed. **Josh** shared his views about this.

"So there was one exercise where I had to like, hold on to a pole and lean forward. I didn't have anything to hold on to so I was just doing it like that […] So after I think three or four days I stopped doing that"

This feedback highlights the importance of considering the home environment and available equipment when prescribing exercises, and potentially providing alternatives or modifications for those without access to specific equipment.
Lastly, some participants mentioned challenges related to finding time to complete the exercises regularly, though this was generally seen as a minor issue. **Chris** talked about this challenge.

"Perhaps the only challenge I face was getting up and doing it;"

This brief comment suggests that for some users, the main challenge was not the toolkit or exercises themselves, but rather the self-discipline required to maintain a regular exercise routine.

In conclusion, the thematic analysis reveals that participants generally perceived the biomechanical biofeedback toolkit as low-risk and safe to use. The main challenges reported were primarily related to the physical demands of the exercise programme, managing pain or discomfort, environmental constraints, and maintaining commitment to the routine. These challenges were generally seen as part of the process rather than significant risks or barriers to using the toolkit. The feedback suggests that while the toolkit itself was well-received in terms of safety, there may be opportunities to enhance the exercise programme by providing clearer guidance on pain management, offering exercise modifications for different environments, and potentially incorporating features to support user motivation and adherence to the programme.

6.4.2.3. Theoretical and conceptual framework of acceptability component: Ethicality

Definition: <u>The extent to which the intervention has good fit with an individual‘s value system</u>

Theme 1: Participants value the technology

This theme "Participants value the technology" emerged from the analysis of interview data, highlighting the positive reception and perceived benefits of the biomechanical biofeedback toolkit. This theme encompasses several subthemes that reflect different aspects of participants' appreciation for the technology.

Subtheme 1: Clarity and encouragement

Participants expressed appreciation for the clear and encouraging nature of the technology, which contributed to a positive overall experience. The clarity of the technology was particularly noteworthy, as it allowed participants to easily understand and engage with the toolkit. This clarity extended to both the mobile application and the data collection process, enhancing the user experience and fostering a sense of confidence in the technology. An illustration of this point was stated by **Nadia**.

"Everything was clear and encouraging, and I had a good experience overall. And I appreciate my time spent here"

This quote exemplifies the positive sentiment towards the technology's user-friendly nature and its ability to provide a supportive environment for participants. The clarity and encouragement offered by the toolkit likely contributed to participants' willingness to engage with the technology and follow through with the prescribed exercises. The encouraging aspect of the technology is particularly important in the context of rehabilitation, as it can help motivate individuals to persist with their treatment plans. By providing clear instructions and positive reinforcement, the toolkit appears to have created an environment conducive to participant engagement and adherence.

Subtheme 2: Increased self-awareness

Participants reported that the technology provided them with valuable insights into their condition and movement patterns, leading to increased understanding and self-awareness. The gait reports and biomechanical feedback offered by the toolkit seem to have played a crucial role in helping participants understand their condition better. This increased understanding appears to have empowered participants, giving them a sense of control over their rehabilitation process. **John** expressed this sentiment

"If nothing else, they'll learn a great deal about about what the what, what's what is wrong exactly, and what, what, what can be done to manage the the situation"

This quote highlights how the technology not only provided treatment but also educated participants about their condition. The increased understanding gained through the use of the toolkit appears to have been highly valued by participants, as it allowed them to make more informed decisions about their health and rehabilitation. The self-awareness fostered by the technology also seems to have contributed to participants' status in managing their condition. By providing objective data and visual feedback, the toolkit appears to have helped participants better understand their body's capabilities and limitations, leading to more effective self-management strategies.

Subtheme 3: Hope for improvement

The technology instilled a sense of hope in participants, particularly those dealing with chronic conditions. Many participants expressed that using the toolkit gave them hope for improvement and to actively proceed with their rehabilitation process. This hope seems to have been particularly impactful for those who had been struggling with long-term conditions and had previously felt discouraged about their prospects for improvement. **Hannah** highlighted this in here statement

"I was very happy to come and try this technology with a a chronic condition, which made me feel like there is a hope to improve and and and well done with your project and thank you very much"

This quote illustrates how the technology not only provided practical benefits but also had a positive psychological impact on participants. The hope generated by the toolkit appear to have been significant factors in participants' positive evaluation of the technology. The biomechanical biofeedback aspect of the toolkit seems to have been reinforced by the visible progress provided through the gait reports and exercise tracking. This tangible evidence of improvement likely contributed to participants' continued engagement with the toolkit and their overall satisfaction with the experience.

In conclusion, the theme "Participants value the technology" is strongly supported by the various subthemes identified in the analysis. The clarity and encouragement provided by the toolkit, the increased understanding and self-awareness fostered, and the hope instilled, all contribute to a robust appreciation for the biomechanical biofeedback toolkit. These findings suggest that the technology has significant potential to positively impact rehabilitation practices and patient outcomes in the field of physiotherapy and movement science.

6.4.2.4. Theoretical and conceptual framework of acceptability component: Affective attitude

Definition: <u>How an individual feels about taking part in an intervention</u>

Theme 1: Impressions about the toolkit and its features

The overarching theme that emerged from the participant interviews was a generally positive impression of the biomechanical biofeedback toolkit and its various features.

This theme can be further divided into several subthemes that highlight different aspects of the participants' experiences and perceptions.

Subtheme 1: Technological innovation and advancement

Participants consistently expressed impressions of the toolkit as technologically advanced and innovative, particularly in the context of physiotherapy. **Salah** articulated this sentiment

"At the beginning I haven't thought that it would look like this. But then when I know what the purpose of everything is, it all made sense. I feel it is a successful way to make a physiotherapy assessment and I appreciate the technology that you used"

This quote reflects the initial surprise and subsequent appreciation for the technological aspects of the toolkit. Participants seemed to recognise the toolkit as a significant advancement in physiotherapy assessment and treatment. Another participant (**Dalia**) had a similar impression

"Was. So uh, it it. It was the first time for me to see such technology actually used in physiotherapy, especially that I received physiotherapy before. And I felt that using the sensors and the mobile application is something advanced. And very useful for understanding exactly what the limitations I have and what. I need to do."

This feedback highlights how the toolkit's technology was perceived as a step forward from traditional physiotherapy methods, offering more precise insights into individual needs and limitations.

Subtheme 2: Visual feedback and representation

Many participants were particularly impressed by the visual aspects of the toolkit, including the avatar representation and exercise videos. An example for this is what **Ahmed** thought.

"Well the technology is is interesting, I personally found it impressive you know by seeing myself moving as an avatar then seeing the the the report showing and and detecting um the way I walked, was interesting really, yeah."

This quote underscores the impact of visual feedback in helping participants understand their movement patterns. The avatar representation seems to have provided a novel and engaging way for users to visualize their gait and posture. Another participant (**Jess**) emphasized the value of video demonstrations.

"I was impressed, especially with the visual exercises in the videos, which were more helpful than any written instructions or the regular exercise pictures."

The feedback suggests that the video demonstrations in the app were particularly effective in guiding users through exercises, offering a clear advantage over traditional written or static image instructions.

Subtheme 3: Personalising treatment approach

Participants appreciated the personalised nature of the toolkit, noting how it provided tailored feedback and exercises based on individual assessments. **Liz** expressed this sentiment.

"No problems using it, I felt it is quite advanced. I have used training apps before but this one was a bit different as it was based on my own movement and my own needs. So that was like a wow to to to mm and and positive impression was immediately after knowing exactly what the toolkit is about."

This quote highlights the perceived value of personalisation in the toolkit. The ability to receive feedback and exercises tailored to individual movement patterns and needs was seen as a significant advantage over generic training apps. Additionally, **Josh** reinforced this impression.

"I was impressed. I think I was, you know, it's an easy system to use. I quite like the ranges that it was my movement. I I haven't seen this before, but it was simple enough. So it was useful. This I think it's a good idea. I mean I. It definitely felt targeted once I was doing my bit, it was given based on my injury. It was. It felt like it was targeted and everything I did really, I felt it strengthened my knee."

This feedback emphasises how the targeted approach of the toolkit contributed to users feeling that the exercises were specifically addressing their individual needs and conditions.

In conclusion, the thematic analysis reveals that participants generally had positive impressions of the biomechanical biofeedback toolkit and its features. They were impressed by its technological innovation, appreciated the visual feedback and personalised approach, and found value in the targeted exercises and assessments. Thus, the overall impression was one of an advanced and useful tools for physiotherapy assessment and treatment. The toolkit's ability to provide objective, data-driven insights into individual movement patterns was particularly well-received, suggesting that this approach has significant potential in the field of physiotherapy and rehabilitation.

6.4.2.5. Theoretical and conceptual framework of acceptability component: Self-efficacy

Definition: The participant's confidence that they can perform the behaviour(s) required to participate in the intervention

Theme 1: Confidence in using the mobile application

The theme that emerged from the participant interviews was a high level of confidence in using the mobile application and toolkit. This theme can be further divided into several subthemes that highlight different aspects of the participants' experiences.

Subtheme 1.1: User-friendliness and intuitiveness

Participants consistently reported that the mobile application was user-friendly and intuitive, which contributed significantly to their confidence in using it. The ease of use was a key factor in their positive experiences. **Jeremy** expressed this sentiment clearly.

"Very confident; it was uh you call it user-friendly, innit, yeah I was very confident. and intuitive."

This quote exemplifies how the application's design facilitated a smooth user experience, allowing participants to navigate and utilise its features without significant difficulties. The intuitive nature of the app meant that users could quickly understand its functionality without extensive training or guidance. **Layla** had a similar view emphasising the app's clarity and straightforwardness.

"MHM. I was very confident when I'm using the app it's very it was very clear and. Straight forward so yeah, I was very confident in using it at the first time. Just do the access for it and the rest was easy."

This feedback suggests that the app's interface and navigation were designed with the user in mind, making it accessible even to those who might not be particularly tech-savvy. The clarity in design and functionality appears to have been a crucial factor in boosting user confidence.

Subtheme 1.2: Familiarity with technology

Many participants noted that their prior experience with similar applications or general comfort with technology contributed to their confidence in using this specific app. **Jack**, here, noted this.

"Perhaps it was. It was all fine. It's all very, very intuitive, very easy to use. I didn't. Yeah, it was. It was fine. I mean, I mean, I assume if you were somebody wasn't familiar with with the technology might be might be difficult. But for me it was very similar to those of other apps I've used. So for different stuff."

This quote highlights how familiarity with technology can enhance user confidence. For those who regularly use mobile applications, the learning curve was minimal, allowing them to focus on the content rather than struggling with the interface.
Another participant (**Jude**) expressed a similar sentiment

"Yeah, I I mean I'm I'm pretty tech savvy, have used apps like it in the past. So it was just just like going into a normal app, there was nothing that made me go, oh, this is a bit odd."

These responses indicate that the app's design aligned well with common mobile application conventions, making it easily accessible to those with prior smartphone experience.
Furthermore, participants appreciated the clear instructions and well-organised content within the app, which contributed to their confidence in using it correctly as **Sulaiman** said.

"I was confident enough to understand the report and and to follow the exercises as you prescribed them, and to complete the required questionnaires."

This feedback suggests that the app provided clear guidance on how to interpret the reports, follow exercise routines, and complete necessary questionnaires. The clarity of instructions seems to have been crucial in ensuring that participants felt capable of using the app as intended. Another participant (**Jacob**) elaborated on the effectiveness of the video content:

"Yeah. So when something new came up. On there, it wasn't like I was swamped. I could see this is an extra feature that that needs to be responded to as a questionnaire. I again, I I spoke well of the of the, of the interlinking of the video and that was that that worked very well because the videos didn't go on for too long and you could actually just look at them."

This quote highlights how the app's content was presented in a manageable and digestible format, preventing users from feeling overwhelmed. The integration of video content, in particular, seems to have been well-received and contributed to users' confidence in performing exercises correctly.

Subtheme 1.3: Initial learning curve

While most participants reported high confidence levels, some noted a brief initial learning period. This subtheme highlights the importance of allowing users time to familiarise themselves with new technology. **Claire** described this process.

"Uh, it's not. Uh. It's not about confidence. I think it's about trying to familiarise myself first with with the application. I think this is this happens with all applications. In general you have to familiarise yourself, you have to go and and check and see the components. Check well, what is this for and. What if I did this? What if I press this button and so it's? It's more of a familiarisation thing, so in general it was, it was great."

This reflection suggests that while the app was generally easy to use, there was still a natural process of exploration and learning that users went through. However, this process does not seem to have significantly hindered overall confidence or usability. **Mathew** shared his experience on this.

"Yeah, initially I wasn't that confident since I was a bit confused with the app. I found it full of options that weren't necessary as it wasn't a part of the exercise of the questionnaires. Once I worked out what the exercises were and how to fill the questionnaires, it was all easy enough."

This feedback indicates that while there might have been some initial confusion, particularly regarding the range of features available, users were able to quickly overcome these challenges and gain confidence in using the app effectively**.**

Theme 2: Adherence to using the mobile application for logging the exercises

Most of the participants in the study showed good adherence to their prescribed exercise plan. They used the mobile application to follow their exercise programme and to log the exercises upon their completion. However, some participants, who did not complete their exercise logs, were asked about the reasons behind this during the interviews. The participants highlighted key factors that could contribute to adhering to their exercise programme, which are discussed below.

Subtheme 2.1: Reasons for not logging exercise completion in the app

One of the prominent subthemes that emerged from the analysis was the "Reasons for not logging exercise completion in the app". Participants cited busy schedules, out of hand circumstances, illness, and competing priorities as reasons for their inconsistent use of the app. This subtheme highlights some challenges faced by users in integrating the app into their daily routines, despite recognising its potential benefits. For instance, **Mike** noted his views about this.

"Although the app and the toolkit was motivating, but sometimes you just can't help it when you're busy and you lack time in some cases."

This quote illustrates the internal conflict experienced by users who acknowledge the app's motivational aspects but struggle to prioritise its use when faced with time constraints. Another participant's (**Amr**) response further reinforces this factor.

"I was away on a day trip that day, so it was a we went on holiday[...]"

This statement demonstrates how planned activities can disrupt the routine of logging exercises, suggesting that adherence to the app may be particularly challenging during non-typical days. Furthermore, as a continuation of this point, **Chris** highlighted an out of hands circumstance, which are any circumstances that participants could not avoid adhering logging their exercises. He highlighted that due to being in such situation, he could not adhere to logging the exercises using the mobile application.

"…the 18th of January I was due to perform exercises and there was I was in workout day. And there was a smash on. The motorway and then. No one was going past it till they cleared the smash. That was only four hours on the motor. I. Didn't get home till past 10. At night. So that was one day…"

This quote demonstrates the willingness of using the mobile application and adhering to logging the exercises but in such circumstances, they would find it challenging to perform the exercises and log them. Additionally, another participant (**Manuel**) noted that it was him being unwell when he could not use the mobile application to log the exercises.

"The two days I didn't. I was sick. Yeah. So I didn't leave my sofa…"

This statement, clearly, indicate that although the mobile application was handy, and its tasks were doable, being ill could just make it challenging and difficult to adhere to.

These findings suggest that while users may have positive attitudes towards the app, external factors such as time limitations and competing commitments significantly impact their ability to consistently engage with it. This insight could be valuable for future app developments, potentially indicating a need for features that accommodate users' varying schedules or provide quick logging options for busy days. In the broader context of the study, this subtheme contributes to the understanding of the complex factors influencing user engagement with mobile health apps.

Theme 3: User satisfaction

User satisfaction theme emerged from the participant interviews and it showed a high level of satisfaction with the biomechanical biofeedback toolkit. This theme can be further divided into several subthemes that highlight different aspects of the participants' experiences.

Subtheme 3.1: Positive overall experience

Participants consistently reported a positive overall experience with the toolkit, expressing satisfaction and enjoyment in using it. **Craige** summarized his experience as follows.

"OK, actually it was. It was an interesting experience. It was great to see maybe where it's going as well. And it was a good experience in general, actually enjoyed being part of it."

This quote reflects the general sentiment shared by many participants, indicating that they found value in being part of the study and appreciated the innovative nature of the toolkit. The experience seems to have been both enjoyable and enlightening for the users as **Carlos** expressed similar satisfaction.

"Everything was clear and encouraging, and I had a good experience overall. And I appreciate my time spent here."

This feedback suggests that the toolkit not only provided a positive experience but also offered clear guidance and encouragement throughout the process. The appreciation expressed by participants indicates that they found the time invested in using the toolkit to be worthwhile.

Subtheme 3.2: Quality of guidance and support

Participants frequently mentioned the high quality of guidance and support they received throughout their experience with the toolkit. **Lionel** commented on this and shared his view.

"I think we've covered most of the stuff around the toolkit. What I would say about the data collection sessions they were they were really great. You were lovely, felt very felt like a very safe space and you felt very confident that you were fully aware of what you were doing. And I wasn't gonna hurt myself or anything. And so, so there's a bit of positive feedback on. That really."

This quote highlights the importance of creating a safe and comfortable environment for participants. The confidence in the researcher's expertise and the feeling of safety contributed significantly to the overall positive experience. Additionally, **Muna** has also echoed similar sentiment.

"No other than it was meticulous. It was well done. The you know the the the data collection itself was was a simple process the you know the person conducting it was was was great, made me feel comfortable in in the session and and then the information that I got at the end was extremely relevant and very easy for me to access the app. There. So it was. It was a really smooth process."

This feedback emphasises the importance of a well-organised and professionally conducted process. The combination of a comfortable environment, relevant information, and easy access to the app all contributed to the participant's satisfaction.

In conclusion, the thematic analysis reveals that participants generally felt very confident in using the mobile application and toolkit. The app's user-friendly design, intuitive interface, clear instructions, and well-organised content all contributed to this confidence. While some users experienced a brief learning curve, this did not significantly impact their overall positive experience. The app's alignment with familiar technology conventions also played a role in facilitating user confidence, particularly for those already comfortable with mobile applications.

6.4.2.6. Theoretical and conceptual framework of acceptability component: Intervention coherence

Definition: The extent to which the participant understands the intervention and how it works

Theme 1: Understanding how the toolkit works

The overarching theme that emerged from the participant interviews was a generally clear understanding of the toolkit's functionality and purpose. Participants demonstrated varying levels of comprehension, but most grasped the core concepts of how the toolkit assessed their movement and informed their exercise prescriptions. This theme can be further divided into several subthemes that highlight different aspects of the participants' understanding.

Subtheme 1.1: Gait analysis and visualisation

Many participants showed an understanding of how the toolkit analysed and visualised their gait, providing insights into their movement patterns. For example, **Kevin** articulated his understanding

"[…] my understanding is that it. It allowed you to sort of plot sort of these sort of graphs and sort of show me the differences between like my left and my right sort of hip or ankle or knee. And then that sort of pointed that out to me."

This quote demonstrates how the visual representation of gait analysis helped participants understand the differences in their movement patterns between affected and non-affected sides. The graphical representation seems to have been particularly effective in conveying this information. Another participant (**Jacob**) echoed this sentiment.

"Yeah, I do. Basically after all sensors were placed, you got me to walk around and do some activities while everything was being recorded. Then yeah you showed me what parts you needed to prescribe exercises for."

This feedback highlights the participants' understanding of the process, from sensor placement to data collection and analysis, leading to exercise prescription.

Subtheme 1.2: Connecting assessment to exercise prescription

Participants demonstrated an understanding of how the toolkit's assessment informed their personalised exercise programmes. For instance, **Heather** noted her understanding of this process.

"[…] compiled sort of evidence and data to show how I was walking. And the specific points in my gait that may differ from as opposed perfect gait. And then I was prescribed a set of specific physio exercises in order to combat those specific [...]"

This quote shows how participants understood the connection between the gait analysis and the subsequent exercise prescription. They recognised that the exercises were tailored to address specific issues identified in their gait. This is reinforced by **Marwan** understanding.

"[…] my understanding is that you used the toolkit to first of all measure current state. You know where where I am, what I was, what? How I was

moving now and and then interrogated that information, explained it to me in layman's terms and then came up with a a set of exercises that would be helpful to sort of correct some of the problems I was having as I understand it"

This feedback demonstrates a clear understanding of the process from assessment to explanation to intervention, highlighting the importance of clear communication in helping participants understand the toolkit's purpose and function.

Subtheme 1.3: Holistic approach to movement analysis

Several participants noted how the toolkit provided insights into the interconnectedness of different joints and body parts in their movement patterns. **Jonson** expressed this understanding with his own words.

"Uh, yes, I think I understand now that how I how I move, how I walk and that the problem or the there's a relation between the ankle and the knee when it comes to the to my problem. And also I feel the exercises now are more tailored and targeting my my problem which helps actually cure my problem."

This statement demonstrates how the toolkit helped participants understand the relationships between different joints in their movement patterns, leading to a more comprehensive understanding of their condition. Furthermore, **Nicola** shared a similar insight.

"Yeah sure, I saw the report findings and I was fascinated how other joints were affected as well, and how uh how my knee became like or looked like it was stiff and I was like not using it. Rather I was loading on other joints […]"

This feedback suggests that the toolkit provided participants with a more holistic view of their movement patterns, helping them understand how different parts of their body interact during movement.

Subtheme 1.4: Technology as a tool for insight

Participants expressed their views for the role of technology in providing detailed insights into their movement patterns. **Robert**, for example, reflected on this.

"I think that by using technology like this that provides accurate information on on how we use our joints and indicates that that this could be why I feel pain and see that through a report is something good. And yeah the suit and

sensors looked cool huh and they all made sense of course with your help and explanations."

This quote highlights how participants viewed the technology as a valuable tool for gaining insights into their condition. The visual aspect of the technology ("suit and sensors looked cool") seemed to enhance engagement with the process. In addition, **Tom** emphasised the value of the technological approach and how it did change his own understanding of his problem.

"100% it's night and day. You know I didn't know. Well, no, I didn't know, actually, that something was wrong in my gait and so on so forth. But clearly is. Yeah, I didn't understand that. I was exacerbating the problem, by the way. I was walking."

This feedback underscores how the toolkit provided insights that participants were not previously aware of, potentially leading to a better understanding of their condition and how to address it.

In conclusion, the thematic analysis reveals that participants generally had a good understanding of how the biomechanical biofeedback toolkit worked. They grasped the concept of gait analysis and visualisation, understood the connection between assessment and exercise prescription, recognised the holistic approach to movement analysis, and appreciated the role of technology in providing insights. This understanding seems to have enhanced their engagement with the exercise programme and their overall perception of the intervention's value. The clear explanations provided by the researcher appear to have been crucial in facilitating this understanding, highlighting the importance of effective communication in the implementation of such technological interventions in physiotherapy and rehabilitation contexts.

Theme 2: Biomechanical biofeedback improvement and suggestions for enhancing the gait report

This theme explores participants' experiences with the biomechanical biofeedback toolkit and their suggestions for improving the gait report. The analysis reveals several subthemes that highlight the strengths of the current approach and areas for potential enhancement.

Subtheme 2.1: Clarity and comprehension of the gait report

Many participants found the gait report clear and understandable, particularly when explained by the physiotherapist. This suggests that the current format of the report is generally effective, especially when accompanied by expert interpretation. **Angela** expressed her views with this point.

"It was very clear it was very, very clear explanation was very good. Yeah, it was."

This quote indicates that the participant found the explanation of the gait report to be highly comprehensible. The repetition of "very clear" emphasizes their satisfaction with the clarity of the information presented. However, some participants noted that they might struggle to understand the report fully without professional guidance as **Mike** stated.

"[…] you have to, you have to explain it."

This response highlights the importance of having a physiotherapist or trained professional present to interpret the data. It suggests that while the report itself may be clear, the technical nature of the information requires expert explanation for full comprehension.

Subtheme 2.2: Visual learning and representation

Several participants expressed a preference for more visual elements in the gait report, suggesting that this could enhance understanding and engagement with the data. This is found on what **Sarah** has noted.

"Maybe I'm quite a visual learner, so maybe like a an example of maybe what I was doing wrong because you can't always visualise it to yourself because it's so natural at that point. So maybe seeing yourself doing it and it was hard, but maybe seeing someone else doing what you're doing."

This quote reveals a desire for visual demonstrations or comparisons to aid in understanding the gait analysis. The participant recognises that it can be challenging to visualise one's own movement patterns, suggesting that visual aids could bridge this gap in comprehension. Further, **Abdi** had an additional suggestion.

"Well, I'd start by saying the information was fascinating and really, really insightful because it definitely told me stuff about my gait that. I did well. I

wouldn't have had a clue and and explained a few things I it was fine for me. I think maybe some sort of. Visual avatar representation of the of it as well. So instead of just looking at the data, sort of like some visual would would also be helpful because you've been showing me, but maybe that. But not you."

This feedback indicates that while the participant found the information insightful, they believe that adding a visual avatar representation that highlights the identified points on the gait report could further enhance understanding.

Subtheme 2.3: Technical language and explanations

Some participants expressed difficulty understanding the technical terminology used in the gait report, suggesting a need for more accessible language or additional explanations. **Alan** commented on this as she had some confusion in understanding the technical terms, that had her to search for their meaning.

"One other thing is well for me. It would be useful or interesting. Like, I don't know anatomy very well. So when it says I'm meant to be doing it, you know, hip abductor or hip abductor, even just the obviously I can Google these things. But I clicked to a little wiki page that just explains or has some like, you know, would be really useful."

This quote highlights the challenge of understanding anatomical terms and suggests that incorporating brief explanations or links to additional information could be beneficial. The participant's willingness to seek out this information independently indicates a desire for deeper understanding. Additionally, also **Sally** echoed a similar sentiment.

"Yeah, I think so. And maybe just. If possible, some sort of explanation because it uses physiotherapy terminology that. I'm not always familiar with and like the. The words they use for, like you know extension."

This feedback reinforces the need for clearer explanations of technical terms, suggesting that the gait report could be more accessible if it included definitions or simplified explanations of physiotherapy terminology.

Subtheme 2.4: Data presentation and comparison

Participants offered suggestions for improving how data is presented and compared within the gait report, focusing on making it easier to see changes over time. **Hamed** had suggested merging gait reports into one place.

"When you're comparing the before and. The after you could sort of merge them. So there were the graphs specifically about the. My hip and tail that. There was a specific word for it that the abduction of my hip and we had two graphs. The abduction of my hip before and after, yeah. And maybe there's a way to sort of put them onto the same graph."

This suggestion indicates a desire for more direct visual comparisons between pre- and post-intervention data. The participant believes that merging graphs could make it easier to see changes and progress over time. **Rob** commented on the potential for improvement in data presentation as well.

"Well, it could be improved by you're showing us a lot of data as soon as we finished and you understand it and I don't know, I I'd quite like to see those reports and yeah, obviously. I I think it would take an hour to explain that to me properly, or maybe half an hour. Yeah, certainly that's that's a lot."

This feedback suggests that while the data presented is comprehensive, it may be overwhelming for some participants. The comment implies that more time for explanation or a more digestible format for presenting the data could be beneficial.

Subtheme 2.5: Accessibility and retention of information

Several participants expressed a desire for the gait report to be more accessible for later reference or to share with others. **Nadia** suggested on adding some text as a solution.

"I think regarding improving the biofeedback, probably maybe add some text to the charts provided. So that in case I forgot or I wanted to explain my condition to someone, I can do that."

This quote indicates a desire for the gait report to be more self-explanatory, allowing participants to review and understand the information independently after the initial explanation. More, **Gaby** echoed a similar sentiment.

"I mean, I think. It was relatively clear. But I mean, I think that's hopefully because I'm, I'm I'm relatively cognizant of the different issues that, that, that it was concerned with. Yeah, I think the one thing that maybe would have perhaps for others being more helpful, is to have written explanation on this report so that it can be be something that can be used later for instance with follow-ups or so. I'd also like to see this report in a printed form and keep it with me if that was possible."

This feedback emphasises the importance of having a tangible, detailed report that participants can refer to later. It suggests that while the verbal explanation was clear, having written explanations would enhance the long-term utility of the gait report.

In conclusion, while participants generally found the biomechanical biofeedback and gait report informative and clear, especially when explained by a professional, there are several areas for potential improvement. These include enhancing visual representations, simplifying technical language, improving data presentation for easier comparison, and making the report more accessible for independent review. Implementing these suggestions could lead to a more comprehensive and user-friendly gait analysis experience for participants.

6.4.2.7. Theoretical and conceptual framework of acceptability component: Perceived effectiveness

Definition: <u>The extent to which the intervention is perceived as likely to achieve its purpose</u>

Theme 1: Performance enhancement factors

The participant's responses in the semi-structured interviews revealed key factors that are related to the effectiveness of the DBBT. Those key factors are structured in the following subthemes, which are as follows, Motivation, engagement, monitoring, personalisation, and benefits. And will be discussed below,

Subtheme 1.1: Motivation factors for using the toolkit

The motivation of using the toolkit was expressed by may participants in the study. They identified crucial elements that reflects on the motivation of using the toolkit, which supports the toolkit's usability and acceptability.

The toolkit's structured exercise programme, complete with start and end dates, emerged as a significant motivational factor. Participants found that having a defined timeframe helped them stay committed to their exercises and provided a sense of direction and purpose. **Deborah** stated highlighted this in her reflection.

"Yes, yes, it is motivating in term of following an exercise programme especially that it has a start and end date so I knew that I should be doing those exercises within this timeframe."

This structure allowed participants to set short-term goals and maintain focus throughout their rehabilitation process. In addition, the gait reports and visual representations of their progress proved to be powerful motivators for many participants. Seeing concrete data about their condition and improvements helped them understand the importance of the exercises and motivated them to continue their efforts. For example, **Mike** shared his views to this point.

"I found it very motivating because I understood so rather than somebody a physiotherapist just saying to you do this. Well, because I'm telling you to really. I mean, I'm sure they're saying for the right reason. What I thought was really helpful about this is that I had have had have a visual. And I also saw the data specific to me."

This data-driven approach not only provided motivation but also enhanced participants' understanding of their condition and the rationale behind their exercise programme. Furthermore, the mobile application emerged as a key motivational tool, with its reminders and user-friendly interface encouraging consistent engagement with the exercise programme. Participants appreciated the convenience and accessibility of having their exercise plan readily available on their phones. **Ibrahim**, for instance, highlighted this concept.

"Alright, I feel that the commitment of completing the tasks that a physiotherapist have asked me to do was the biggest motivation for me. Also, seeing all of the finding form the report you shared made me think more and

say that I need to do those exercises to make my joints work better and to activate my muscles. What also motivated me is the mobile app, I had received reminders to use it, so that was part of what made my try my best not to miss a day."

The reminders and easy-to-use interface of the app helped participants maintain their exercise routine and feel more accountable for their progress. Lastly, the sense of accountability and personal responsibility was something that motivated participants to using the toolkit. participants felt a commitment to complete the exercises, knowing that their progress was being monitored and that they had been entrusted with a personalised plan. As **Akkish** informed that.

"Yeah, like I said to you, I felt with the app and with having you given it to me. Yeah, it felt like I had personal responsibility and. You were watching me, but yeah, I thought it felt like you were going to check how it is. Are they doing it? Which it didn't have that feeling? Yes."

This sense of accountability served as an additional motivational factor, encouraging participants to adhere to their exercise programmes.

In conclusion, the "Motivation to use the toolkit" subtheme reveals that the biomechanical biofeedback toolkit successfully motivated participants through its personalised approach, structured programme, visual feedback, mobile application features, and by fostering a sense of accountability. These elements combined to create a comprehensive motivational framework that encouraged consistent engagement with the rehabilitation process and fostered a positive attitude towards recovery. The participants' experiences highlight the importance of incorporating these motivational elements in rehabilitation tools and interventions. By addressing both the physical and psychological aspects of rehabilitation, the toolkit not only provided necessary exercises but also created an environment that encouraged adherence and active participation in the recovery process.

Subtheme 1.2: The toolkit monitoring feature

The analysis reveals several key aspects of the monitoring feature that informs the effectiveness of the toolkit and confirms that it fits for its purpose. Many participants highlighted the toolkit's ability to facilitate self-monitoring, which enhanced their sense of accountability, self-awareness, and engagement with the exercise programme. The mobile application, in particular, played a crucial role in this aspect as **Jacob** highlighted this from his experience.

"Yeah, well, I felt that I was monitored to an extent, so I knew when I'm coming to meeting you again, you will be aware of how many exercises I've done. So, I think that I was watching myself and feeling that I have a mission that I must complete."

This quote illustrates how the monitoring feature created a sense of responsibility and motivation to complete the prescribed exercises. Moreover, the toolkit's monitoring features allowed participants to track their progress visually, which many found motivating and informative. The ability to see completed exercises and progression in difficulty levels was particularly appreciated, explained by **Hannah**.

"Right, I guess that monitoring my own progress when I submit the completed my daily tasks was something nice. It also felt great when I had a look and found myself completed all the exercises that I was asked to do."

This visual representation of progress served as a positive reinforcement for participants, encouraging continued engagement with the programme. Additionally, participants recognised that the toolkit offered a multi-faceted approach to monitoring, combining the mobile application, biomechanical biofeedback, and exercise logging. This comprehensive approach was seen as a strength of the toolkit. For example, **Jimmy** explained this with his own words.

"Yeah monitoring is quite interesting in this toolkit, because everything is based on it, I believe that having the biomechanical feedback from the first and the second time is part of the monitoring because you would notice and share any changes that happened. Also the monitoring through using the mobile app because exercises had to be logged and pain questionnaires had to be submitted, so yeah monitoring is quite good in here."

This holistic monitoring approach provided participants with a more complete picture of their progress and condition. What’s more is that some participants felt that the

monitoring feature created a sense of ongoing clinician involvement, even between in-person appointments. This perceived connection to the healthcare provider was seen as motivating and reassuring. **Julia** talked about this point and highlighted the monitoring of her daily improvement.

"It made my confidence more because there is like someone monitoring my my my improvement every day."

This perception of continuous clinical oversight may have contributed to increased adherence and engagement with the exercise programme.

Furthermore, while many participants found the monitoring features helpful, some identified areas for potential improvement. These included the ability to customise reminder times and the desire for more visible progress tracking over longer periods. **Rozario** suggested to having the ability to change the auto reminders from fixed to flexible allowing the second users to set up their own reminders.

"And I'm sorry, I just remembered I wanted to say that the reminders were nice and it pushes you get up and do what you suppose to do but I didn't like that I couldn't change the reminder time on the app and that would have been really useful."

Such feedback highlights the importance of user customisation in enhancing the effectiveness of monitoring features. It's worth noting that there was some variability in how participants perceived the intensity of monitoring. While some felt closely monitored, others perceived the monitoring as less continuous or intense as **Kane** observed.

"Umm I don't feel that there was continuous monitoring. Uh I mean I was defiantly monitoring my my exercises logs but that was only if I intended to use the app. But if let's say I decided not to use the app, I don't think that monitoring would take place."

This variability suggests that the perceived level of monitoring may depend on individual engagement with the app and toolkit features.

In conclusion, the subtheme reveals that participants generally found the monitoring aspects of the toolkit to be beneficial and motivating. The combination of self-monitoring, progress tracking, and perceived clinician involvement created a supportive environment for adherence to the exercise programme. However, the

analysis also highlights areas for potential improvement, such as increased customization options and more visible long-term progress tracking. The findings underscore the importance of incorporating effective monitoring features in rehabilitation toolkits. These features not only provide valuable data for clinicians but also serve to engage and motivate patients in their recovery process. Future developments in similar toolkits could focus on enhancing user customisation, improving long-term progress visualization, and maintaining a balance between self-monitoring and perceived clinical oversight to optimise patient engagement and outcomes.

Subtheme 1.3 Engagement with the toolkit

Engagement is one of the key elements that explores the acceptability of using the toolkit in actual life. Thus, in this section, is what participants have said in relation to this regard.

Many participants found the mobile application to be engaging due to its interactive features. The ability to watch exercise videos, receive reminders, and log completed exercises contributed to a sense of active participation. Jonathan noted that the reminders and exercise videos on the mobile application were parts that increased his engagement with the toolkit.

"the engagement Um I thought of the videos and the reminders mainly as the engaging parts where I received a reminder to do my exercises and watch the videos so there was that that interaction with the phone and meself."

This quote highlights how the app's features facilitated ongoing engagement with the rehabilitation process. Also, the visual representation of progress and the ability to track completed exercises were frequently mentioned as engaging aspects of the toolkit. Participants found motivation in seeing their progress and completing daily goals. **Cathren** noted that part of the engagement with the toolkit was related to exercise completion.

"Yeah as I told you the tick boxes were fun and I felt engaging with the app as every time I complete an exercise, I tick my completion, which made me have some sort of goal to just say to myself I'm half way through and I still have some more exercise sets that I should do before the end of my day. So it's kind of engaging and I liked that."

This visual feedback mechanism served as a form of gamification, making the rehabilitation process more engaging and rewarding. Similar to participant's views regarding the monitoring features regarding the auto reminders send by the mobile application, the reminders feature was frequently mentioned as an engaging element. It helped participants stay accountable and pushed them to complete their exercises regularly. **Alex** shared his own views from his experience.

"Yes of course, I felt engaged once you shared the report with me, then explaining what type of exercises I needed to do, which were all found on the mobile app as prescribed. Also the videos that I watched were engaging as I was trying to do the exercise similar to the video. And something that I personally likes is the reminders, the auto auto reminders that I received were encouraging to the exercises and I felt engaged by that."

These reminders served as a bridge between the clinical assessment and daily rehabilitation activities, maintaining engagement over time. Some participants found the use of technology itself to be engaging, viewing the toolkit as an innovative approach to physiotherapy. For example, **Jess** highlighted her own experience.

"Yeah, I think it was. I'm a fan of tech, so I think it was a, you know, an engaging way of doing it rather than just the traditional way of physio."

This suggests that the integration of technology can enhance engagement for some patients, particularly those who are comfortable with digital tools.

In conclusion, the subtheme reveals that participants generally found the biomechanical biofeedback toolkit to be engaging across multiple dimensions. The combination of interactive app features, visual feedback, personalised approach, reminders, and innovative technology created a comprehensive engagement strategy that resonated with most participants. These findings highlight the importance of designing rehabilitation tools that not only provide effective exercises but also actively engage patients in their recovery process. The multi-faceted approach to engagement employed by this toolkit appears to be successful in maintaining patient interest and participation over time. Future developments in similar toolkits could focus on further personalising engagement strategies, potentially incorporating more gamification elements or adaptive features that respond to individual preferences and progress. The positive reception of this engaging approach suggests that integrating similar strategies in other rehabilitation

contexts could lead to improved patient adherence and potentially better clinical outcomes. However, it's important to note that engagement is a personal experience, and flexibility in how patients can interact with such toolkits remains crucial for accommodating diverse needs and preferences.

Subtheme 1.4. Personalisation feature of the toolkit

The personalisation and targeting features of the toolkit was brought up in the interviews as an effective way that characterised this toolkit. Participants expressed appreciation for the toolkit's personalised and comprehensive approach to their condition. This holistic perspective was seen as a crucial factor, as it addressed not just the specific knee issue but also considered other joints and overall movement patterns. **Donald**, for instance, expressed that the personalisation in the toolkit provided a wholistic care for his condition.

"[…] knowing that the knee issue that I have is affecting my movement, which is something that can be improved. Then by providing the plan to help in the movement and not focusing on my knees, rather, it felt like it is something wholistic so that you were looking at other joints as well."

This personalised approach made participants feel that their individual needs were being addressed, which in turn increased their motivation to engage with the toolkit. Additionally, participants appreciated the comprehensive nature of the toolkit, which included biomechanical assessments and personalised exercise programmes. This holistic approach contributed to a sense of being fully engaged in their rehabilitation as **Kim** expressed.

"[…] Starting from the you introducing the sensors in the beginning ending up with having a report and as I mentioned a personalised programme adding a lot, the app where you can see your exercises and watch the videos, so I believe that personalisation is something that is is clear in this experience."

The integration of various components created a cohesive and engaging rehabilitation experience. Furthermore, participants consistently reported that the exercises felt personalised to their specific condition. The perception that the exercises were designed specifically for them enhanced their engagement and confidence in the intervention. **Hala** acknowledged that the toolkit provided the personalised feature to her condition.

"Sure sure it was only targeting what was found on the report, which which is the important part on limiting the move movement. And yeah it felt like it is personalised because what you told me about was basically what I have so it is surely personalised."

This quote highlights the connection participants made between their assessment results and the prescribed exercises, reinforcing the sense of personalisation. Moreover, the explanation provided by the healthcare professional about why specific exercises were prescribed significantly contributed to the perception of personalisation. This context helped participants understand the rationale behind their exercise programme. **Tommy** illustrated this point as he pointed out that the exercises provided were personalised and not generic.

"Overall, I see that it is quite personalised based on what was found on my movement, but in the app, if it wasn't for you explaining what those prescribed exercises are, it would feel like its generic properties. However, telling me why those exercises were prescribed in particular is definitely a personalised touch."

This feedback underscores the importance of clear communication in enhancing the perception of personalisation. Similarly, most participants appreciated that the exercises were not generic but focused on their specific problems and needs. This targeted approach increased their motivation to adhere to the programme. **Naida** highlighted this with an emphasis on the exercises being designed only for her.

"Of course. Yeah, of course it was. It was personalised, because all the exercises I have done was focused on my needs, my lower limbs. My problem so so. Yeah, I it's not just a normal exercise to just to. To move my body, but it's focused, it focuses on the problem."

This perception of a tailored approach enhanced participants' belief in the effectiveness of the intervention. The direct link between the biomechanical assessment and the prescribed exercises was noted by several participants as a key factor in perceiving the intervention as personalised. **Jude** said that a major part of the toolkit was the personalisation and knowing that the exercises were targeted to their own case.

"Yeah. So I think that was the the biggest one is getting exercises for you. And due to the data that you've obtained."

This integration of assessment and intervention reinforced the scientific and personalised nature of the approach.

Some participants appreciated that the exercise prescription took into account their personal preferences and circumstances, such as when and where they could perform the exercises. **Richard** supported this from his reflection.

"Yeah yeah sure the personalisation is clear here as all of the exercises were targeting my own issue and the exercises you prescribed were carefully chosen based on the discussion we had on when and where I can do the exercises and uh what sort of what type of exercises I prefer to do."

This level of customization enhanced the perception of a truly personalised approach. In addition,

the personalised approach not only tailored the exercises but also improved participants' understanding of their condition, which in turn increased their motivation to engage with the programme as **Jimmy** reflected on this point.

"Yeah, yeah. Yeah, like I said, I think it's. It's mainly helped. I think my understanding and then because of that that informed everything else. You know, it felt personalised. I could see how it worked. It motivated me. And said yeah, that that was how it helped."

This quote illustrates how personalisation can lead to a cascade of positive outcomes, including better understanding and increased motivation.

In conclusion, this subtheme reveals that participants overwhelmingly perceived the biomechanical biofeedback toolkit as highly personalised and targeted to their individual needs. This perception was built on several factors: the tailored exercise prescription based on biomechanical assessment, clear explanations of the rationale behind the exercises, alignment with individual needs and preferences, and the integration of assessment and intervention. The strong sense of personalisation appears to have several positive effects

1. Increased engagement with the exercise programme
2. Enhanced confidence in the effectiveness of the intervention
3. Improved understanding of their condition and the rehabilitation process
4. Heightened motivation to adhere to the prescribed exercises

These findings highlight the importance of not only providing personalised interventions but also ensuring that patients perceive and understand this personalisation. The combination of tailored exercises, clear communication, and consideration of individual circumstances seems to create a powerful sense of personalisation that enhances the overall effectiveness of the intervention.

Overall, this subtheme underscores the value of personalised approaches in rehabilitation and the importance of effectively communicating this personalisation to patients to maximize engagement and potential outcomes.

Subtheme 1.5: Reported benefits after using the toolkit

The subtheme "Reported benefits after using the toolkit" emerged from the reflective thematic analysis of participant feedback on the biomechanical biofeedback toolkit. This subtheme explores the various improvements and positive outcomes that participants experienced after engaging with the intervention. The analysis reveals several key aspects of the reported benefits.

Many participants reported significant improvements in their physical capabilities, particularly in terms of mobility and strength. These improvements were often noted in everyday activities and previously challenging tasks as Bob has explained.

"I feel a little bit more confident in doing so and and got up to uh I've been up to 16K since and beforehand I was only on around 8 to 9, but I feel a little bit more confident and and that's probably a little, I would say due to the to the exercises that were given and me continuing it on after as well."

This quote highlights the substantial increase in physical capacity and the associated boost in confidence, directly attributed to the toolkit's exercises. Additionally, participants repeatedly mentioned the perception of increased knee strength and stability. This improvement was particularly noticeable during weight-bearing activities such as walking and climbing stairs. **Jess** noted pointed out that the strength gained from the prescribed exercises resulted in becoming more active.

"I would also like to thank you because after using this toolkit because I feel now my knee is stronger and I felt this especially when I am walking and climbing stairs."

This feedback suggests that the targeted exercises provided by the toolkit effectively addressed knee-specific issues, leading to tangible improvements in functional strength. In terms of pain reduction, several participants reported a decrease in pain levels, although the extent and timing of pain reduction varied among individuals. Some experienced immediate relief, while others noted gradual improvement over time. **James** shared that small improvements in his knee pain problem was appreciated and made him to overall feel better.

"although I did find the exercises were making. My knee sore. As I was doing them. But yeah, no, no, that was fine because later I started to feel slightly betters and the sore is getting lesser especially when I walk, but I still feel some soreness if I was setting for a long time or after waking up in the morning, but yeah yeah I feel ok."

This quote illustrates the complex nature of pain reduction, highlighting that while some discomfort might be experienced during the exercise process, overall pain levels tended to decrease with continued use of the toolkit. Additionally, one of the reported benefits that participants highlighted was the increased confidence in movement. Participants frequently mentioned feeling more confident in their movements and daily activities. This increased confidence appeared to be closely linked to the physical improvements they experienced as **Hamed** said.

"Yeah, genuinely I do. I feel just a bit more confident and just in general like less pain. Yeah, in silly little things that I thought were silly anyway, but kind of was bugging me. So yeah, definitely."

This enhanced confidence suggests that the benefits of the toolkit extended beyond physical improvements to positively impact participants' psychological well-being and quality of life. Improved overall body awareness was also a benefit that participants have felt. Moreover, some participants reported a heightened awareness of their body mechanics and movement patterns, which they attributed to the comprehensive nature of the toolkit's approach. **Peter** mentioned his increased awareness of improving and getting better.

"before I was tested today I I knew that I was improving my flexion because when I was walking with better flexibility on my left side on my left heel and being aware of of of, of trying to to match how I was, how my heel strike was working between my left and my right. But I was able. I knew I was walking faster. I knew, and it was almost effortless."

This increased body awareness suggests that the toolkit not only provided physical benefits but also educated participants about their movement patterns, potentially leading to long-term improvements in biomechanics. Further, motivation for continued physical activity was reported by
several participants as they indicated that their positive experiences with the toolkit motivated them to continue exercising and engage in more physical activity, even beyond the prescribed programme. As an example, **Katy** highlighted that after using the toolkit, she got healthier again especially after stop being active during the pandemic.

"because as I told you earlier I stopped doing any sort of sports since the pandemic, but once I got used to it, I felt it was a worthy thing to do and I felt later that maybe this is what I was missing to get healthier again."

This suggests that the toolkit may have broader health benefits by encouraging participants to adopt more active lifestyles.

In conclusion, the current subtheme reveals a wide range of positive outcomes experienced by participants. These benefits span physical improvements such as increased strength, mobility, and pain reduction, as well as psychological benefits like enhanced confidence and body awareness. The diversity of reported benefits underscores the comprehensive nature of the toolkit's impact on participants' overall well-being. These findings highlight the potential of biomechanical biofeedback toolkits to provide multifaceted benefits in rehabilitation contexts. The combination of targeted exercises, personalised feedback, and increased body awareness appears to create a synergistic effect, leading to improvements that extend beyond the initial focus of the intervention. The reported benefits also suggest that such toolkits may have long-term positive impacts by encouraging continued physical activity and increased body awareness. This potential for sustained benefit is particularly valuable in the context of chronic conditions or long-term rehabilitation needs. Overall, this subtheme underscores the effectiveness of the biomechanical biofeedback toolkit in providing tangible, multifaceted benefits to participants, supporting its potential as a valuable tool in rehabilitation and physical therapy contexts.

6.5. Conclusion

The thematic analysis of participant interviews revealed consistently positive findings across all six Theoretical Framework of Acceptability (TFA) components, demonstrating strong overall acceptability of the biomechanical biofeedback toolkit. Participants perceived minimal opportunity costs whilst expressing enthusiasm for future implementation and global adoption of the technology in healthcare settings, including telemedicine applications. The burden associated with toolkit use was viewed as low, with reported challenges primarily relating to normal exercise demands rather than technological barriers.

The intervention demonstrated strong ethicality, aligning well with participants' value systems through its clarity, encouraging nature, and capacity to increase self-awareness and instil hope for improvement. Participants held overwhelmingly positive affective attitudes towards the toolkit, being particularly impressed by its technological innovation, visual feedback features, and personalised approach. High levels of self-efficacy were evident, with participants demonstrating confidence in using the mobile application due to its user-friendly and intuitive design.

Intervention coherence was well-established, as participants clearly understood the toolkit's functionality and the connections between gait analysis, exercise prescription, and holistic movement assessment. The perceived effectiveness was strongly supported, with participants experiencing tangible improvements in strength, mobility, pain reduction, and movement confidence whilst appreciating the toolkit's motivational, engaging, and personalised characteristics.

The synthesis of findings across all TFA components indicates that the biomechanical biofeedback toolkit successfully achieved high acceptability amongst participants. The intervention was perceived as a valuable, effective, and innovative approach that successfully integrated advanced technology into physiotherapy practice whilst maintaining strong user engagement, satisfaction, and clinical benefits. These findings suggest significant potential for the toolkit's implementation in clinical settings and its contribution to enhancing rehabilitation outcomes.

6.5. Usability findings

6.5.1. System usability scale (SUS)

For usability evaluation, the system usability scale was utilised. In Table 17 the mean and standard deviation of each question score and of the final score are presented. Additionally, the frequency of each answer is also highlighted.

Table 16 System Usability Scale

SUS Variables	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	Mean ± (SD) of SUS score
SUS questions	Frequency (%)	Frequency (%)	Frequency (%)	Frequency (%)	Frequency (%)	
Q1: I think that I would like to use this system frequently.	1 (4%)	0	4 (16%)	7 (28%)	13 (52%)	3.20 ± (1.00)
Q2: I found the system unnecessarily complex.	15 (60%)	7 (28%)	2 (8%)	1 (4%)	0	3.44 ± (0.82)
Q3: I thought the system was easy to use.	0	0	5 (20%)	8 (32%)	12 (48%)	3.28 ± (0.79)
Q4: I think that I would need the support of a technical person to be able to use this system.	16 (64%)	5 (20%)	3 (12%)	0	1 (4%)	3.40 ± (1.00)
Q5: I found the various functions in this system were well integrated.	0	1 (4%)	7 (28%)	5 (20%)	12 (48%)	3.12 ± (0.97)
Q6: I thought there was too much inconsistency in	15 (60%)	6 (24%)	3 (12%)	0	1 (4%)	3.40 ± (0.86)

this system.						
Q7: I would imagine that most people would learn to use this system very quickly.	0	0	2 (8%)	11 (44%)	12 (48%)	3.48 ± (0.58)
Q8: I found the system very cumbersome to use.	19 (76%)	5 (20%)	1 (4%)	0	0	3.72 ± (0.54)
Q9: I felt very confident using the system.	0	0	2 (8%)	11 (44%)	12 (48%)	3.40 ± (0.64)
Q10: I needed to learn a lot of things before I could get going with this system.	16 (64%)	5 (20%)	2 (8%)	2 (8%)	0	3.40 ± (0.95)
	33.84 ± (5.61)					
	84.6					

(SUS) = System usability scale. (%) = Percentage. (SD) = Standard deviation.

Table 17 illustrates the ten questions of the system usability scale. The SUS is a 5-point Likert scale, and the answers range from strongly disagree to strongly agree. . The table presents the mean score from all participants for each question. The total mean score was 33.84. In SUS, to identify the final score, the mean score should be multiplied by 2.5, which equals an excellent (84.6) as a final SUS score.

6.5.2. Adherence findings

This section presents participant adherence to the mobile application, based on the completion rates of two anticipated tasks: logging exercise sessions and submitting patient-reported outcome measures (PROMs). All participants (N = 25) used the mobile application to follow their prescribed exercise programme, log completed sessions, and complete self-reported questionnaires and scales.

A total of 350 exercise sessions were prescribed—calculated as 14 sessions per participant over 14 days, multiplied by 25 participants. Of these, 221 sessions were successfully logged through the application, resulting in a completion rate of 63%.

For PROMs, each participant was expected to complete four self-reported measures, yielding a total of 100 expected submissions (4 PROMs × 25 participants). Of these, 76 PROMs were completed and submitted via the application, corresponding to a completion rate of 76%.

Table 17 Frequency of Self-Reported Measures Completed by Participants via the Mobile Application

Participants	Frequency of self-reported measures (questionnaires and scales) submitted by each participant)				
Frequency	X1	X2	X3	X4	Total
P1	✓	×	×	×	1 / 4
P2	✓	✓	×	×	2 / 4
P3	✓	✓	✓	✓	4 / 4
P4	✓	✓	✓	✓	4 / 4
P5	✓	✓	✓	✓	4 / 4
P6	✓	×	×	×	1 / 4
P7	✓	✓	×	×	2 / 4
P8	✓	✓	×	×	2 / 4
P9	✓	✓	✓	✓	4 / 4
P10	✓	✓	✓	✓	4 / 4
P11	✓	✓	×	×	2 / 4
P12	✓	✓	✓	✓	4 / 4
P13	✓	✓	✓	✓	4 / 4
P14	✓	×	×	×	1 / 4
P15	✓	✓	✓	✓	4 / 4
P16	✓	✓	✓	×	3 / 4
P17	✓	✓	✓	✓	4 / 4
P18	✓	✓	✓	×	3 / 4

P19	✓	×	×	×	1 / 4
P20	✓	✓	✓	×	3 / 4
P21	✓	✓	✓	✓	4 / 4
P22	✓	✓	✓	✓	4 / 4
P23	✓	✓	✓	✓	4 / 4
P24	✓	✓	✓	✓	4 / 4
P25	✓	✓	✓	×	3 / 4

(✓) = completed. (×) = Not completed.

Table 18 highlights the adherence of each participant in completing their self-reported measures through using the mobile application. The chart illustrates that the total number of administered self-reported measures per individual equals 4 in total. In total, (n = 13, 52%) of the participants have completed and submitted the self-reported measures via using the mobile application. On the other hand, there was (n = 4, 16%) of the participants who submitted their self-reported measures less than the total number as follows, (n = 4, 16%) of the participants submitted their self-reported measures 3 out of 4 times, (n = 4, 16%) of the participants submitted their self-reported measures 2 out of 4 times, and (n = 4, 16%) of the participants submitted their self-reported measures 1 out of 4 times)

Table 18 Adherence of Exercise Sessions Log Using the Mobile Application Per Participant.

Participants	Frequency of exercises logged by each participant														
	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	Total
P1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	13 / 14
P2	×	×	×	×	×	×	×	×	×	×	×	×	×	×	0 / 14
P3	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	×	×	11 /14
P4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	×	×	11 / 14
P5	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	14 / 14
P6	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	14 / 14
P7	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	×	12 / 14
P8	✓	✓	✓	✓	✓	✓	✓	×	×	×	×	×	×	×	7 / 14
P9	✓	✓	✓	✓	✓	×	×	×	×	×	×	×	×	×	5 / 14
P10	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	13 / 14
P11	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	13 / 14
P12	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	×	12 / 14
P13	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	13 / 14
P14	✓	✓	✓	✓	✓	✓	✓	✓	×	×	×	×	×	×	8 / 14
P15	✓	✓	✓	✓	✓	✓	✓	✓	×	×	×	×	×	×	8 / 14
P16	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	×	×	11 / 14
P17	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	×	×	×	10 / 14

P18	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	×	×	11 / 14
P19	×	×	×	×	×	×	×	×	×	×	×	×	×	×	0 / 14
P20	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	×	12 / 14
P21	✓	✓	✓	✓	✓	✓	✓	✓	×	×	×	×	×	×	8 / 14
P22	✓	✓	✓	✓	×	×	×	×	×	×	×	×	×	×	4 / 14
P23	✓	×	×	×	×	×	×	×	×	×	×	×	×	×	1 / 14
P24	×	×	×	×	×	×	×	×	×	×	×	×	×	×	0 / 14
P25	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	×	×	×	10 / 14

(✓) = completed. (×) = Not completed

Table 19 highlights the adherence of each participant in logging their exercise sessions through using the mobile application. The chart illustrates that the total number of prescribed exercise sessions per individual equals 14 sessions in total. (n = 19, 76%) of the participants have logged equals to, or more than the half of the total number of their prescribed sessions (≥ 7 exercise session logs). On the other hand, (n = 6, 24%) of the participants have logged equals to, or less than the half of the total number of their prescribed session (≤ 7 exercise session logs)

6.6. Biomechanical findings

6.6.1. General gait parameters

The general gait parameters of the study participants are presented in the table below (20). The table includes the minimum, maximum, and mean values of speed, cadence, distance, number of steps, duration, step length of the affected and the non-affected sides in two timepoints.

Table 19 General Gait Parameters

Timepoint	Timepoint 1	Timepoint 2
Values	**Mean ± (SD)**	**Mean ± (SD)**
Speed (m/s)	1.26 ± (0.052)	1.26 ± (0.054)
Cadence (steps/min)	112.86 ± (8.17)	109.48 ± (7.41)
Distance (m)	20.14 ± (2.18)	22.66 ± (3.38)
Number of steps	24.16 ± (6.87)	26.12 ± (5.26)
Duration (s)	12.94 ± (4.07)	14.42 ± (3.31)
Affected-side step length (cm)	67.59 ± (2.79)	68.82 ± (3.20)
Non-affected-side step length (cm)	67.48 ± (3.41)	70.90 ± (3.08)

(Min) = minimum. (Max) = maximum. (SD) = standard deviation. (m/s) = meter per second. (Steps/min) = steps per minute. (m) = meter. (cm) = centimetre. (s) = seconds.

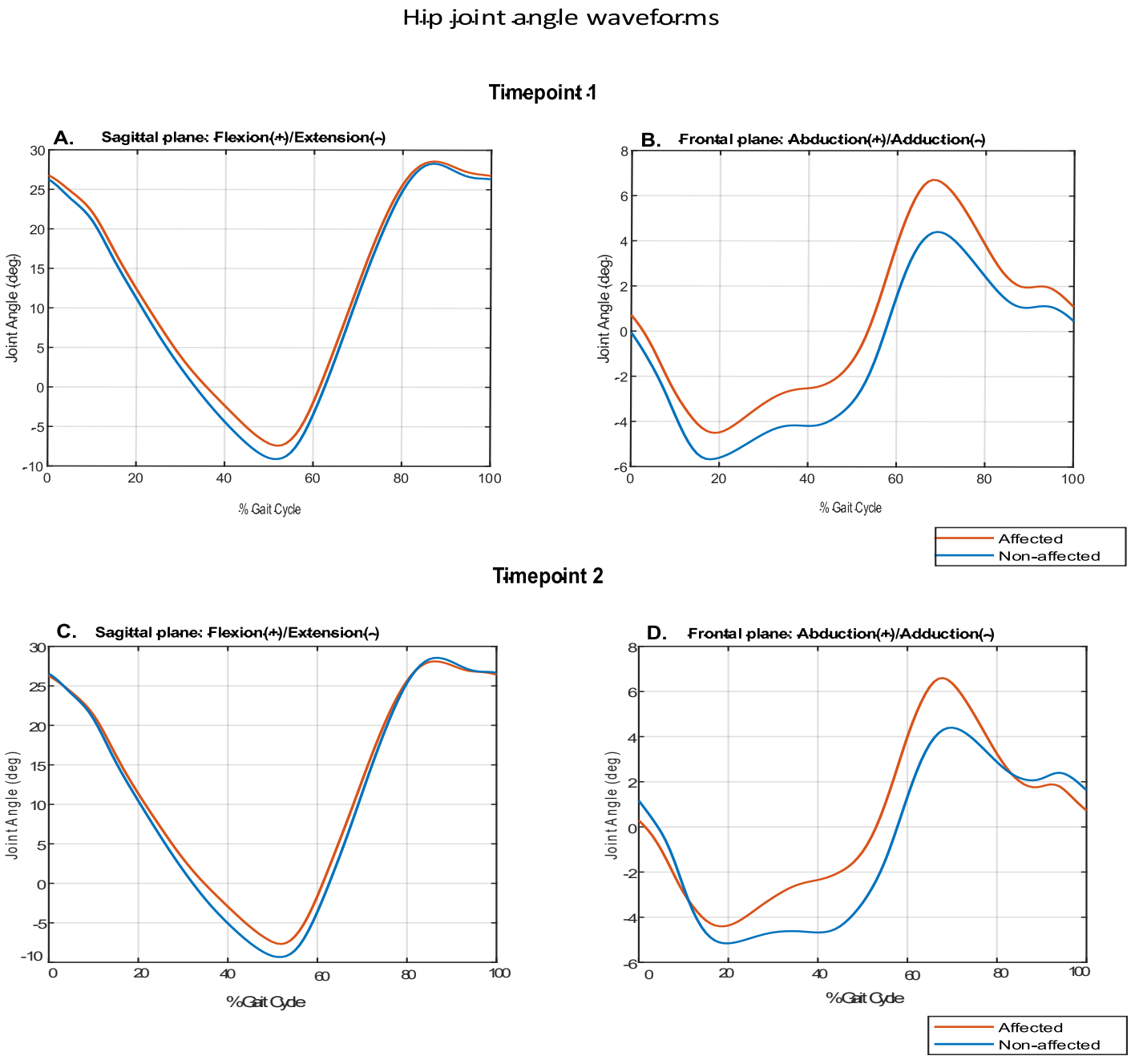
The descriptive parameters, mean and standard deviation of the general gait parameters are presented in table 20. The table highlights the findings in two timepoints. The speed had relatively no changes between the timepoints (1.26 ±

0.052) in the first timepoint compared to (1.26 ± 0.054) in the second timepoint. Furthermore, the cadence was the only value that was slightly decreased in the second timepoint compared to the first timepoint with mean and (SD) of 112.86 ± (8.17) in timepoint 1 compared to 109.48 ± (7.41) in timepoint 2. The distance, number of steps, and duration were all slightly increased in the second timepoint compared to the first timepoint with mean and (SD) of (22.66 ± 3.38, 26.12 ± 5.26, and 14.42 ± 3.31, respectively) in the second timepoint compared to (20.14 ± 2.18, 24.16 ± 6.87, and 12.94 ± 4.07, respectively) in the first timepoint. Similarly, both the affected and the non-affected side step length were slightly increased in the second timepoint with mean and (SD) of 68.82 ± (3.20) and 70.90 ± (3.08) in the second timepoint compared to 67.59 ± (2.79) and 67.48 ± (3.41) in the first timepoint.

6.6.2. Biomechanical (kinematics) joint angles

In this section, the kinematics findings are presented in two timepoints including the lower limb joint waveforms and tables that include the numerical results of the maximum and minimum joint angles and joints ROM from both frontal and sagittal planes. It is worth noting that tables in this section explain the highlights from the waveforms.

Figure 16 Hip Joint Waveform – Gait Cycle



In figure 16, waveform A and C present the mean waveforms from all participants of the hip joint from the sagittal plane in timepoint 1 and timepoint 2 with an illustration of the hip flexion and extension movement over the whole gait cycle (0 – 100%). On the other hand, waveforms B and D present the mean waveforms from all participants of the hip joint from the frontal plane in timepoint 1 and timepoint 2 with an illustration of the hip abduction and adduction movement over the whole gait cycle (0 – 100%).

Furthermore, in table 21 below, the mean peak flexion angle, mean peak extension angle, and mean ROM of the hip joint are presented in both timepoint 1 and timepoint 2; however, the peak joint angles are also divided into two gait phases (stance and swing). Similarly, the table presents the mean peak abduction angle, mean peak adduction angle, and mean ROM of the hip joint in two timepoints, and in stance and swing phases of the gait cycle.

Table 20 Hip Joint Kinematics

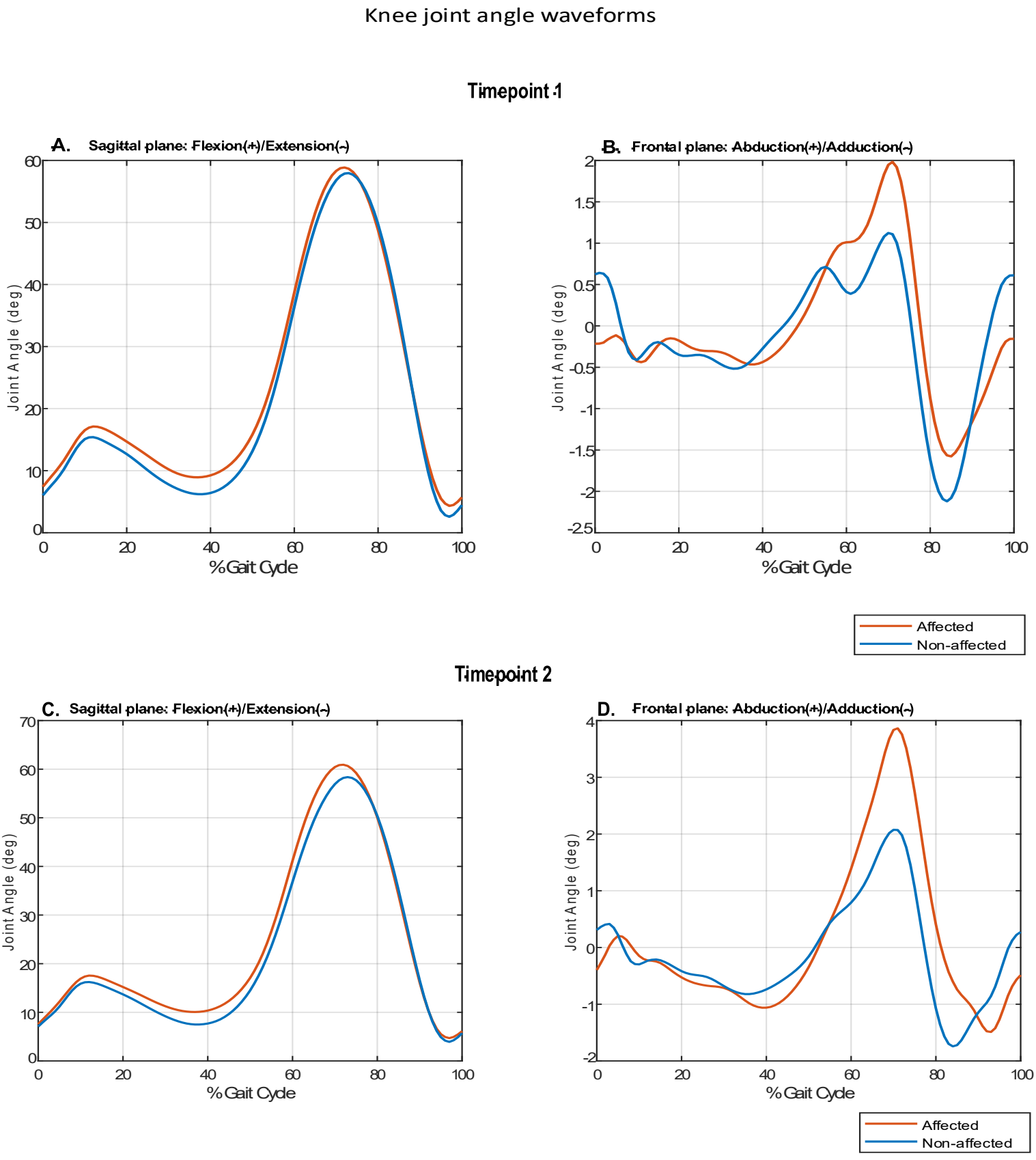
Analysis plane	Timepoint	Timepoint 1		Timepoint 2	
	Joint	Hip joint		Hip Joint	
	Knee pain side	Affected mean ± (SD)	Non-affected mean ± (SD)	Affected mean ± (SD)	Non-affected mean ± (SD)
Sagittal plane	↑ Angle / stance	26.77 ± (4.44)	26.26 ± (4.18)	26.28 ± (5.33)	26.55 ± (4.82)
	↑ Angle / swing	28.56 ± (4.42)	28.29 ± (4.10)	28.10 ± (6.49)	28.55 ± (5.75)
	↑ Angle / gait cycle	29.08 ± (4.06)	28.69 ± (4.14)	28.59 ± (5.11)	29.18 ± (4.31)
	↓ Angle / stance	-7.41 ± (4.51)	-9.09 ± (4.26)	-7.68 ± (6.21)	-9.33 ± (5.31)
	↓ Angle / swing	-0.58 ± (4.44)	-2.14 ± (4.18)	-0.26 ± (5.33)	-2.28 ± (4.82)
	↓ Angle / gait cycle	-7.73 ± (4.57)	-9.32 ± (4.43)	-7.98 ± (6.26)	-9.85 ± (5.49)
	ROM / stance	34.51± (3.17)	35.58 ± (2.46)	34.26 ± (3.78)	36.41 ± (2.92)
	ROM / swing	29.64 ± (2.92)	30.80 ± (2.87)	28.83 ± (4.01)	31.44 ± (3.97)
	ROM / gait cycle	36.82 ± (3.44)	38.01 ± (2.46)	36.57 ± (4.28)	39.03 ± (3.26)
	Angle at initial contact	26.77 ± (4.44)	26.26 ± (4.19)	26.28 ± (5.33)	26.55 ± (4.82)
	↑ Angle / stance	3.87 ± (2.18)	1.56 ± (3.17)	3.99 ± (3.01)	1.33 ± (4.10)
	↑ Angle / swing	6.70 ± (3.57)	4.40 ± (3.13)	6.60 ± (3.01)	4.40 ± (3.50)

Frontal plane	↑ Angle / gait cycle	6.97 ± (1.75)	5.22 ± (2.76)	7.20 ± (2.15)	6.01 ± (2.18)
	↓ Angle / stance	-4.50 ± (2.74)	-5.67 ± (2.01)	-4.40 ± (2.02)	-5.16 ± (1.76)
	↓ Angle / swing	1.08 ± (1.94)	0.45 ± (1.83)	0.73 ± (2.12)	1.63 ± (2.36)
	↓ Angle / gait cycle	-4.99 ± (2.56)	-6.63 ± (1.44)	-5.03 ± (1.89)	-6.79 ± (1.70)
	ROM / stance	9.58 ± (2.58)	9.47 ± (2.72)	9.76 ± 2.98	11.07 ± (2.79)
	ROM / swing	6.54 ± (3.53)	6.07 ± (2.70)	7.27 ± (3.55)	7.31 ± (2.93)
	ROM / gait cycle	11.96 ± (2.74)	11.85 ± (2.89)	12.23 ± (2.69)	12.79 ± (2.36)
	Angle at initial contact	0.72 ± (3.85)	-0.06 ± (3.09)	0.29 ± (3.33)	1.16 ± (3.82)

(↑ Angle) = Maximum angle. (↓ Angle) = Minimum angle. ROM = Range of motion. Stance = gait stance phase. Swing = gait swing phase. (SD) = Standard deviation.

The findings highlight notable trends in hip joint biomechanics across the sagittal and frontal planes for the affected and non-affected sides of participants with CKP. In the sagittal plane, maximum joint angles during stance, swing, and the gait cycle exhibited minimal variations between Timepoint 1 and Timepoint 2 for both sides, with values remaining relatively stable. Minimum joint angles showed a similar trend on the affected side, while the non-affected side demonstrated slight decreases, particularly during the gait cycle. ROM in the sagittal plane remained consistent for the affected side but displayed a modest increase on the non-affected side during stance and the gait cycle. In the frontal plane, maximum joint angles showed minor increases for the affected side during stance and the gait cycle, potentially reflecting improved joint positioning. Conversely, the non-affected side exhibited a slight reduction in maximum angles during stance. Minimum joint angles were largely stable, though the non-affected side experienced a small decrease during the gait cycle. ROM increased marginally for both sides, particularly for the non-affected side during stance and the gait cycle.

Figure 17 Knee Joint Waveform – Gait Cycle



In figure 17, waveform A and C present the mean waveforms from all participants of the knee joint from the sagittal plane in timepoint 1 and timepoint 2 with an illustration of the knee flexion and extension movement over the whole gait cycle (0 – 100%). On the other hand, waveforms B and D present the mean waveforms from all participants of the knee joint from the frontal plane in timepoint 1 and timepoint 2 with an illustration of the knee abduction and adduction movement over the whole gait cycle (0 – 100%).

Furthermore, in table 22 below, the mean peak flexion angle, mean peak extension angle, and mean ROM of the knee joint are presented in both timepoint 1 and timepoint 2; however, the peak joint angles are also divided into two gait phases (stance and swing). Similarly, the table presents the mean peak abduction angle, mean peak adduction angle, and mean ROM of the knee joint in two timepoints, and in stance and swing phases of the gait cycle.

Table 21 Knee Joint Kinematics

Analysis plane	Timepoint	Timepoint 1		Timepoint 2	
	Joint	Knee joint		Knee Joint	
	Knee pain side	Affected mean ± (SD)	Non-affected mean ± (SD)	Affected mean ± (SD)	Non-affected mean ± (SD)
Sagittal plane	↑ Angle / stance	38.68 ± (6.48)	36.41 ± (7.74)	41.15 ± (4.47)	36.82 ± (7.17)
	↑ Angle / swing	58.87 ± (3.25)	57.95 ± (4.59)	60.91 ± (3.37)	58.37 ± (5.13)
	↑ Angle / gait cycle	59.27 ± (3.94)	58.71 ± (3.34)	61.20 ± (3.67)	59.08 ± (3.88)
	↓ Angle / stance	7.42 ± (2.40)	6.03 ± (3.44)	7.58 ± (2.12)	7.07 ± (2.94)
	↓ Angle / swing	4.33 ± (2.76)	2.57 ± (3.57)	4.69 ± (3.11)	3.91 ± (3.14)
	↓ Angle / gait cycle	3.78 ± (2.06)	2.04 ± (3.22)	3.92 ± (2.15)	2.51 ± (2.31)
	ROM / stance	32.08 ± (5.81)	31.47 ± (5.40)	34.22 ± (5.22)	31.01 ± (5.93)
	ROM / swing	55.33 ± (4.84)	56.49 ± (4.09)	57.28 ± (4.85)	55.96 ± (5.82)
	ROM / gait cycle	55.49 ± (4.56)	56.66 ± (4.08)	57.28 ± (4.85)	56.57 ± (5.07)
	Angle at initial contact	7.41 ± (2.40)	6.03 ± (3.44)	7.58 ± (2.12)	7.07 ± (2.94)
	↑ Angle / stance	1.01 ± (1.16)	0.71 ± (1.22)	1.39 ± (1.55)	0.79 ± (1.93)
	↑ Angle / swing	1.98 ± (0.74)	1.12 ± (0.80)	3.86 ± (0.92)	2.07 ± (0.81)

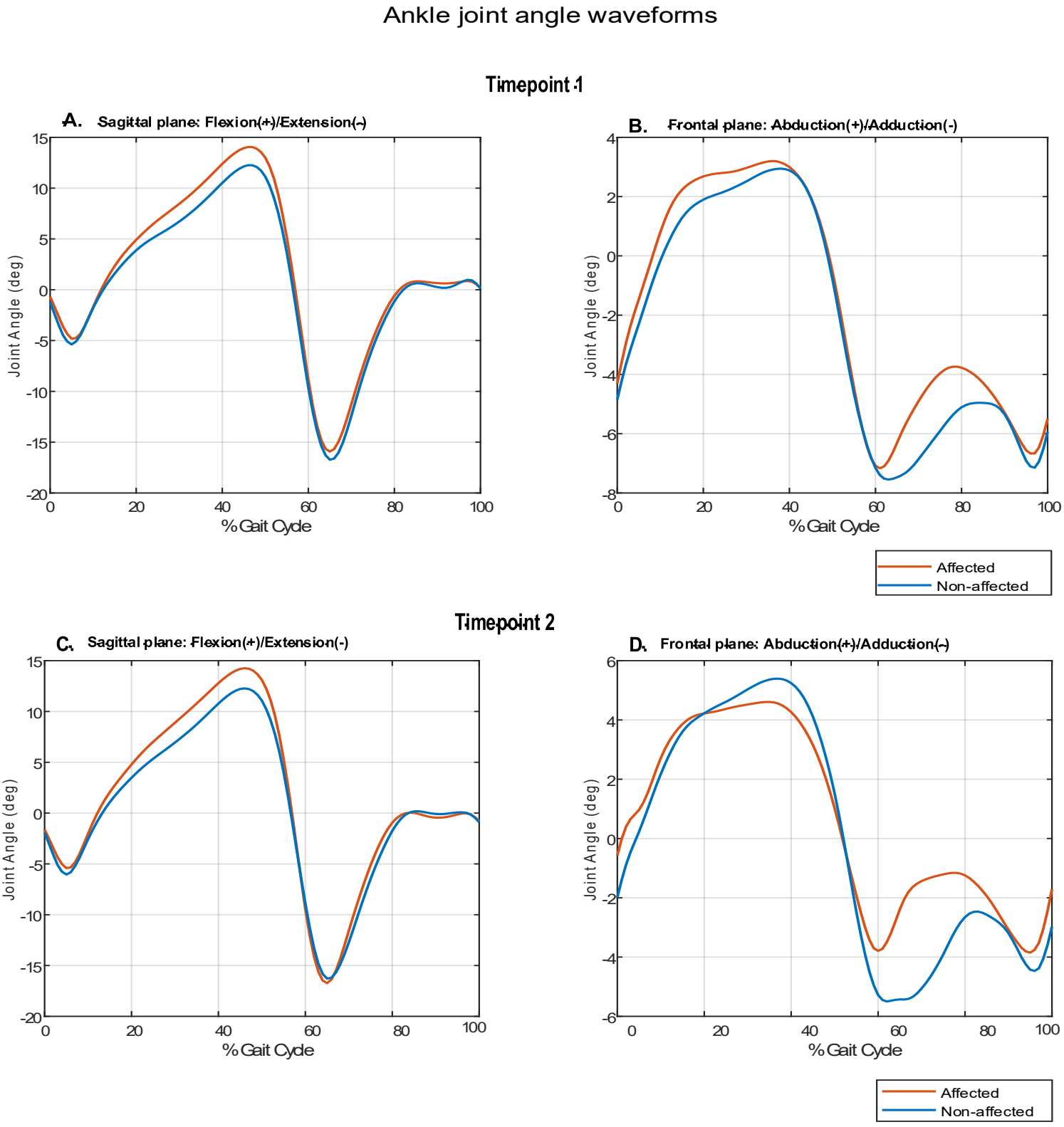
Frontal plane	↑ Angle / gait cycle	3.42 ± (2.38)	3.00 ± (1.86)	4.67 ± (2.46)	.16 ± (3.69)
	↓ Angle / stance	-0.47 ± (0.83)	-0.52 ± (1.00)	-1.06 ± (0.83)	-0.82 ± (1.34)
	↓ Angle / swing	-1.58 ± (0.76)	-2.12 ± (0.75)	-1.49 ± (0.75)	-1.74 ± (0.87)
	↓ Angle / gait cycle	-2.88 ± (1.30)	-3.08 ± (1.36)	-2.81 ± (0.80)	-3.32 ± (1.18)
	ROM / stance	2.77 ± (1.08)	3.19 ± (1.18)	3.63 ± (1.26)	3.44 ± (1.96)
	ROM / swing	5.94 ± (2.84)	5.91 ± (1.79)	6.89 ± (2.87)	7.17 ± (3.10)
	ROM / gait cycle	6.30 ± (2.57)	6.08 ± (2.00)	7.46 ± (2.57)	7.49 ± (3.64)
	Angle at initial contact	-0.22 ± (0.78)	0.62 ± (1.10)	-0.39 ± (0.99)	0.31 ± (1.07)

(↑ Angle) = Maximum angle. (↓ Angle) = Minimum angle. ROM = Range of motion. Stance = gait stance phase. Swing = gait swing phase. (SD) = Standard deviation.

In table 22, The knee joint findings reveal several trends across the sagittal and frontal planes for the affected and non-affected sides in individuals with CKP. In the sagittal plane, maximum joint angles during stance, swing, and the gait cycle increased slightly from Timepoint 1 to Timepoint 2 on the affected side, with the non-affected side showing minor changes. Minimum joint angles remained relatively stable for both sides, though the affected side experienced a slight increase during swing and the gait cycle. ROM in the sagittal plane demonstrated an upward trend for the affected side during stance, swing, and the gait cycle, whereas the non-affected side showed minor fluctuations.

In the frontal plane, maximum joint angles during stance, swing, and the gait cycle increased for both sides, with more pronounced changes on the affected side, indicating potential improvements in joint alignment. Minimum joint angles showed slight decreases across phases, particularly on the non-affected side during swing and the gait cycle. ROM in the frontal plane increased slightly for both sides across all phases, with the most notable improvement observed on the affected side during swing and the gait cycle.

Figure 18 Ankle Joint Waveform – Gait Cycle



In figure 18, waveform A and C present the mean waveforms from all participants of the ankle joint from the sagittal plane in timepoint 1 and timepoint 2 with an illustration of the ankle flexion and extension movement over the whole gait cycle (0 – 100%). On the other hand, waveforms B and D present the mean waveforms from all participants of the ankle joint from the frontal plane in timepoint 1 and timepoint 2 with an illustration of the ankle abduction and adduction movement over the whole gait cycle (0 – 100%).

Furthermore, in table 23 below, the mean peak flexion angle, mean peak extension angle, and mean ROM of the ankle joint are presented in both timepoint 1 and timepoint 2; however, the peak joint angles are also divided into two gait phases (stance and swing). Similarly, the table presents the mean peak abduction angle, mean peak adduction angle, and mean ROM of the ankle joint in two timepoints, and in stance and swing phases of the gait cycle.

Table 22 Ankle Joint Kinematics

Analysis plane	Timepoint	Timepoint 1		Timepoint 2	
	Joint	Ankle joint		Ankle Joint	
	Knee pain side	Affected mean ± (SD)	Non-affected mean ± (SD)	Affected mean ± (SD)	Non-affected mean ± (SD)
Sagittal plane	↑ Angle / stance	14.05 ± (2.95)	12.25 ± (3.32)	14.26 ± (2.99)	12.27 ± (4.23)
	↑ Angle / swing	0.86 ± (1.93)	0.97 ± (2.46)	0.04 ± (2.58)	0.18 ± (3.52)
	↑ Angle / gait cycle	14.58 ± (2.56)	12.67 ± (3.30)	14.78 ± (3.26)	13.00 ± (4.08)
	↓ Angle / stance	-8.83 ± (7.56)	-9.61 ± (6.77)	-9.46 ± (6.10)	-8.91 ± (7.59)
	↓ Angle / swing	15.93 ± (2.36)	-16.73 ± (2.89)	-16.73 ± (2.19)	-16.29 ± (2.55)
	↓ Angle / gait cycle	-16.87 ± (6.12)	-17.41 ± (6.71)	-17.54 ± (4.14)	-17.51 ± (5.32)
	ROM / stance	25.04 ± (4.54)	23.67 ± (4.33)	25.25 ± (4.97)	23.75 ± (3.85)
	ROM / swing	19.11 ± (5.60)	19.33 ± (5.95)	18.83 ± (4.38)	18.88 ± (5.18)
	ROM / gait cycle	31.46 ± (5.36)	30.08 ± (5.68)	32.33 ± (4.93)	30.52 ± (5.16)
	Angle at initial contact	-0.68 ± (3.57)	-1.19 ± (3.85)	-1.63 ± (3.40)	-1.92 ± (4.32)
	↑ Angle / stance	3.20 ± (3.08)	2.94 ± (4.71)	4.61 ± (2.34)	5.39 ± (2.64)
	↑ Angle / swing	-3.74 ± (3.51)	-4.96 ± (3.65)	-1.16 ± (2.15)	-2.47 ± (2.94)

Frontal plane	↑ Angle / gait cycle	3.97 ± (3.01)	3.22 ± (4.21)	5.53 ± (2.19)	6.09 ± (2.85)
	↓ Angle / stance	-7.08 ± (5.31)	-7.16 ± (3.80)	-3.79 ± (4.80)	-5.28 ± (5.24)
	↓ Angle / swing	-7.17 ± (5.39)	-7.55 ± (4.43)	-3.85 ± (2.30)	-5.50 ± (5.23)
	↓ Angle / gait cycle	-8.43 ± (5.06)	-9.26 ± (4.89)	-5.58 ± (3.63)	-7.53 ± (6.54)
	ROM / stance	11.65 ± (2.97)	10.83 ± (3.10)	9.99 ± (3.61)	11.64 ± (4.24)
	ROM / swing	5.21 ± (2.13)	5.34 ± (2.28)	5.47 ± (2.45)	6.01 ± (2.64)
	ROM / gait cycle	12.40 ± (3.07)	12.48 ± (4.37)	11.11 ± (3.30)	13.62 ± (5.83)
	Angle at initial contact	-4.31 ± (5.39)	-4.85 ± (4.60)	-0.56 ± (3.45)	-1.98 ± (5.45)

(↑ Angle) = Maximum angle. (↓ Angle) = Minimum angle. ROM = Range of motion. Stance = gait stance phase. Swing = gait swing phase. (SD) = Standard deviation.

In table 23, the ankle joint findings reveal distinct trends across the sagittal and frontal planes for the affected and non-affected sides in participants with CKP. In the sagittal plane, maximum joint angles during stance and the gait cycle showed slight increases from Timepoint 1 to Timepoint 2 for both sides, with the affected side displaying a more pronounced change. Minimum joint angles demonstrated small decreases during the gait cycle, with similar trends on both sides. ROM during stance and the gait cycle increased slightly for the affected side, while the non-affected side remained relatively stable. However, ROM during swing showed minimal variation across timepoints for both sides.

In the frontal plane, maximum joint angles during the gait cycle increased on both sides, with the non-affected side showing a more substantial improvement. Minimum joint angles decreased for both sides across all phases, particularly during the gait cycle on the affected side. ROM exhibited mixed trends, with increases in swing and the gait cycle for the non-affected side, while the affected side showed slight reductions in stance and the gait cycle. These findings suggest a general trend towards improved joint mobility and alignment, particularly in the sagittal plane for the affected side and in the frontal plane for the non-affected side, potentially reflecting positive adaptations to rehabilitation interventions.

6.7. Participants self-reported outcomes (PROMs) scores findings

The table below presents the PROMs scores mean and standard deviation of the participants who filled in the questionnaires and scales using the mobile application

Table 23 PROMs Scores at Two Timepoints

Variables	Timepoint 1	Timepoint 2
Self-reported measures	Mean±(SD)	Mean±(SD)
WOMAC	20.84 ± (14.22)	14.11 ± (14.19)
NPRS	39.20 ± (21.50)	31.11 ± (21.52)
TSK	36.48 ± (6.43)	32.83 ± (7)
SES6G	6.79 ± (1.72)	6.91 ± (2.07)
PHQ-9	5.16 ± (3.33)	4.06 ± (3.13)

(WOMAC) = Western Ontario and McMaster Universities Arthritis Index. (TSK) = TAMPA scale for kinnesiophobia. (NPRS) = Numerical pain rating scale. (SES6G) = The Self-efficacy for managing chronic disease 6-item scale (SES6G). (PHQ-9) = patient health questionnaire

Table 24 highlights the mean scores of five questionnaires and scales that were filled by the participants in two timepoints. WOMAC score at the first timepoint was 20.84 ± (14.22); whereas in the second timepoint the score was 14.11 ± (14.19), which

indicates a decrease in the score. Similarly, the NPS, TAMPA, and PhQ-9, scores were decreased in the second timepoint compared to the first time point. Only the SEMCD score highlights a slight increase in favor of the first time point (6.79 ± 1.72) compared to the second timepoint (6.91 ± 2.07).

Chapter 7

Discussion

7.1. Introduction

The current project aimed to evaluate the acceptability and usability of a DBBT for the physiotherapy management of individuals with CKP. This aim was addressed through the research question: “Is a digital biomechanical biofeedback toolkit (DBBT) acceptable and usable to individuals with chronic knee pain?”. Thus, this chapter discusses the findings of the current study in line with the evaluation of the acceptability and usability of the DBBT. Furthermore, the chapter begins with an overview of participant demographics, providing important context for understanding the relevance of the study population to the evaluation of the DBBT's acceptability and usability. This is followed by a detailed discussion of the findings with the existing literature.

7.2. General study findings

A total of 25 participants were recruited, encompassing a diverse demographic profile in terms of age, gender, and BMI (BMI). The sample included 14 males and 11 females, with a mean age of 37 years and a mean BMI of 26 kg/m². This diversity allowed the evaluation of the DBBT across different life stages and body compositions, enhancing the real-world relevance of the findings.

Acceptability was explored using the theoretical framework of acceptability (TFA), with findings mapped to its core constructs and in line with the DBBT features. Participants generally perceived the DBBT as highly acceptable, citing positive affective attitudes towards the toolkit, a strong sense of intervention coherence, perceived effectiveness, and self-efficacy. Key features contributing to these perceptions included the personalised exercise prescription informed by gait analysis, the provision of detailed visual biofeedback through gait reports, the inclusion of exercise video demonstrations, an automated reminder system, and structured activity tracking via exercise logging and participants reported outcomes (PROMs) submissions. Participants consistently reported that the DBBT was

understandable, relevant to their individual needs, and supportive of their rehabilitation goals.

Objective kinematic and spatiotemporal data, collected through wearable sensors, provided additional supportive evidence for participants' shared experiences. Subtle improvements were observed across several gait parameters, such as modest increases in knee ROM and step length, alongside stable walking speeds, reflecting enhanced movement confidence and control without suggesting clinically significant changes over the short intervention period. Similarly, PROMs data observations indicated reductions in reported pain, functional disability, fear of movement, and depressive symptoms, as well as a slight increase in self-efficacy, aligning with participants' reflections on perceived benefits.

Regarding usability, the system achieved an excellent system usability scale (SUS) score of 84.6, as defined by Bangor et al. (2009), indicating high participant satisfaction with the ease of use, efficiency, and design of the DBBT. Complementing this SUS evaluation, engagement metrics demonstrated a pooled adherence rate of 63% for exercise logging and 76% for the submission of PROMs over a two-week period. Together, these findings indicate strong usability performance across the study participants.

7.3. Demographics

Understanding the demographic characteristics of the sample is critical for interpreting the findings and assessing the representativeness of this study in relation to the broader CKP population. The following section discusses the key demographic features of the sample including gender distribution, age, and BMI. 9After that, in continuation of the demographic's discussion, the findings from PROMs, spatiotemporal parameters, and kinematic findings are presented to further assess the representation of the current study population compared to the broader CKP population.

7.3.1. Participant demographics in the context of chronic knee pain

The present study recruited 25 participants with self-reported CKP, comprising 14 males and 11 females. Although females are often reported to have a slightly higher prevalence of chronic musculoskeletal pain (Mills et al. 2019), the gender distribution in the current study remains reasonably balanced. This slight overrepresentation of

males may reflect the specific recruitment context and sampling method, rather than a true deviation from the broader CKP population. Convenience sampling, as employed in this study, often limits the diversity of the sample by relying on voluntary participation (Etikan et al. 2016), and logistical factors such as study location, accessibility, and post-pandemic behaviours that may have influenced willingness to participate across genders (Galasso et al. 2020).

The mean age of participants was 37 ± (16.03) years, with an age range spanning from 19 to 71 years. This broad age distribution aligns with evolving understandings of CKP, which is no longer regarded solely as a condition of older adults. Recent research highlights a rising prevalence of CKP among younger populations, often associated with sports injuries, physical occupational demands, or obesity (Silverwood et al. 2015; Culvenor et al. 2019). Studies such as that by Driban et al. (2017) have demonstrated that individuals who sustain knee injuries in early adulthood are at increased risk of developing CKP by midlife. Furthermore, Richmond et al. (2013) found that even recreational athletes exhibited higher rates of CKP symptoms compared to inactive individuals.

Importantly, the younger mean age (37 ± 16.03) and broad age range (19 to 71) observed in the current study offer a valuable opportunity to evaluate the acceptability and usability of the DBBT across different age groups. Both younger adults (18 and 25 year) and older adults (>65) (NHS 2025) were included in the evaluation, promoting digital health inclusivity and reflecting the real-world diversity seen among individuals with CKP. Digital health interventions should increasingly be designed to accommodate users across the lifespan, ensuring that technological solutions are accessible, engaging, and usable for a wide demographic (Choi and DiNitto 2013; Seifert et al. 2021).

Regarding body composition, the sample demonstrated a mean BMI (BMI) of 26 ± (2.9) kg/m², ranging from 20.5 to 32.7 kg/m². This distribution captures individuals across the normal weight, overweight, and obesity categories. Elevated (BMI) has been consistently associated with an increased risk of CKP, particularly among individuals classified as overweight or obese (Jiang et al. 2012; Zheng and Chen 2015). Increased body mass exerts greater mechanical load on the knee joint during

daily activities, which can exacerbate pain symptoms even in the absence of radiographic joint damage (Felson et al. 2013).

Participants ranged from normal weight to overweight and obese classifications, allowing the acceptability and usability of the intervention to be assessed across diverse body compositions. This is particularly important, as individuals with higher BMI may experience different biomechanical challenges, movement patterns, and digital engagement behaviours compared to those with lower BMI (Backholer et al. 2012). This inclusive approach aligns with growing recommendations in digital health research to develop technologies that are adaptable, user-friendly, and supportive for individuals across a spectrum of body types and functional abilities (Pagoto et al. 2013).

In summary, the participants in the current study have completed submitting PROMs as part of their experience while using the DBBT. The PROMs findings are discussed below within the context of participants demographic.

7.3.2. Participant-reported outcome measures (PROMs)

Participant-reported outcome measures (PROMs) were completed by participants through the DBBT's mobile application, Kinduct Athlete, as part of its integrated features. Each participant was asked to submit four entries over the two-week intervention period. While this process was part of the DBBT experience, the resulting scores were not shared with participants. Instead, they were collected exclusively for research purposes and later used to evaluate adherence, as discussed later in the usability section of the discussion chapter. This approach allows for meaningful comparison with existing literature and helps contextualise symptom severity, psychological wellbeing, and self-management capacity with the published research. PROMs that were collected in the current study include the WOMAC, NPRS, TSK, PHQ-9, and SES6G, and the findings were reported as an overall mean and standard deviation (mean ± SD).

7.3.2.1. The western Ontario and McMaster universities osteoarthritis index - WOMAC

The average baseline WOMAC score in this study was 20.84 ± (14.22). According to Collins et al. (2011), WOMAC scores between 0–20 represent mild, 21–40 indicate moderate, 41–60 reflect severe symptoms, and scores above 60 suggest extreme impairment. This, locate the current study's population in the mild to moderate range.

The study by Rafiq et al. (2021) recruited 30 participants with knee OA from a community physiotherapy clinic and implemented a 3-month exercise mobile app–based intervention. Their sample showed a baseline WOMAC score of 10.63 ± (2.46), which is lower than in the present study. Their recruitment approach targeted individuals at an early stage of OA, whereas the current study used voluntary recruitment through convenience sampling, which may have led to the inclusion of participants with a wider range of symptom severity. This is also reflected in the larger standard deviation (SD = 14.22) in the current sample.

Furthermore, Nelligan et al. (2021) conducted a 24-week web-based exercise intervention involving 206 individuals with knee OA recruited from primary care referrals. Their participants had a higher baseline WOMAC score 26.7 ± (11.8), indicating more severe symptoms. Similarly, Mesa-Castrillon et al. (2024) conducted a six-month digital exercise trial with 59 participants recruited through hospital outpatient clinics. Their baseline WOMAC score was 34.8 ± (17.6), suggesting a more impaired population.

These comparisons illustrate that the current study population was less impaired than those in hospital-based studies but more diverse in symptom presentation than samples targeting early-stage OA. As suggested by Etikan et al. (2016), convenience sampling in health research can lead to a heterogeneous participant pool, which may explain the broad score distribution observed here.

7.3.2.2. Numerical pain rating scale - NPRS

The average baseline NPRS score in this study was 39.20 ± (21.50). In their study, Jensen et al. (2003) highlighted that NPRS scores of 0–29 indicate mild pain, 30–69 indicate moderate pain, and 70–100 indicate severe pain. According to this classification, the current study's sample could be within the moderate pain range.

Yamamoto et al. (2022) conducted a 12-week digital home exercise programme with 45 participants recruited through hospital advertisements. Their baseline pain score was 58 ± (27.3), indicating higher average pain severity than observed in the current study. In contrast, Teepe et al. (2022) recruited individuals with knee OA from outpatient clinics for a mobile app intervention and reported a verbal-NPRS baseline pain score of 2.97 ± (1.91). When converted to a 0–100 scale, this approximates a mean score of 29.7, placing their participants at the upper end of the mild pain category according to Jensen et al. (2003).

These studies show a range of baseline pain severity. The current study's moderate pain score and high standard deviation suggest a heterogeneous population; however, the values still fall within the expected range for individuals with CKP, likely due to the voluntary, convenience-based recruitment strategy used (Etikan et al. 2016).

7.3.2.3. Tampa scale for kinesiophobia – TSK and patient health questionnaire-9 - PHQ-9

The mean baseline TSK score in the current study was 36.48 ± (6.43). Vlaeyen et al. (1995) identified TSK score ranking in which scores between 25–34 indicate low fear, 35–41 indicate moderate fear, and 42–68 indicate high fear of movement. Thus, the current study population falls within the moderate fear of movement category.

Direct comparisons for TSK scores in digital health studies among CKP populations are quite limited. However, while Godziuk et al. (2023) did not use the TSK, they evaluated mental wellbeing using the Warwick-Edinburgh Mental Wellbeing Scale (WEMWBS) among 72 individuals with knee OA recruited through rehabilitation centres. Their participants had a baseline WEMWBS score of 50.3 ± (10.1), indicating average mental wellbeing with probability of clinical depression (Tennant et al. 2007). The mean age in Godziuk et al. (2023) is 65 ± (7) years. Though the psychological construct is different, the older age profile and clinical context may contribute to different psychological presentations than those observed in the current study.

The moderate TSK score in the current study, paired with a relatively narrow standard deviation, which suggest that the population had some fear of movement, but not at extreme levels. The relatively young mean age (37 ± 16.03) may have

contributed to this result. Younger individuals are typically less prone to fear-avoidance beliefs and more likely to be physically active, which could account for the moderate kinesiophobia observed in this study (Larsson et al. 2016).

Furthermore, PHQ-9 is a tool used for screening, diagnosing, monitoring, and measuring the severity of depression (Kroenke et al. 2001) and the average baseline score in the current study was 5.16 ± (3.33). According to Kroenke et al. (2001), PHQ-9 scores of 0–4 indicate minimal depression, 5–9 mild, 10–14 moderate, 15–19 moderately severe, and 20–27 severe depression. This indicate that the current study sample had relatively low mood disturbance, reinforcing the population score from the TSK. The current sample demonstrated mild depressive symptoms with relatively low variability (SD = 3.33). The observed PHQ-9 scores fall within representative ranges for individuals with CKP, supporting the generalisability of the sample to similar populations.

7.3.2.4. Self-efficacy for managing chronic disease scale 6-item scale - SES6G

The average baseline SES6G score in the current study was 6.79 ± (1.72). This score places the current study sample within the moderate-to-high self-efficacy category according to established interpretation by Lorig et al. (2001).

This level of self-efficacy aligns with findings from previous digital health studies involving individuals with CKP. For example, Joseph et al. (2022) investigated a 12-week digital programme with 76 participants diagnosed with knee OA and reported a baseline self-efficacy mean score of 54.6 ± (10.9) on a 0–100 scale, consistent with moderate levels. Likewise, Shewchuk et al. (2021), who recruited 90 adults with OA from community settings, reported a PAM-10 (Patient Activation Measure) mean baseline score of 80.4 ± (9.1), indicating moderate self-management confidence.

The consistency across studies may reflect the motivational profiles of participants typically drawn to such interventions, where moderate self-efficacy is common and may serve as a foundation for digital engagement and behaviour change (Lorig et al. 2006).

In conclusion, these PROMs findings suggest that participants in the current study typically exhibited mild-to-moderate levels of pain, disability, psychological symptoms, and self-management confidence. Additionally, compared with clinical and hospital-based samples, the current study population showed greater variability,

consistent with a convenience sample. These differences underscore the importance of tailoring digital interventions to accommodate diverse symptom profiles.

7.3.3. Spatiotemporal parameters

Spatiotemporal parameters (ST) in the current study were collected using MVNX wearable sensors during a walking task conducted in an out-of-laboratory environment. Data were captured and processed through the MotionCloud system, which generated detailed gait report for each participant. The discussed parameters included walking speed, step length for both the affected and non-affected sides, and cadence. All values are presented as mean and standard deviation (mean ± SD). This demographic-oriented perspective provides deeper insight into the functional presentation of the study population and supports the justification for personalised intervention planning.

7.3.3.1. Speed

The average walking speed in the current study was 1.26 ± (0.052) m/s, which is higher than typically reported in CKP populations. In their study, Dai et al. (2023) conducted a 3D motion capture study over a 10-metre walkway in a laboratory and found that individuals with knee OA walked at a mean speed of 0.83 ± (0.29) m/s, while healthy controls walked at 1.03 ± (0.18) m/s. Similarly, Ismailidis et al. (2021) used wearable motion sensors on a treadmill and reported walking speeds of 0.95 ± (0.22) m/s among OA participants and 1.24 ± (0.16) m/s in healthy controls.

The relatively faster speed observed in the current study may be partly explained by the setting. Gait assessments were performed in a familiar, real-world corridor, which may have encouraged participants to walk more naturally and confidently. Supporting this, Fukuchi et al. (2019) found that 25 healthy adults walked significantly faster outdoors (1.44 ± 0.14 m/s) than in a laboratory (1.28 ± 0.13 m/s), attributing the difference to increased comfort. Similarly, Semaan et al. (2022) noted that treadmill walking can alter natural gait, often reducing speed and step length compared to overground walking.

The low standard deviation in the current sample (SD = 0.052 m/s) reflects a high degree of consistency across participants. Brach et al. (2008), who analysed walking speed variability among older adults with musculoskeletal conditions (mean age = 74.9 years), suggested that SD values below 0.10 m/s indicate functional

homogeneity. This consistency, despite the presence of CKP, suggests that many participants maintained stable walking patterns. These findings highlight the variation in how CKP population presents across individuals and reinforce the value of personalised rehabilitation strategies.

7.3.3.2. Step length – affected side and non-affected side

In the current study, the average step length on the affected side increased from 67.59 ± (2.79) cm at baseline to 68.82 ± (3.20) cm at follow-up, while the non-affected side increased from 67.48 ± (3.41) cm to 70.90 ± (3.80) cm. These values suggest relatively symmetrical gait patterns.

Farrokhi et al. (2015) conducted a gait laboratory analysis comparing individuals with mild (n = 38) and severe (n = 44) knee OA. Using a 3D motion capture system over a 10-metre walkway, they reported mean step lengths of 70 ± (0.08) cm for the mild OA group and 65 ± (0.08) cm for the severe OA group. Although there is a discrepancy in Farrokhi et al. (2015) group distribution, in the context of the demographics, the step lengths of the current study sample (particularly on the non-affected side) fall within the mild OA range suggesting functional similarity.

Likewise, Schmitt et al. (2015) found shorter step lengths (55 ± 0.10 cm) in knee OA patients (n = 20) compared to individuals with hip OA (n = 30) (58 ± 0.10 cm), walking in a lab setting. The current study's longer step lengths, on both sides, highlight a less impaired population in comparison to those typically recruited from clinical rehabilitation settings and indicates reduced gait asymmetry contributing to more stable and energy-efficient walking (Ardestani et al. 2016).

7.3.3.3. Cadence

In this study, a decrease in cadence was observed between the two timepoints, with values dropping from 112.86 ± 8.17 steps/min at timepoint 1 to 109.48 ± 7.41 steps/min at timepoint 2. Notably, this reduction occurred without any change in walking speed, which remained stable at 1.26 ± 0.052 m/s and 1.26 ± 0.054 m/s, respectively, and accompanied by an increase in step length on both the affected and non-affected sides. This inverse relationship between cadence and step length is a well-documented gait adaptation under conditions of constant speed; as

individuals take longer steps, they naturally require fewer steps per minute Ardestani et al. (2016).

These findings are consistent with the work of Ardestani et al. (2016), who found that individuals often adjust cadence in response to changes in step length to maintain steady walking speed. Anderson et al. further noted that decreased cadence alongside increased step length may reflect improved gait efficiency and motor control in certain populations, although such adaptations may also affect joint loading and energy expenditure.

Taken together, the observed decrease in cadence alongside stable walking speed and increased step length represents a coordinated gait adaptation that maintains walking efficiency. This pattern suggests that participants were able to optimise their gait characteristics during the study period. This also reinforces the variability and uniqueness of populations with CKP and indicates the importance of personalised digital interventions.

7.3.4. Kinematic parameters

Kinematic data in the current study were collected using MVNX wearable sensors during walking tasks performed in an out-of-laboratory environment. The kinematic data collected was only for descriptive comparisons to reflect adherence to the exercises from the app. The data were processed through the MotionCloud system, which generated joint-level movement metrics across multiple gait phases. Parameters collected include joint angles and ranges of motion (ROM) for the hip, knee, and ankle joints, captured in both the sagittal and frontal planes covering the whole gait cycle. All findings were reported using the format of mean and standard deviation (mean ± SD).

As with other biomechanical measures, interpreting kinematic findings in relation to participant demographics is essential. This approach allows for contextualised comparisons with published literature, aiding in the identification of CKP population movement patterns. Additionally, understanding joint-level motion within a demographic framework could enhance the ability to characterise functional status and supports the argument for personalised rehabilitation approaches based on individual movement profiles.

In the current study, knee ROM on the affected side was 32.08 ± (5.81°), and 31.47 ± (5.40°) on the non-affected side from the sagittal plane at stance phase. These values are lower than those reported by Dai et al. (2023), who found a sagittal knee ROM of 40.23 ± (10.24°) in 33 patients with knee OA, yet higher than those reported by Ismailidis et al. (2021), who studied 22 unilateral knee OA patients scheduled for total knee replacement using wearable inertial sensors. Ismailidis et al. (2021) reported that affected-side knee flexion ROM during stance was 15.9 ± (5.7°), with the unaffected side showing 19.6 ± (6.3°). This variability across studies (ranging from ~16° to ~40°) demonstrates the diverse presentation of movement restrictions within CKP populations, likely reflecting differences in severity, functional status, and individual adaptation strategies. The positioning of our findings within this spectrum suggests our participants fall between mild-moderate and severe presentations documented in the literature.

Furthermore, at initial contact, our participants presented a knee angle of 7.41 ± (2.40°) on the affected side from the sagittal plane, which is consistent with findings in early-stage OA populations. For instance, Farrokhi et al. (2015) reported initial contact angles of 6.1 ± (6.5°) in 20 individuals with mild OA, further supporting the interpretation that our sample displayed functional characteristics typical of early-stage knee pathology. In contrast, Tanpure et al. (2024) reported higher knee angle at heel strike (14.48 ± 5.77°) in 21 participants. However, Tanpure et al. (2024) highlighted that those participants were diagnosed with moderate knee OA, which helps to situate our sample along a severity continuum, leaning toward the milder end.

Moreover, at the hip joint, sagittal plane angle at heel strike was 26.77 ± 4.44°, comparable to values reported by Tanpure et al. (2024) for individuals with knee OA (26.65 ± 11.07°). In the frontal plane, the hip angle was 0.72 ± 3.85°, closely aligned with Fukaya et al. (2019) findings in early OA (0.44 ± 4.38°). However, the variation in standard deviations across studies (ranging from 3.85° to 11.07°) and the different classification approaches used, from early OA to moderate-severe presentations, highlight the inherent diversity within CKP populations. This variability reflects the heterogeneous nature of CKP, where individuals may present with different severity levels, compensatory strategies, and functional adaptations despite sharing similar symptom profiles. The positioning of our findings across this spectrum of reported

values demonstrates that CKP populations encompass a wide range of movement presentations, emphasising the importance of recognising this diversity when developing and evaluating interventions for individuals with knee-related symptoms.

In the current study, ankle joint angles at heel strike in the sagittal plane showed a baseline value of –0.68 ± (3.57°), indicating a slightly plantarflexed position. These values differ from those reported by Tanpure et al. (2024), who observed dorsiflexed angles of 2.06 ± (4.05°) and 2.69 ± (3.86°) in their moderate (n = 21) and severe (n = 46) OA groups, respectively. The discrepancy may reflect individual gait adaptations influenced by comfort or stability (Mündermann et al. 2005; Ro et al. 2019), particularly in overground walking contexts (Riley et al. 2007). Although not typical in early OA, this finding may reflect compensatory strategies to redistribute load or stabilise the limb during stance (Mills et al. 2013).

Moreover, swing-phase data at baseline from our participants further illustrate the biomechanical diversity among participants. Affected side knee ROM during swing was 55.33 ± (4.84°), with maximum flexion angle of 58.87 ± (3.25°). These values are closely aligned with those reported by Ismailidis et al. (2021), who observed a swing-phase ROM of 50.0 ± (7.3°) and maximum flexion angle of 59.0 ± (8.6°) in 22 participants. When comparing our findings to those of Tanpure et al. (2024) and Ismailidis et al. (2021), such asymmetries and within-group variability, even among individuals classified under the same diagnostic category, underscore the heterogeneity of CKP. In their study, Bacek et al. (2022) noted that joint impairments often result in a range of compensatory strategies, such as hip hiking or altered limb trajectories, that produce similar functional outcomes despite differing underlying kinematic patterns. This observation holds true in our cohort, where no single joint or plane exhibited a uniform movement signature across participants.

Collectively, the baseline kinematic profile presented here supports the assertion that our participants could suffer from mild to moderate knee impairment. Importantly, the findings also reveal meaningful inter-individual differences, supporting the case for personalised rehabilitation approaches that address specific movement limitations. Digital interventions, such as the DBBT used in this study, offer the flexibility to incorporate individual biomechanical data into personalised treatment plans, thereby maximising their potential benefit.

7.4. Conclusion

Taken together, the findings from the PROMs, spatiotemporal parameters, and kinematic data demonstrate that participants in the current study exhibited a diverse range of physical and psychological characteristics among our participants. The mild-to-moderate scores across PROMs, the relatively preserved gait performance, and the variability in joint mechanics all reflect the heterogeneity commonly observed in CKP, particularly when samples are drawn through voluntary and community-based recruitment. This diversity reinforces the importance of personalising rehabilitation strategies and tailoring digital interventions to meet the unique needs and movement profiles of each individual. In light of this, the following section explores the acceptability of the DBBT, beginning with its personalisation feature, and how it may have contributed to participants' engagement, perception of effectiveness, and overall experience.

7.5. The acceptability of the digital biomechanical biofeedback toolkit (DBBT)

This section presents a critical evaluation of the acceptability of the DBBT based on participants' experiences. The discussion draws primarily on the findings from semi-structured interviews and is explained according to the constructs of the theoretical framework of acceptability (TFA), which provided a structured lens for interpretation. By mapping participants' reflections onto TFA components such as affective attitude, intervention coherence, self-efficacy, and perceived effectiveness, a nuanced understanding of the DBBT's acceptability was developed. Throughout this section, both interviews' findings and objective measures, including kinematic and spatiotemporal parameters and patient-reported outcome measures (PROMs), are integrated to support and contextualise the interpretations. The goal was to demonstrate how different features of the DBBT influenced users' experiences and to critically explore the factors that shaped the overall acceptability of the intervention.

7.5.1. The role of the digital biomechanical biofeedback toolkit's personalisation feature

Participants in the current study identified the personalisation feature of the DBBT as a key factor contributing to their experience. Personalisation was achieved through the interpretation of each participant's biomechanical gait report, highlighting alterations in joint kinematics and the overall spatiotemporal gait parameters. These

details were then used to prescribe exercises personalised to individual movement patterns and physical needs.

Findings from the reflexive thematic analysis of participant interviews, which were guided by the TFA (Sekhon et al. 2017), indicated that personalisation in the current study was closely linked to the components of affective attitude and perceived effectiveness. Affective attitude refers to how individuals feel about engaging with an intervention, which in the current study is the DBBT. In this context, participants reported that the DBBT's personalisation of the exercises enhanced their motivation and confidence in engaging with the DBBT, as they felt exercises were personalised to their individual needs and physical capabilities. This interpretation was further supported by the kinematic data used to personalise the exercises.

The kinematic analysis not only informed the personalised prescription but also reflected participants' experiences of improved mobility and functional confidence, as reported in the thematic analysis. For example, sagittal knee ROM on the affected side improved by approximately 1.8°, indicating enhanced flexibility during gait. Similarly, stance-phase knee ROM increased by around 2.1°, which may reflect reduced stiffness or a greater functional ROM. These findings represent group-level mean changes, and while modest, they support participants' reported improvements in joint function and movement confidence. Rather than being treated as definitive clinical outcomes, these changes offer explanatory value as they help illustrate why participants found the DBBT motivating to engage with, resulting in a positive affective attitude. Additionally, by demonstrating that the DBBT adapted to each user's unique movement profile, the kinematic data reinforced the sense of personalisation and contributed to a stronger perceived effectiveness.

In addition, the participant-reported outcome measures (PROMs) provided complementary support for the interpretation that participants perceived the DBBT as effective and motivating, which could be due to its personalised nature. However, it is crucial to acknowledge that those changes could also be due to other factors such as individual variability in motivation, symptom fluctuation, or placebo-related responses to digital health interventions. Therefore, the direction or magnitude of change in PROMs should be interpreted with caution, particularly given the short intervention period and absence of a control group (Yardley et al. 2016). On a group

level, pain scores (NPRS) decreased by 8.09 points, and functional disability WOMAC scores declined by 6.73 points, while self-efficacy (SES6G) increased slightly by 0.12 points. These changes indicate improvements in symptom management and confidence in self-management. They were consistent with participants' reflections in the thematic analysis. For example, several individuals described feeling stronger, more confident in movement, and more able to manage their symptoms, particularly when climbing stairs or walking longer distances. Such reflections align with the TFA components of affective attitude and perceived effectiveness, highlighting the value of the DBBT in both emotional and functional terms. Additionally, it is also plausible that some of these reported improvements were influenced by psychosocial factors, such as enhanced self-efficacy and reassurance gained through interaction with the technology (Yijia et al. 2024).

Furthermore, several studies (Bostrøm et al. 2022; Davergne et al. 2023; McHugh et al. 2025; Gell et al. 2024; Stevenson et al. 2024) have used exercise-based digital health applications with CKP, and like the current study, have highlighted the value of personalisation in enhancing user motivation and confidence (affective attitude).

The research by Bostrøm et al. (2022) conducted semi-structured interviews with 15 participants living with chronic pain utilising an app-based cognitive-behavioural pain self-management programme called EPIO. The application provided personalised exercise support by enabling users to choose when and how to engage with guided physical and relaxation exercises, allowing them to align their practice with personal routines, preferences, and pain levels. In line with our findings, the authors found that the personalisation feature enhanced motivation among participants to engage with the digital intervention.

Furthermore, a systematic review and meta-analysis conducted by Davergne et al. (2023) included 10 studies with a total of 1,050 participants, 93% of whom were adults. The authors aimed to assess the effectiveness of exercise-based mobile applications providing personalised exercise videos in people with disabilities. One of the outcomes assessed was confidence in exercise performance. The findings indicated that there was a small amount of evidence that such applications led to small to moderate improvements in users' confidence in performing exercises from home.

While Davergne et al. (2023) reported low-quality evidence for the effect of personalisation on confidence, their findings were constrained by methodological limitations, including high risk of bias, inconsistencies in outcome measurement, and heterogeneous study populations. Importantly, the types of personalisation reviewed were often limited to exercise videos rather than interventions adapted to individual physical needs or therapeutic goals. In contrast, the current study demonstrated that participants experienced enhanced confidence through a more comprehensive form of personalisation embedded within the DBBT. Personalisation in this study extended beyond exercise videos to include exercise prescription based on biomechanical data, individual needs, and user preferences. This deeper integration of personalised exercise was consistently linked by participants to improved motivation and confidence in engaging with the DBBT. Both Davergne et al. (2023) and our findings suggest that more holistic, data-informed personalisation, such as that offered by the DBBT, may better support confidence-building in exercise-based digital health interventions, leading to more positive affective attitudes among users.

An important finding in the current study is that participants found the personalised exercise plan made the DBBT feel more relevant and aligned with their personal goals. In the TFA, this aligns with the perceived effectiveness component, which refers to the extent to which an intervention is seen as likely to achieve its intended outcomes. This finding is echoed in a body of research that has emphasised the importance of personalisation in shaping users' belief in the appropriateness and effectiveness of digital health interventions (McHugh et al. 2025; Gell et al. 2024; Stevenson et al. 2024). Across these studies, when exercise or programme content was personalised to individual needs, participants were more likely to perceive the intervention as meaningful, manageable, and capable of improving their symptoms. Conversely, limited or absent personalisation was associated with reduced engagement and doubts about the intervention's effectiveness.

For example, McHugh et al. (2025) conducted a qualitative study with 18 individuals diagnosed with CKP, aiming to evaluate the acceptability and user engagement with two distinct electronic rehabilitation programmes: Group e-rehab, a remotely delivered, physiotherapist-led group intervention (8-week programme), and My Knee UK, a self-directed, web-based exercise platform. Both interventions focused on improving lower-limb strength and functional mobility through prescribed home

exercises. Using in-depth semi-structured interviews and inductive thematic analysis, the researchers found that participants in both groups valued personalised support, particularly when exercises were matched to their physical capabilities and pain levels. Participants described the personalisation as enhancing the perceived usefulness and credibility of the intervention, thereby reinforcing its perceived effectiveness.

Gell et al. (2024) employed a mixed methods design to assess user experiences with three commercially available mobile applications designed for home-based exercise among adults with knee OA (N = 30). Participants engaged with the apps over a four-week period, during which they were asked to complete pre-set exercise routines. Following this, semi-structured interviews were conducted to explore usability and engagement. A major theme identified was the lack of discussions or input in exercise selection. Many participants reported that some exercises were too challenging or did not accommodate their joint limitations, which led to frustration and decreased engagement. The perceived lack of personalisation made the interventions feel less relevant and less effective in addressing their specific needs.

Similarly, Stevenson et al. (2024) conducted a qualitative study involving 20 participants with knee OA who used a mobile application designed to support physical activity. The app included three core components: a daily physical activity tracking tool, an educational content library, and access to social support via peer forums. Over a six-week usage period, participants' experiences were captured through semi-structured interviews and analysed using thematic analysis. Participants frequently complained from the app's failure to adapt to individual preferences or limitations. Some participants noted that the activity suggestions were generic or unsuitable for their condition, which reduced their confidence in the programme's ability to produce meaningful outcomes.

Taken together, these studies reinforce the current study's findings by demonstrating that exercise-based digital interventions which incorporate personalisation, mainly through personalised exercise prescription, adaptive content, or user input, are more likely to be perceived as effective by individuals with CKP. When users feel that an intervention addresses their unique physical capabilities, preferences, and

limitations, they are more confident in its potential to support meaningful outcomes, aligning directly with the perceived effectiveness component of the TFA.

7.5.2. Objective biofeedback and visual gait report

Participants in the current study identified the DBBT's visual biofeedback report as a highly influential feature in shaping their engagement and understanding of movement. This feature aligned with two components of the TFA: intervention coherence, which refers to how well users understand the intervention and how it works, and affective attitude, which captures how individuals feel about engaging with the intervention (Sekhon et al. 2017).

The visual biofeedback provided through the DBBT offered participants a gait report comprising waveforms and numerical data, comparisons between affected and non-affected sides, and clear indications of movement asymmetries. This form of targeted feedback enhanced intervention coherence by helping participants make sense of their joint mechanics and understand how the prescribed exercises related to specific movement deficits. By making biomechanical concepts visible, the DBBT appeared to strengthen users' conceptual grasp of the intervention's purpose and logic, which are key components of intervention coherence as defined within the TFA (Sekhon et al. 2017). Several participants, particularly those who identified as visual learners, reflected that being able to see differences between their limbs or observe movement representations helped them understand patterns they were previously unaware of. This enhanced their ability to understand both the problem and the DBBT logic.

Comparable findings have been reported in previous research. For exempel, van den Noort et al. (2015) investigated real-time visual feedback for gait retraining in seventeen healthy subjects (mean age 28.2 ± 7.6 years) who walked on an instrumented treadmill whilst receiving four different types of visual feedback on knee adduction moment and hip internal rotation angle. Crucially, they found that participants were able to effectively interpret and respond to the visual displays, demonstrating that well-designed visual feedback enhanced participants' intuitive understanding of their movement mechanics and enabled them to comprehend how their gait patterns related to the targeted biomechanical parameters. This finding underscore how visual biofeedback can improve intervention coherence by making

complex movement concepts accessible and meaningful to users. Additionally, Richards et al. (2017) in their systematic review of twelve studies found that visual feedback on knee adduction moment produced large effect sizes, suggesting that coherent, direct visualisation of the target biomechanical parameter enhances users' ability to understand and modify their movement patterns effectively.

The sense of increased understanding and movement awareness reported by participants was further supported by existing biomechanical and digital health literature. For example, Ismailidis et al. (2021) conducted a study involving 30 individuals with knee OA and used inertial measurement units (IMUs) to assess joint kinematics during gait. Their analysis revealed consistent asymmetries in sagittal and frontal plane movement between affected and non-affected limbs, especially reduced knee ROM and altered alignment. While their study focused on measurement rather than intervention, it demonstrated the prevalence and clinical relevance of movement asymmetries in people with CKP. In the current study, similar asymmetries were visualised and communicated directly to users, which participants described as improving their understanding of their condition; thus, enhancing intervention coherence and promoting a sense of clarity around their rehabilitation.

Further insight is offered by Pila et al. (2023) and Stern et al. (2022), who investigated the acceptability of digital decision-support tools for patients with OA undergoing surgical planning. Both studies involved platforms that presented PROM-based reports to help guide discussions around joint replacement. Pila et al. (2023) found that participants appreciated receiving personalised feedback about their health but expressed a desire for clearer explanations of how their symptoms related to function and surgical need. A key limitation was the lack of objective movement data, which left users feeling uncertain about what their scores meant in practical or physical terms. Similarly, Stern et al. (2022) reported that PROM-based feedback improved communication and decision-making confidence but acknowledged that the absence of biomechanical or clinical metrics restricted the depth of user understanding.

In contrast to these PROM-only systems, the DBBT provided users with detailed biomechanical biofeedback, including comparisons between limbs and changes in joint range and alignment. Participants in the current study described this

visualisation as improving their comprehension of movement problems and clarifying the rationale behind their exercises, both of which are core indicators of intervention coherence.

The kinematic findings provided additional explanatory support for participants reported enhanced understanding. At the group level, sagittal knee ROM on the affected side improved by 1.8°, stance-phase ROM increased by 2.1°, and maximum knee flexion rose by 2.47°. Frontal plane knee ROM increased by 1.16°, and alignment shifted slightly in the valgus direction (−0.22° to −0.39°). Ankle alignment also moved toward a more neutral position (−4.31° to −0.56°). While these changes were modest and not interpreted as clinical outcomes, they offered explanatory value by helping reinforce participants' developing understanding of how their movement patterns related to their symptoms and rehabilitation, which are key indicators of enhanced intervention coherence (Sekhon et al. 2017).

Furthermore, participants also described positive feelings about engaging with the biofeedback system, consistent with the TFA component of affective attitude. The novelty and clarity of the visual representations contributed to a stronger emotional connection with the DBBT. Some participants expressed that seeing their movement visualised, such as through an avatar or comparative graphs, made the experience more interesting and engaging. These visualisations were presented and shared through the Xsens Analyse software and the Motioncloud website, which were used to collect and process the movement data and generate the gait report. This positive emotional response was not only linked to interest but also to a stronger sense of motivation to engage with the DBBT. These reactions indicate a positive emotional response to using the DBBT, which aligns with the TFA component of affective attitude.

Collectively, these findings reinforce the added value of biomechanical feedback in digital interventions. While PROM-based systems can enhance awareness and communication, their limitations are well-documented when it comes to functional interpretation. The DBBT addressed this gap by providing a data-rich, visually accessible report that supported both comprehension and motivation. This integration of personalised movement insight contributed to participants' belief that the intervention was logical, interesting, and relevant to their needs aligning with the

TFA components of intervention coherence and affective attitude and ultimately enhancing the toolkit's overall acceptability.

7.5.3. Video demonstrations feature of the digital biomechanical biofeedback toolkit

From our participants reflections, the video demonstration feature embedded in the DBBT emerged as a valued element that supported participants' confidence, clarity, and engagement. Videos were delivered through the Kinduct Athlete mobile app, presenting each personalised exercise with a clear visual guide. Participants accessed these videos after receiving their tailored exercise programme and were expected to complete them independently at home. Participant reflections aligned strongly with three components of the theoretical framework of acceptability, perceived effectiveness, self-efficacy, and affective attitude, each contributing to the toolkit’s overall acceptability.

Perceived effectiveness is defined as the extent to which individuals believe an intervention is likely to achieve its intended purpose (Sekhon et al. 2017). The video demonstrations within the DBBT contributed to participants' perceived effectiveness of the intervention. Participants described the videos as interactive and easy to follow, with the visual demonstrations helping them stay focused and complete exercises successfully. This positive experience with the video content strengthened participants' confidence that the DBBT would be effective in helping them achieve their rehabilitation goals, thereby enhancing their belief in the intervention's potential to deliver meaningful outcomes.

These findings are supported by Godziuk et al. (2023), who conducted a mixed-methods evaluation of a web-based intervention involving 102 individuals with knee OA. Their programme included weekly instructional videos and OA-specific educational content. Of these, 53 participants took part in semi-structured interviews. While users appreciated the availability of exercise videos, many highlighted that the content was overly generic and did not address their individual needs or limitations, which could be an issue that undermined their confidence in the programme’s value. In contrast, the DBBT used in the current study embedded video demonstrations that were informed by the personalised exercise programmes, which participants described as feeling relevant and easier to follow. This perception appeared to

reinforce the sense that the intervention was purposeful and capable of producing tangible outcomes.

Group-level kinematic findings in the current study offer further support for this interpretation. For example, knee flexion during the stance phase improved by 2.4° and ankle dorsiflexion increased by 2.2°. While not clinically significant, these subtle changes may reflect more accurate or consistent exercise execution, possibly supported by the clarity of the video demonstrations. A recent experimental study by Mbada et al. (2025) adds further support. The authors compared clinic-based strengthening exercises (CbSE) with asynchronous video-based strengthening exercises (AVbSE) in 52 patients with knee OA. The AVbSE group received detailed video demonstrations and were telemonitored for adherence and performance. Both groups demonstrated improvements in knee ROM, with the video group improving by 11.7° after eight weeks. These findings suggest that video-based instruction can facilitate movement accuracy and reinforce engagement, particularly when the content is well-structured and consistent, which are qualities that were also described by participants in the current study.

Furthermore, self-Efficacy, another TFA component, is defined as the confidence a participant feels in their ability to perform the behaviours required to engage with an intervention (Sekhon et al. 2017). Participants highlighted that the videos were short, focused, and delivered clear messages about how to perform the exercises. They appreciated that the demonstrations did not go too fast, which helped them feel confident that they were doing the exercises correctly.

These findings are consistent with the study by Weber et al. (2024), which evaluated a 12-week mobile app-based programme among 32 OA patients. The app featured video demonstrations for 2–3 exercises per session. Participants noted that the videos helped them feel more independent when exercising at home. However, unlike the DBBT, Weber's app lacked performance feedback, which some participants found limiting. The confidence expressed by DBBT users may be partly attributed to the integrated approach combining video with biomechanical biofeedback (gait report) before and after using the DBBT, which strengthened their sense of control leading to increased self-efficacy.

Moreover, affective Attitude, defined as how individuals feel about the intervention emotionally (Sekhon et al. 2017), was another TFA component that linked to participants views regarding the video demonstrations. Participants described the videos as impressive, helpful, and more useful than paper instructions. In particular, they contrasted their experience with the DBBT videos against static exercise photos or written instructions, which they found unclear and uninspiring. Several expressed that the ease and visual quality of the videos lead to feeling more engaged with the DBBT. This aligns with findings from Davergne et al. (2023), who reviewed mobile app-based programmes for musculoskeletal conditions and found that the inclusion of video content improved user engagement, particularly when videos were short and targeted. Their meta-analysis concluded that video-based interventions were among the top contributors to improved self-efficacy and emotional satisfaction in digital rehabilitation programmes. The DBBT's brief and accessible exercise videos appeared to strike a balance between clarity and emotional resonance, enhancing the affective attitude among the users.

In conclusion, the video demonstration feature of the DBBT supported multiple dimensions of acceptability through the TFA lens. It increased engagement by making exercises feel interactive and personally relevant (perceived effectiveness), promoted user confidence through clear and simple visual delivery (self-efficacy), and evoked a positive emotional response due to its ease and professional quality (affective attitude). Supported by both participant perspectives and kinematics outcomes, this feature exemplifies how thoughtful digital design can facilitate high acceptability in home-based rehabilitation.

7.5.4. Reminder system and routine formation

The reminder system embedded within the DBBT was consistently identified by participants as a practical and supportive feature that encouraged routine formation and sustained engagement. Delivered via the Kinduct Athlete mobile app, reminders were automatically triggered to prompt users to complete their prescribed exercises and submit PROMs. While technically simple, this feature aligned with multiple components of the TFA, particularly perceived effectiveness and affective attitude.

From a TFA standpoint, perceived effectiveness is defined as the extent to which an individual believes the intervention will achieve its intended goals (Sekhon et al.,

2017). Participants in the current study reported that reminders helped them stay on track with their rehabilitation efforts, especially in the context of unsupervised home-based care. Furthermore, participants expressed that the reminding system improved their motivation to engage more with their exercise programmes, which led to increased perceived effectiveness of the DBBT. Additionally, several participants highlighted that the reminders facilitated routine building that was reflected in increased commitments to engage with their programme.

These observations are in line with findings from Pelle et al. (2021), who conducted an exploratory study within a larger RCT involving 214 participants with knee OA. The study evaluated a self-management mobile app that included reminder systems, goal setting, and symptom monitoring. Among the 113 participants who actively engaged with the intervention, reminders were one of the most valued features. Participants viewed reminders as behavioural "nudges" that supported task completion and reinforced accountability.

Likewise, Gell et al. (2024) employed qualitative interviews with 17 patients and 18 physiotherapists to explore the use of three commercial exercise apps for knee OA. All apps incorporated reminder functions. Gell et al. (2024) illustrated that participants identified reminders as crucial in facilitating motivation and accountability, particularly when they knew their progress was being monitored. One therapist described reminders as a light-touch system of support that improved adherence without overwhelming users. These findings parallel the current study's results, where reminders were appreciated for supporting autonomy while also reinforcing structured participation, and in line to the increased perceived effectiveness of the DBBT leading to higher acceptability.

Additional support comes from Stevenson et al. (2024), who conducted a 12-week mixed-methods study involving 38 participants using a digital app to promote physical activity in knee OA. The app included reminder alerts that were reported by users to be one of the few components that fostered consistent participation. Qualitative feedback from Stevenson et al. (2024) study participants highlighted reminders as helpful in sustaining day-to-day adherence, echoing findings from the DBBT study. However, Stevenson et al. also acknowledged that without visual demonstration or personalised adjustment, engagement levels declined over time.

This comparison emphasises that while reminders are valuable, they achieve greater effectiveness when integrated into a broader personalised system, as was the case with the DBBT

The current findings also revealed subtle distinctions in how reminders shaped emotional and psychological engagement. This aligns with the TFA component of affective attitude, which refers to how individuals feel about participating in an intervention (Sekhon et al., 2017). Several participants described reminders as encouraging or helpful in staying committed, indicating that the function carried positive emotional value. Rather than being perceived as intrusive, they were interpreted as supportive cues, reinforcing users' intentions. These reflections align with outcomes from Nelligan et al. (2021), who studied 206 knee OA participants in an RCT evaluating a digital exercise intervention that included behavioural reminder text messages. The authors reported a gradual decline in engagement, from 97% in month one to 61% by month six, but highlighted reminders as a crucial feature for maintaining motivation during the early phases. This observation mirrors participant reflections in the present study, where reminders helped initiate routine behaviour and establish continuity.

In spite of DBBT reminders were viewed by most participants as lightweight and minimally demanding, some participants requested improvements, such as the ability to customise reminder timing. For instance, few participants explained that it would have been better if they could have the ability to change the reminder time, highlighting that the fixed default times did not always align with daily routines. This feedback suggests that future iterations of the DBBT could benefit from enhanced flexibility to accommodate diverse user schedules, a modification that aligns with broader calls for user-tailored digital health experiences (Davergne et al. 2023; Simblett et al. 2018).

Moreover, although the reminders themselves did not directly affect clinical parameters, their potential indirect effects can be inferred from increased engagement levels. PROMs in the current study showed a reduction in fear of movement (TSK decreased by 3.65 points), reduced pain (NPRS dropped by 8.09 points), and improved self-efficacy (SEMCD increased by 0.12 points). While these outcomes cannot be causally attributed to reminders, they provide supporting

evidence that features promoting consistent engagement may facilitate psychological readiness and sustained participation, both of which are critical in CKP self-management.

In summary, the reminder system embedded within the DBBT played a supportive and motivating role in the rehabilitation journey of participants. By prompting action, reinforcing structure, and providing a sense of continuity, this feature enhanced users' perceived effectiveness and emotional connection to the intervention, without adding notable burden. The findings align with broader literature demonstrating that well-designed reminder systems can strengthen behavioural engagement and contribute to digital health acceptability, particularly when paired with other supportive features like personalisation and visual feedback. As such, the reminder system can be considered a strategically effective design element that reinforces the DBBT's acceptability among CKP populations.

7.5.5. Exercise logging and Participant-reported outcome measures submission feature

The exercise logging and PROMs submission features were accessible to participants through the Kinduct Athlete mobile application after they had received their personalised exercise programmes. Once at home, participants could access their prescribed exercises and log each session upon completion. In parallel, the application prompted them to complete a series of PROMs including the WOMAC for pain and function, TSK for fear of movement, SES6G and NPRS. While these features were primarily implemented to monitor engagement and adherence, which is discussed in the usability section below, participants' reflections demonstrated how such feature also supported their interaction with the intervention in ways aligned with the theoretical framework of acceptability.

According to Sekhon et al. (2017), self-efficacy refers to the participant's confidence in their ability to perform the behaviours required to participate in an intervention. In the current study, participants consistently described the logging of their completed exercises and PROMs submission processes as easy to use and clearly presented within the mobile application. This sense of simplicity and clarity appeared to enhance their confidence in using the platform independently. This directly reflects self-efficacy, as participants felt capable of completing tasks without external

assistance. The design of the application, including elements such as tick-boxes and automatic prompts, allowed participants to engage with the intervention in a way that felt manageable, further supporting their belief in their ability to maintain participation.

In addition to facilitating ease of use, these features contributed to a sense of progress and behavioural control. Several participants explained that ticking off completed sessions or submitting PROMs gave them a feeling of accomplishment and continuity. These small but routine actions helped reinforce the belief that they were making an active contribution to their recovery. This again reflects self-efficacy, as participants recognised that their own actions were necessary and sufficient for engaging with the programme. Importantly, this belief was not limited to the physical tasks but extended to the digital interaction with the intervention, which strengthened their confidence in using the system independently over time.

The use of these features also shaped participants' belief in the potential benefit of the DBBT. According to Sekhon et al. (2017), perceived effectiveness is defined as the extent to which a person believes that the intervention is likely to achieve its intended purpose. While the PROMs submission function did not offer personalised feedback, the app provided users with a confirmation message indicating that their responses were successfully submitted. The primary purpose of this process was to track usage and support adherence monitoring within the study. In contrast, the exercise logging feature offered a more immediate and intuitive form of visual feedback: when a session was marked as complete, a green icon appeared to signal successful completion. This simple visual cue helped participants distinguish between completed and pending sessions, reinforcing a sense of progress and routine. Many participants reported that this visible confirmation encouraged them to stay on track and contributed to the feeling that their continued participation was meaningful. This perception of making steady, goal-directed progress supports the core construct of perceived effectiveness, as it reflects participants' belief that the intervention was both purposeful and capable of producing beneficial outcomes.

These findings regarding self-efficacy and perceived effectiveness are particularly important when considering sustained engagement with digital interventions. Research examining adherence patterns in mobile-based rehabilitation programmes

provides valuable context for understanding how these TFA constructs translate into long-term participation and real-world implementation. Yamamoto et al. (2022) highlighted the importance of adherence in their mobile-based home exercise programme for individuals with knee OA. In their 12-week study involving 20 participants, users engaged with video-guided exercises through a split-screen app interface that allowed them to view both demonstrations and their own movements. Although the study reported high adherence (mean 82.4% ± 15.3%) and noted improvements in pain and stiffness, the authors did not investigate the reasons why some participants may not have fully adhered to the programme. In contrast, the current study not only tracked engagement via exercise logs and PROMs submissions but also explored non-adherence directly through thematic analysis. Participants who were unable to consistently log their exercises cited a range of barriers including time constraints, illness, unexpected events, and competing priorities. These insights provide critical context by showing that lapses in engagement were not due to system limitations or lack of confidence in using the platform, but rather to external, often unavoidable, life circumstances. This distinction is important for understanding self-efficacy within the TFA framework, as it demonstrates that participants maintained confidence in their ability to use the intervention effectively, even when external factors prevented consistent engagement.

In addition, the importance of progress tracking is emphasised by Weber et al. (2024), who evaluated a 12-week mobile intervention involving 32 adults with OA (20 knee OA, 9 hip OA, 3 both). Although their app included educational and exercise content, it lacked a self-logging feature. In post-study interviews, participants expressed frustration at their inability to track performance, noting that the absence of a progress-tracking function reduced their motivation and engagement. This finding directly contrasts with the current study, where participants consistently described the DBBT's logging feature as motivating, reinforcing, and supportive of their experience. The comparison highlights how the presence or absence of simple digital tools can significantly shape perceived effectiveness and overall intervention acceptability.

In summary, the exercise logging and PROMs submission features were more than operational tools; they were perceived by participants as manageable, useful, and

reinforcing. By enabling independent interaction, providing structure, and encouraging reflection, these features supported both self-efficacy and perceived effectiveness, contributing to participants' belief in the value of the DBBT. The ability to confidently navigate the system and visualise progress in real time supported sustained engagement and demonstrated how simple features, when designed and implemented thoughtfully, can enhance digital intervention acceptability by strengthening the psychological foundations of participation under the TFA framework.

7.6. The usability of the digital biomechanical biofeedback toolkit (DBBT)

This section presents an evaluation of the usability of the DBBT. Usability assessment was conducted through two complementary approaches: the System Usability Scale (SUS) administered to participants upon study completion to generate a mean final score across all participants, and quantitative analysis of adherence rates throughout the study duration. The System Usability Scale (SUS) is a widely recognised psychometric instrument that evaluates the perceived usability of technological systems across ten standardised items, measuring effectiveness, efficiency, and user satisfaction (Brooke 1996; Bangor et al. 2009). The current study achieved an excellent SUS score of 84.6 (Bangor et al. 2009). Adherence was measured through two primary engagement tasks completed by participants using the Kinduct Athlete mobile application from home and presented as percentages: exercise logging adherence of 63% (calculated as the number of logged exercise sessions divided by the total number of prescribed sessions) and PROMs submission adherence of 76% (calculated as the number of completed and submitted PROMs divided by the total number of PROMs administered). The usability evaluation was conducted specifically in the context of the DBBT's key features, examining how effectively participants could navigate and utilise the various components of the digital toolkit. Although the primary usability assessment was conducted through the SUS and adherence rates, the semi-structured interviews, primarily designed to evaluate acceptability, revealed additional insights into usability from participants' expressions and experiences, which are used here to further support and contextualise the usability findings. By combining standardised usability measurements with behavioural engagement data and qualitative insights, this evaluation aims to provide a comprehensive understanding of how effectively

participants could interact with the DBBT and maintain consistent use over time, offering insights into the practical implementation of the DBBT and its usability.

7.6.1. Digital biomechanical biofeedback toolkit's personalisation feature and usability

Personalisation was achieved through the interpretation of each participant's biomechanical gait report, highlighting alterations in joint kinematics and the overall spatiotemporal gait parameters. These details were then used to prescribe exercises personalised to individual movement patterns and physical needs.

In the current study, the DBBT achieved an excellent SUS score of 84.6, indicating that participants found the system highly usable and user-friendly (Bangor et al. 2009). The personalisation feature directly addresses each of the three core SUS dimensions: effectiveness was enhanced because participants could achieve their rehabilitation goals more successfully through exercises tailored to their specific movement patterns; efficiency was improved as participants spent less time understanding irrelevant content and could focus on exercises specifically designed for their needs; and user satisfaction increased because participants felt valued and understood through the individualised approach. This explanation could help in illustrating the excellent SUS score achieved in the current study, as participants recognised that the DBBT was specifically designed around their individual biomechanical profiles rather than delivering standardised exercise content.

When examining the broader literature on digital health interventions for CKP, the relationship between personalisation and usability could be illustrated. Joseph et al. (2022) evaluated a web-based aerobic exercise programme among 25 participants with knee OA, delivering standardised exercise content through a website platform, and reported a SUS score of 77.5, indicating good but not excellent usability (Bangor et al. 2009). Their intervention lacked personalisation based on individual movement patterns or functional assessments, instead of providing personalised exercise programmes. Similarly, Weber et al. (2024) assessed a mobile application among 32 individuals with OA (20 knee, 9 hip, 3 both), providing generic exercise and physical activity education programmes through video demonstrations and standardised scheduling, achieving a SUS score of 71.3, which represents acceptable but still not excellent usability (Bangor et al. 2009). In contrast, Shewchuk et al. (2021) reported

a considerably lower SUS score of 57.8 for their self-management mobile application tested with 18 knee OA patients, which included symptom tracking and activity suggestions but lacked personalised exercise options. Participants noted that this intervention fall short to adapt individual needs or provide tailored content. These comparative findings suggest that the degree of personalisation implemented may be a critical determinant of usability outcomes, with the current study's comprehensive biomechanical-based personalisation potentially explaining the substantially higher SUS score achieved compared to interventions offering limited or no personalisation.

Furthermore, although the interviews were conducted primarily to evaluate acceptability, they revealed key details that support the usability findings. Participants consistently expressed that the personalised nature of the DBBT made the system feel intuitive and relevant to their specific needs. Many individuals described how the exercises felt appropriately matched to their physical capabilities and movement limitations, which enhanced their confidence in navigating and using the system. Participants noted that because the exercises were clearly connected to their individual gait analysis results, they found it easier to understand the purpose of each exercise and follow the prescribed exercises. This sense of confidence and relevance contributed to a smoother user experience, as participants felt the system was designed specifically for them rather than requiring them to adapt to generic content. The personalised approach also reduced confusion and uncertainty about exercise selection, which could be attributed to the excellent SUS score.

The SUS findings are further supported by the supplementary kinematic, spatiotemporal, and PROMs data, which were measured descriptively at group-level and are not intended to demonstrate clinical significance. Rather, these findings help support the usability outcomes and their interpretation. Kinematic analysis revealed group-level improvements in joint function, including enhanced sagittal knee ROM on the affected side (approximately 1.8° improvement) and increased stance-phase ROM (around 2.1° improvement). These descriptive changes could indicate that participants were successfully engaging with their personalised exercise programmes and experiencing some functional benefits. Similarly, spatiotemporal parameters showed group-level improvements in gait characteristics, including increased step length on both affected and non-affected sides, suggesting enhanced

movement engagement with the intervention. The PROMs data further illustrated the group-level outcomes associated with the personalised approach, with reductions in pain scores (NPRS decreased by 8.09 points) and functional disability (WOMAC decreased by 6.73 points), alongside slight improvements in self-efficacy. These descriptive group-level improvements suggest that the high usability ratings reflected genuine user engagement with a system that participants found both easy to use and potentially beneficial, supporting the interpretation that personalisation contributed meaningfully to the overall usability experience.

Adherence represents another critical indicator of usability, as systems that are difficult to use typically exhibit poor engagement rates (Sieverink et al. 2017). Adherence can be defined as the extent to which users engage with and complete prescribed activities within a digital health intervention, often measured through completion rates and sustained usage patterns (Kelders et al. 2012). In the current study, exercise logging adherence achieved a rate of 63%, while PROMs submission adherence reached 76%. The interpretation of these adherence rates must be considered within the context of existing digital health interventions for musculoskeletal conditions.

Joseph et al. (2023) evaluated a 12-week web-based aerobic exercise programme involving 25 participants with knee OA and 4 with hip OA, which included information pages, weekly-updated exercise programmes, and motivational emails. They reported that 15 participants (51.7%) used the website consistently throughout the 12 weeks and considered this rate to be high, justifying their interpretation by noting its comparability to other research in the field. Importantly, the authors highlighted that there is no universally accepted benchmark for adherence in digital health interventions, emphasising that adherence rates should be evaluated based on their comparability with existing literature rather than against absolute standards. Within this context, the current study's adherence rates of 63% and 76% for exercise logging and PROMs submission respectively can be considered favourable when compared to similar digital interventions for OA populations.

Further, the research by Sieverink et al. (2017) demonstratesd that log data analysis can provide continuous and objective insights into the actual usage of different components of eHealth technology by users. The authors emphasise that

understanding how users interact with intervention components can inform improvements to engagement. In the context of the current study, the biomechanical-based personalisation may have contributed to the observed adherence rates through mechanisms identified in the thematic analysis. Participants expressed that understanding the connection between their gait analysis results and prescribed exercises enhanced their engagement with the intervention, as they could see the evidence-based rationale for their specific exercise programme. Furthermore, studies examining exercise-based digital interventions have found that participants who perceive exercises as specifically targeted to their needs demonstrate better programme adherence compared to those receiving generic content (Davergne et al. 2023). The current study's approach of using personalised exercise programmes may have strengthened this perception of relevance and appropriateness, potentially contributing to the sustained engagement reflected in the adherence rates for both exercise logging and PROMs submission requirements.

This interconnected chain of personalisation leading to enhanced SUS scores and subsequently improved adherence rates demonstrates the high usability of the DBBT. The personalisation feature created a foundation of effectiveness, efficiency, and user satisfaction that manifested in the excellent SUS score of 84.6, which in turn supported sustained user engagement reflected in the adherence rates of 63% for exercise logging and 76% for PROMs submission. This sequential relationship illustrates how the biomechanical-based personalisation approach not only improved immediate user experience but also facilitated engagement with the intervention, ultimately establishing the DBBT as a highly usable digital health solution for individuals with CKP.

7.6.2. The objective biomechanical biofeedback and visual gait report

In the current study, the visual biomechanical biofeedback was provided to participants through their personalised gait report, including waveform and numerical data, comparisons between affected and non-affected sides, and indications of movement asymmetries.

The DBBT's excellent SUS score of 84.6 can be attributed to the objective biomechanical biofeedback and visual gait report features (Brooke 1996; Bangor et al. 2009). This feature directly enhanced the core SUS dimensions: effectiveness

was strengthened because participants could clearly visualise their movement patterns and understand their functional limitations through objective data; efficiency was improved as participants could quickly grasp complex biomechanical information through visual representations rather than requiring lengthy explanations; and user satisfaction increased because participants felt empowered with concrete, evidence-based information about their condition. This theoretical foundation could help explaining the excellent SUS score achieved in the current study, as participants recognised that the DBBT provided them with unprecedented access to objective data about their own movement patterns.

When examining the broader literature on digital health interventions for CKP, the relationship between objective biofeedback provision and usability becomes particularly clearer. Weber et al. (2024) assessed a mobile application among 32 individuals with OA (20 knee, 9 hip, 3 both), providing generic exercise programmes through video demonstrations and standardised scheduling, achieving a SUS score of 71.3. However, their intervention notably lacked features that provided participants with direct feedback on performance or progress, representing a limitation in user engagement.

Similarly, Shewchuk et al. (2021) reported a considerably lower SUS score of 57.8 for their self-management mobile application tested with 18 knee OA patients. Participants specifically criticised this intervention for failing to provide meaningful feedback on their condition or progress, with users expressing desire for real-time or personalised responses about their health status. In contrast, Biebl et al. (2021) evaluated a mobile application that used camera technology to analyse movement and provide real-time audiovisual feedback during exercise performance, demonstrating successful guidance of participants toward correct technique. Although they did not report SUS scores, participants responded positively to receiving immediate feedback about their movement quality. However, studies evaluating feedback provision through PROMs alone have shown mixed results.

Pila et al. (2023) assessed the acceptability of digital decision-support reports among OA patients, which generated feedback based solely on PROMs data for surgical planning discussions. While participants generally appreciated receiving feedback on their health, they expressed strong desire for reports that included clearer

explanations and, critically, wanted to understand how their condition affected their function and movement - information that was missing due to the report's reliance solely on PROMs. Similarly, Stern et al. (2022) evaluated digital reports based only on self-reported data for surgical decision-making among patients with musculoskeletal conditions, finding that while participants valued receiving health status information, the absence of objective clinical or biomechanical insights limited the reports' perceived credibility and usefulness. These comparative findings suggest that the provision of comprehensive objective biomechanical biofeedback, rather than limited real-time feedback or feedback based solely on PROMs, may be a critical determinant of usability outcomes, with the current study's detailed visual gait reports potentially explaining the substantially higher SUS score achieved compared to interventions offering limited or subjective-only feedback capabilities.

More, from our participants reflections, key details that support the usability findings were revealed. Participants consistently expressed that receiving their visual gait reports made the system feel credible and scientifically grounded. Many individuals described how seeing their own movement data represented in waveforms and numerical formats enhanced their trust in the system and increased their confidence in using the technology. Participants noted that the visual comparisons between affected and non-affected sides helped them understand their condition more clearly, which made the overall system easier to navigate and use effectively. The objective nature of the biofeedback reduced participants' uncertainty about their condition and treatment, contributing to a smoother user. The visual representation of movement asymmetries also helped participants better understand the rationale behind their prescribed exercises, making the system feel more coherent and user-friendly.

The SUS findings are further supported by the supplementary kinematic, spatiotemporal, and PROMs data. Kinematic analysis revealed group-level improvements in joint function, including enhanced sagittal knee ROM on the affected side (approximately 1.8° improvement) and increased stance-phase ROM (around 2.1° improvement). These descriptive changes indicate that participants were successfully engaging with the visual biofeedback and translating the objective information into functional improvements through their exercise programmes. Similarly, spatiotemporal parameters showed group-level improvements in gait characteristics, including increased step length on both affected and non-affected

sides, suggesting that the visual feedback helped participants understand and address their movement limitations. The PROMs data further illustrated the group-level outcomes associated with receiving objective biofeedback, with reductions in pain scores (NPRS decreased by 8.09 points) and functional disability (WOMAC decreased by 6.73 points), alongside slight improvements in self-efficacy. These descriptive group-level improvements suggest that the high usability ratings reflected genuine user engagement with objective information that participants found both understandable and actionable, supporting the interpretation that visual biofeedback contributed meaningfully to the overall usability experience.

Regarding adherence, the current study achieved rates of 63% for exercise logging and 76% for PROMs submission. Research by Sieverink et al. (2017) demonstrates that log data analysis can provide continuous and objective insights into the actual usage of different components of eHealth technology by individual users. The relationship between biofeedback provision and adherence is particularly evident when comparing different approaches to feedback delivery. Yamamoto et al. (2022) recruited 20 individuals with knee OA and utilised a mobile application that provided real-time visual biofeedback during unsupervised home exercise sessions. Their app displayed exercise videos at the top of the screen while allowing participants to observe themselves performing exercises through the front-facing camera at the bottom, providing immediate visual feedback on movement execution. The researchers attributed significant improvements in pain and stiffness to exceptionally high adherence rates (mean 82.4%), suggesting that providing participants with real-time visual feedback enhanced their motivation to consistently engage with the intervention. However, their feedback mechanism was limited to visual self-observation during exercise performance and did not include comprehensive biomechanical analysis or detailed movement data interpretation.

In the context of the current study, the provision of objective biomechanical biofeedback through visual gait reports may have contributed to the observed adherence rates through mechanisms identified in the thematic analysis. Participants expressed that receiving concrete, visual evidence of their movement patterns and limitations enhanced their motivation to engage with the intervention, as they could see objective proof of their condition rather than relying solely on subjective symptom reports. Furthermore, studies examining feedback mechanisms in digital

health interventions have found that providing users with objective data about their performance or condition can enhance engagement and adherence (Saleem et al. 2021). The current study's approach of delivering comprehensive visual biofeedback through gait reports may have strengthened participants' understanding of their condition and the importance of following their prescribed exercise programmes, potentially contributing to the sustained engagement reflected in the adherence rates for both exercise logging and PROMs submission requirements.

This interconnected chain of objective biofeedback provision leading to enhanced SUS scores and subsequently improved adherence rates demonstrates the high usability of the DBBT. The visual gait report feature created a foundation of effectiveness, efficiency, and user satisfaction that manifested in the excellent SUS score of 84.6, which in turn supported sustained user engagement reflected in the adherence rates of 63% for exercise logging and 76% for PROMs submission. This sequential relationship illustrates how the provision of objective biomechanical biofeedback not only improved immediate user experience through enhanced understanding and trust but also facilitated long-term engagement with the intervention, ultimately establishing the DBBT as a highly usable digital health solution for individuals with CKP.

7.6.3. Digital biomechanical biofeedback toolkit’s video demonstration feature

The video demonstration feature was delivered to our participants through the Kinduct Athlete mobile app, presenting each personalised exercise with a clear visual guide. Participants accessed these videos after receiving their tailored exercise programme and were expected to complete them independently at home.

The DBBT's excellent SUS score of 84.6 could be attributed to the video demonstration feature (Bangor et al. 2009). This feature directly enhanced the core SUS dimensions: effectiveness was strengthened because participants could correctly perform their prescribed exercises through clear visual guidance; efficiency was improved as video demonstrations provided immediate access to proper exercise techniques without requiring additional support; and user satisfaction increased because participants felt confident about performing exercises correctly without requiring additional supervision. This link between the core SUS components and the video demonstration feature could facilitate the explanation of the excellent

SUS score in the current study, as participants recognised that the DBBT provided them with comprehensive guidance for independent exercise completion.

When examining the broader literature on digital health interventions for CKP, the relationship between video demonstrations and usability could particularly become evident, with personalisation emerging as a critical differentiating factor. Weber et al. (2024) assessed a mobile application among 32 individuals with OA (20 knee, 9 hip, 3 both), providing generic exercise and physical activity education programmes through video demonstrations and standardised scheduling, achieving a SUS score of 71.3, which represents acceptable but not excellent usability. Crucially, their intervention included video content, but these were generic demonstrations not tailored to individual needs or conditions, potentially limiting their effectiveness in addressing specific patient requirements. This limitation becomes more apparent when considering Godziuk et al. (2023), who evaluated a web-based digital intervention among 102 patients with knee OA, with 53 participants taking part in semi-structured interviews to explore their experiences. Although the intervention included exercise videos with instructional guidance and participants expressed positive views toward the platform, particularly regarding the exercise video content, a frequently reported drawback was the lack of exercise personalisation. Participants specifically noted that the exercise content was too generic and not tailored to their specific needs, highlighting how the absence of personalised video demonstrations can undermine user satisfaction despite the presence of visual guidance.

Further, our participants voice consistently expressed that having access to video demonstrations made the system feel comprehensive and supportive for independent exercise completion. Many individuals described how seeing visual demonstrations of their specific exercises enhanced their confidence in performing movements correctly without supervision. Participants noted that the video guidance reduced uncertainty about proper exercise technique and helped them feel more secure about completing exercises at home. The visual nature of the demonstrations was particularly valued by participants who found written or static image instructions insufficient for understanding complex movements. The availability of video content also contributed to participants' sense that the system was professional and well-designed, enhancing their overall trust in the technology and willingness to engage with the prescribed programme.

Regarding adherence, a critical usability indicator reflecting sustained user engagement (Sieverink et al. 2017 and Kelders et al. 2012), the current study achieved rates of 63% for exercise logging and 76% for PROMs submission. The relationship between video demonstrations and adherence is particularly evident when examining studies that have evaluated different approaches to exercise guidance. Gell et al. (2024) conducted a qualitative study to explore the views of 18 physiotherapists and 17 individuals with knee OA regarding the use of mobile applications for home exercise. Participants interacted with three commercial exercise apps featuring home-based programmes, exercise tracking tools, reminder systems, instructional videos, and pre-loaded exercise libraries. Through interviews, participants consistently highlighted that having access to video demonstrations improved their sense of accountability and motivation to complete exercises correctly.

However, participants noted that the generic nature of available videos limited their effectiveness, expressing desire for more personalised video content that addressed their specific conditions and limitations. In the context of the current study, the provision of personalised video demonstrations may have contributed to the observed adherence rates through mechanisms identified in the thematic analysis. Participants expressed that having access to clear visual guidance for their specific exercises enhanced their confidence in performing movements correctly and independently, reducing barriers to consistent exercise completion. The personalised nature of the video content, tailored to each participant's prescribed exercise programme, may have strengthened their understanding of proper technique and increased their motivation to maintain regular exercise completion. The current study's approach of delivering personalised video demonstrations through the mobile application may have reduced participants' uncertainty about exercise performance and enhanced their self-efficacy, potentially contributing to the sustained engagement reflected in the adherence rates for both exercise logging and PROMs submission requirements.

The SUS findings are further supported by the supplementary kinematic, spatiotemporal, and PROMs data. Knee joint kinematic analysis revealed group-level improvements including enhanced maximum knee flexion during swing phase with an increase of 2.04° on the affected side, which could be attributed to improved

movement confidence and exercise technique following video-guided instruction. Knee ROM during stance phase showed an improvement of 2.14° on the affected side, potentially indicating better functional movement patterns that could be achieved through proper exercise execution guided by video demonstrations. These descriptive changes indicate that participants were successfully following video demonstrations and performing exercises with sufficient accuracy to achieve functional benefits in knee mobility.

While Thiengwittayaporn et al. (2023) demonstrated that exercise instructions alone can contribute to improved ROM outcomes, the current study's addition of personalised video demonstrations may have enhanced participants' ability to execute exercises with greater precision and confidence, potentially explaining the observed kinematic improvements. Similarly, ankle joint parameters showed group-level improvements in frontal plane maximum angles during stance phase with an increase of 1.41° on the affected side, suggesting enhanced movement control, and ankle ROM during the gait cycle improved by 0.87° on the affected side, indicating more efficient movement patterns. The depression scores (PHQ-9) demonstrated a meaningful reduction of 1.10 points, which could be attributed to increased confidence and self-efficacy gained through clear video-guided exercise instruction, alongside improvements in functional disability with WOMAC scores decreasing by 6.73 points, potentially reflecting enhanced functional capacity achieved through proper exercise technique. These descriptive group-level improvements suggest that the high usability ratings reflected genuine user engagement with video content that participants found both clear and actionable, supporting the interpretation that video demonstrations contributed meaningfully to the overall usability experience

In conclusion, the video demonstration feature created a foundation of effectiveness, efficiency, and user satisfaction that manifested in the excellent SUS score of 84.6, which in turn supported sustained user engagement reflected in the adherence rates of 63% for exercise logging and 76% for PROMs submission. This sequential relationship illustrates how personalised video demonstrations not only improved immediate user experience through enhanced understanding and confidence but also facilitated engagement with the intervention, ultimately establishing the DBBT as a highly usable digital health solution for individuals with CKP.

7.6.4. Digital biomechanical biofeedback toolkit's reminding system feature

In the current study, reminders were automatically triggered to prompt users to complete and log their prescribed exercises and submit PROMs via the Kinduct Athlete mobile app. The DBBT's excellent SUS score of 84.6 can be attributed to the reminder system feature (Brooke 1996; Bangor et al. 2009). This feature directly enhanced the core SUS dimensions: effectiveness was strengthened because reminders helped participants maintain consistent engagement with their prescribed routines; efficiency was improved as automated prompts helped participants maintain their exercise schedules without additional effort; and user satisfaction increased because participants felt supported and guided throughout their rehabilitation journey. This foundation could assist in explaining the excellent SUS score achieved in the current study, as participants recognised that the DBBT actively supported their engagement rather than leaving them to manage their programme independently.

Looking at the broader literature on digital health interventions for CKP, the relationship between reminder systems and usability becomes can be explored. Pelle et al. (2021) conducted an exploratory study within a larger randomised controlled trial involving 214 participants with knee OA, evaluating a mobile application that included self-monitoring, goal-setting, and reminder systems. Among the 113 active users who completed goal activities, the mean SUS score was 69.2, suggesting above-average usability (Bangor et al. 2009). The authors specifically noted that the reminder feature was effective in promoting engagement with the digital intervention, highlighting its importance for sustained user interaction. Similarly, Nelligan et al. (2021) evaluated a web-based strengthening exercise programme with behavioural text reminders among 206 knee OA patients using a randomised controlled trial design.

In addition, the intervention group received access to a website with OA information and a self-guided exercise programme, whilst the control group received information only. The study demonstrated that engagement declined from 97% in the first month to 61% in the final month over 24 weeks, but the authors specifically highlighted the value of reminder text messages in maintaining engagement throughout the intervention period. In contrast, studies without reminder systems have shown poorer usability outcomes. Shewchuk et al. (2021) reported a considerably lower SUS score

of 57.8 for their self-management mobile application tested with 18 knee OA patients. Interviews revealed several limitations, including the absence of reminders as one gap that contributed to lower user satisfaction and engagement. These comparative findings suggest that the inclusion of automated reminder systems may be a critical determinant of usability outcomes, along with other features. In the current study, comprehensive reminder functionality potentially helped explaining the higher SUS score achieved compared to interventions lacking such supportive features.

From the current study's interviews, participants consistently expressed that receiving automated reminders made the system feel supportive and helped them maintain consistent engagement with their exercise programmes. Many individuals described how the reminders helped them establish routines and maintain accountability, making the system easier to integrate into their daily lives. Participants noted that the automated nature of the reminders was particularly appreciated, as they felt supported without feeling overwhelmed or pressured. The reminder system also helped participants feel more confident about following their prescribed exercises, contributing to an overall positive user experience.

The SUS findings are further supported by the supplementary kinematic, spatiotemporal, and PROMs data, which were measured descriptively at group level and are not intended to demonstrate clinical significance. Hip ROM during the gait cycle showed a decrease of 0.25° on the affected side, potentially indicating more controlled and efficient hip movement patterns with reduced excessive compensation. Such descriptive changes could indicate that participants were successfully responding to reminders and maintaining consistent engagement with exercises targeting hip mobility.

Similarly, spatiotemporal parameters showed group-level improvements, with cadence reducing by 3.38 steps per minute, suggesting more controlled and deliberate movement patterns, as the stride length–cadence relationship is related to energy expenditure optimisation and involves interactions between the basal ganglia and supplementary motor area for optimal efficiency (Egerton et al. 2011), while walking distance increased by 2.52 metres, indicating enhanced functional capacity, since walking speed is indicative of an individual's functional capacity and general

health status, with the measure being predictive of a range of outcomes including response to rehabilitation and functional dependence (Fritz and Lusardi 2009).

These changes align with evidence that muscle weakness leads to compensatory mechanisms whereby non-impaired muscle groups attempt to maintain normal walking patterns (Knarr et al. 2012). Moreover, the kinesiophobia scores (TSK) demonstrated a meaningful reduction of 3.65 points, which could be attributed to increased confidence through consistent reminder-supported exercise engagement, alongside improvements in self-efficacy scores of 0.12 points. These descriptive group-level improvements suggest that the high usability ratings reflected genuine user engagement with a supportive system that helped participants maintain consistent behaviour patterns, supporting the interpretation that the reminder system contributed meaningfully to the overall usability experience.

Regarding adherence, the current study achieved rates of 63% for exercise logging and 76% for PROMs submission. The relationship between reminder systems and adherence can be highlighted when examining comparative studies. Nelligan et al. (2021) specifically highlighted that reminder text messages were valuable for maintaining engagement in their web-based exercise programme, with the intervention group showing improvements compared to controls who received information only.

The authors noted that whilst engagement naturally declined over the 24-week period, the reminder system helped sustain participation longer than might have been achieved without such support. In the context of the current study, the automated reminder system may have contributed to the observed adherence rates, which is also supported through mechanisms identified in the thematic analysis. Participants expressed that receiving regular prompts helped them maintain consistency with their exercise routines and assessment submissions, reducing the likelihood of forgetting or postponing required activities. The reminder system effectively bridged the gap between clinical supervision and independent home-based exercise completion, providing ongoing support that participants might otherwise lack during unsupervised periods. The current study's approach of delivering automated, contextually appropriate reminders may have strengthened participants' routine maintenance and programme adherence, potentially contributing

to the sustained engagement reflected in the adherence rates for both exercise logging and PROMs submission requirements.

Overall, reminder system implementation could be an important feature that leads to enhanced SUS scores and subsequently improved adherence rates. The reminder feature created a foundation of effectiveness, efficiency, and user satisfaction that manifested in the excellent SUS score of 84.6, while supporting sustained user engagement reflected in adherence rates of 63% for exercise logging and 76% for PROMs submission. This sequential relationship illustrates how automated reminder systems not only improved immediate user experience but also facilitated adherence with the intervention, ultimately establishing the DBBT as a highly usable digital health solution for individuals with CKP.

7.6.5. Exercise logging and participant-reported outcome measures submission feature

Participants accessed the exercise logging and PROMs submission features through the Kinduct Athlete mobile application following receiving of their individualised exercise programmes. Upon completing home-based exercise programmes, participants could record and log their exercises within the mobile application. Concurrently, the system prompted users to complete and PROMs, encompassing WOMAC for assessing pain and functional status, TSK for evaluating movement-related fear, the SES6G, and NPRS.

The DBBT's excellent SUS score of 84.6 could be attributed to the exercise logging and PROMs submission feature (Brooke 1996 and Bangor et al. 2009). This feature enhanced the core SUS dimensions: effectiveness was strengthened because participants could systematically track their progress and provide meaningful feedback about their condition; efficiency was improved as the integrated logging system eliminated the need for separate tracking methods or additional appointments for outcome assessment; and user satisfaction increased because participants felt actively involved in monitoring their rehabilitation progress and communicating with their healthcare providers. This explanation in line to SUS main components could explain the final SUS score in the current study.

The most critical aspect of the exercise logging and PROMs submission feature lies in its relationship to adherence. The current study achieved adherence rates of 63%

for exercise logging and 76% for PROMs submission, which represent meaningful engagement levels that warrant examination within the broader literature context. Research by Sieverink et al. (2017) emphasises that log data analysis provides continuous and objective insights into actual usage patterns of eHealth technology components, noting that understanding user interaction with intervention features can inform engagement improvements.

The importance of integrated exercise logging features becomes evident when examining studies that specifically evaluated self-monitoring capabilities within digital health interventions. Shewchuk et al. (2021) reported a considerably lower SUS score of 57.8 for their self-management mobile application tested with 18 knee OA patients. Through interviews, participants revealed several critical limitations, including inadequate exercise tracking functionality that contributed to lower user satisfaction and engagement. This finding underscores the advantage of the current study's comprehensive exercise logging feature, which may have contributed to the substantially higher SUS score of 84.6 by addressing user needs for systematic activity tracking and progress monitoring.

A particularly distinctive aspect of the current study's DBBT is the integration of PROMs submission as an interactive feature within the mobile application, rather than using these measures solely as research outcome assessments. While many digital health intervention studies have utilised PROM measures such as WOMAC, TSK, and other validated instruments, these have typically been administered as external outcome measures for research purposes rather than as integrated self-monitoring tools. Studies by Nelligan et al. (2021), Pelle et al. (2021), Thiengwittayaporn et al. (2023), and Godziuk et al. (2023) all employed various PROMs as outcome measures, but these were administered separately from the intervention platforms for research data collection purposes. The current study's approach of embedding PROMs submission as an integral feature represents a significant advancement, transforming standardised clinical assessment tools into active self-monitoring capabilities that participants could use to engage with their treatment progress in real-time.

The differential adherence rates between exercise logging (63%) and PROMs submission (76%) provide important insights into the practical challenges

participants faced with different self-monitoring tasks. However, the thematic analysis revealed that lower exercise logging adherence was primarily due to external circumstances rather than the nature of the task itself. Participants cited practical barriers such as busy schedules, being away from home, unexpected circumstances like traffic delays, and illness as the main reasons for not logging their exercises. These findings indicate that the difference in adherence rates reflected real-world challenges of maintaining consistent self-monitoring behaviours rather than differences in task preference or meaningfulness.

This integration of PROMs as an interactive feature enhanced participants' sense of clinical engagement and self-efficacy. By regularly completing and submitting validated outcome assessments through the mobile application, participants gained ongoing insight into their symptom patterns, functional improvements, and psychological responses. The thematic analysis revealed that participants particularly valued the toolkit's comprehensive monitoring features, with many expressing satisfactions when completing their daily tasks and appreciating that the personalised approach made them feel their exercises were specifically targeted to their individual needs.

The SUS findings are further supported by supplementary kinematic, spatiotemporal, and PROMs data, which help explain the usability outcomes and adherence patterns observed. The successful completion of PROMs assessments at 76% adherence enabled meaningful outcome tracking, including kinesiophobia score reductions of 3.65 points (TSK), depression score improvements of 1.10 points (PHQ-9), and functional disability decreases of 6.73 points (WOMAC). The exercise logging adherence of 63% facilitated documentation of activity patterns that corresponded with observed kinematic improvements, including knee flexion increases of 2.04° and knee ROM enhancements of 2.14° on the affected side.

This interconnected relationship between exercise logging, integrated PROMs submission, and adherence patterns demonstrates the critical role of comprehensive self-monitoring in establishing the DBBT's high usability. The innovative integration of clinical assessment tools as interactive capabilities created a foundation of user engagement and clinical relevance that manifested in the excellent SUS score of 84.6, while sustained adherence rates reflected genuine user commitment to the

intervention. This approach not only improved immediate user experience through enhanced sense of progress and clinical connection but also facilitated long-term engagement, ultimately establishing the DBBT as a highly usable and clinically meaningful solution for individuals with CKP.

7.6.6. Conclusion

The usability evaluation of the DBBT demonstrates exceptional performance across multiple assessment dimensions, with the excellent SUS score of 84.6 reflecting genuine user satisfaction with a comprehensive digital health solution. The evaluation revealed that each core feature of the DBBT, personalisation, objective biomechanical biofeedback, video demonstrations, reminder systems, and exercise logging with integrated PROMs submission, contributed synergistically to the overall usability experience. The personalisation feature enhanced effectiveness, efficiency, and user satisfaction by delivering tailored content that addressed individual movement patterns and rehabilitation needs, distinguishing the DBBT from generic digital interventions that achieved lower usability scores in comparable populations. The objective biomechanical biofeedback through visual gait reports provided participants with unprecedented access to evidence-based information about their condition, fostering trust and understanding that enhanced their confidence in using the system. Video demonstrations offered clear, personalised guidance that enabled independent exercise completion, whilst automated reminder systems provided ongoing support that helped participants maintain consistent engagement with their rehabilitation programmes.

The adherence rates of 63% for exercise logging and 76% for PROMs submission, when considered within the context of existing digital health interventions for musculoskeletal conditions, represent meaningful engagement levels that reflect both the system's usability and participants' genuine commitment to the intervention. Importantly, the integration of PROMs submission as an interactive self-monitoring feature, rather than merely an external research assessment tool, represents a significant advancement in digital health intervention design that enhanced participants' sense of clinical engagement and progress tracking capabilities.

The supplementary kinematic, spatiotemporal, and PROMs data provide additional support for the usability findings, demonstrating that participants' positive

experiences with the DBBT translated into meaningful engagement with their rehabilitation programmes. The interconnected relationship between high usability scores, sustained adherence rates, and descriptive improvements in functional outcomes illustrates how thoughtfully designed digital health features can create a foundation for effective patient engagement and clinical relevance.

Collectively, these findings establish the DBBT as a highly usable digital health solution that successfully addresses the complex needs of individuals with CKP through comprehensive, personalised, and user-centred design principles. The exceptional usability outcomes achieved demonstrate the potential for biomechanical-based digital interventions to enhance rehabilitation delivery whilst maintaining high levels of user satisfaction and sustained engagement.

7.7. Discussion chapter conclusion.

This discussion chapter has demonstrated that the DBBT is both highly acceptable and usable for individuals with CKP. The 25 participants, representing a diverse demographic profile with mild-to-moderate symptom presentation, provided a clinically relevant sample that validated the toolkit's broad applicability across varied patient presentations.

The acceptability evaluation, mapped to the theoretical framework of acceptability, revealed consistently positive outcomes across its core constructs. Participants demonstrated positive affective attitudes, enhanced intervention coherence through clear biomechanical explanations, increased self-efficacy in independent system use, and strong perceived effectiveness of the personalised approach. These findings were supported by group-level improvements in kinematic parameters, spatiotemporal measures, and patient-reported outcomes.

The usability assessment demonstrated exceptional performance, with an excellent System Usability Scale score of 84.6 and meaningful adherence rates of 63% for exercise logging and 76% for patient-reported outcome measures submission. These outcomes substantially exceeded comparable digital health interventions reported in the literature.

Central to both acceptability and usability was the synergistic integration of five core DBBT features: personalisation through biomechanical gait analysis, objective

biofeedback via visual gait reports, personalised video demonstrations, automated reminder systems, and integrated exercise logging with patient-reported outcome measures submission. Each feature contributed distinctively to the overall user experience, creating a comprehensive digital health solution that addressed key limitations in existing interventions.

The findings establish the DBBT as a significant advancement in digital health technology for CKP management, successfully bridging the gap between clinical assessment and home-based rehabilitation through evidence-based, personalised intervention delivery. The high acceptability and usability outcomes provide a strong foundation for future clinical implementation and broader adoption of biomechanical-based digital health interventions in musculoskeletal care.

Chapter 8

Conclusion

8.1 Main conclusion

This thesis aimed to evaluate the acceptability and usability of a digital biomechanical biofeedback toolkit (DBBT) for the physiotherapy management of individuals with chronic knee pain. Through a mixed-methods design that combined qualitative and quantitative approaches, the study explored how individuals engaged with the DBBT in a real-world context, and what features contributed to its overall relevance in community-based rehabilitation.

The findings demonstrated that the DBBT was highly acceptable and usable. Thematic analysis of participant reflections, structured using the theoretical framework of acceptability (TFA), revealed strong alignment with key components such as affective attitude, perceived effectiveness, and intervention coherence. These positive perceptions were shaped by the DBBT's features, particularly personalisation, visual biomechanical biofeedback gait report, reminding system, video demonstrations, and exercise logging and PROMs submission features. Usability was also high, as indicated by a system usability scale (SUS) score of 81.2 and strong adherence rates for both exercise logging (63%) and PROMs submission (72%).

Supplementary data, including joint kinematics, spatiotemporal parameters, and validated PROMs, provided contextual support for these findings. Participants' movement patterns and self-reported outcomes were broadly consistent with similar clinical populations, reinforcing the relevance of the intervention. These objective measures did not serve as direct clinical indicators of change but offered valuable insight into how the toolkit supported participants' understanding of their physical function and pain.

This research contributes to the growing field of technology-enhanced rehabilitation by demonstrating how wearable sensor-based biofeedback can be meaningfully integrated into digital platforms to support personalised physiotherapy. The DBBT addressed several limitations commonly associated with existing digital health

interventions, particularly the lack of personalisation, objective feedback, and real-world engagement. Moreover, the study offers a model for how acceptability and usability can be systematically evaluated using established frameworks and mixed-methods analysis.

Overall, this thesis provides foundational evidence that a DBBT can be both acceptable and usable for individuals with CKP. It highlights the potential for combining objective biomechanical assessment with accessible digital delivery to enhance engagement, personalisation, and self-management in musculoskeletal rehabilitation.

8.2. Primary research question

“Is a digital biomechanical biofeedback toolkit (DBBT) acceptable and usable to individuals with chronic knee pain?”

8.3. Key findings

Acceptability: Participants, for the thematic analysis, demonstrated strong positive attitudes toward the toolkit, perceiving it as technologically innovative and personally relevant. The low perceived burden, combined with high ethical alignment with participants' values, indicates that the DBBT fits well within users' health management approaches. Participants showed excellent understanding of how the toolkit works and expressed enthusiasm for its future implementation in healthcare settings. The perceived effectiveness was particularly notable, with participants reporting tangible benefits including increased knee strength, improved confidence, and reduced pain levels.

Usability: The combination of high SUS scores, adherence rates (63% for exercise logging, 76% for PROMs completion), and positive user feedback indicates that the DBBT successfully balances functionality with ease of use. The user-friendly mobile application design and intuitive interface contributed significantly to the positive usability experience.

8.4. Thesis strengths

Methodological rigor

The study employed a robust mixed-methods design grounded in established theoretical frameworks. The systematic application of the TFA provided comprehensive insight into multiple dimensions of acceptability, while the pragmatic philosophical approach enabled effective integration of quantitative and qualitative data sources.

Use of validated instruments to support robustness and credibility

The research utilised multiple validated instruments including the SUS for usability, established PROMs for clinical outcomes, and validated wearable sensor technology for objective biomechanical assessment. This multi-faceted approach provided triangulation of findings and enhanced the credibility of conclusions.

Real-world implementation

This research implemented the DBBT in participants' home environments over a two-week period. This approach strengthens the applicability of findings to real-world clinical practice.

Theoretical foundation

The systematic use of the TFA ensured that acceptability was comprehensively evaluated across cognitive, emotional, and behavioural dimensions. This theoretical grounding provides a strong foundation for interpreting findings and planning future research.

Technology integration

The successful integration of advanced wearable sensor technology (Xsens MVN), automated gait analysis (MotionCloud), and mobile health platforms (Kinduct) demonstrates the practicality and potential for implementing sophisticated biomechanical biofeedback systems in community settings.

8.5. Limitations

limitations of this study concern the risk of bias embedded within its design. Potential sources include reliance on participant self-reported data, which may not consistently reflect actual behaviour or experience, and the active involvement of the researcher in data collection, which may have influenced how information was obtained or interpreted. The professional background of the researcher as a physiotherapist may also have introduced expectancy bias, with a tendency to anticipate or value positive outcomes from the DBBT. This possibility was further reinforced by prior formal training in the system's use, whereas participants did not receive equivalent training. Such differences in expertise may have shaped perceptions of usability and effectiveness and influenced the way outputs were communicated. Additionally, the lack of clinician input into the developed version of the toolkit represents a limitation, as perspectives from other healthcare professionals were not incorporated during the design and development phase. Collectively, these factors highlight the potential influence of bias and the need for further research that incorporates independent validation and broader stakeholder involvement.

The sample size of 25 participants was suitable for an in-depth evaluation of user experience. Convenience sampling was used, welcoming individuals who were both available and willing to participate during the study period. However, the opportunity to recruit a larger sample was constrained by the limited timeframe of a doctoral research project. Despite this, the sample's clinical and demographic characteristics, including pain intensity, functional status, and movement patterns, closely reflected those commonly reported in the literature for individuals with CKP. This strengthens the transferability of the findings to similar clinical populations in physiotherapy contexts.

Further, the study included individuals with CKP without restricting to a single pathology, such as OA or patellofemoral pain syndrome. Although this reduces diagnostic specificity, it reflects the heterogeneous nature of real-world clinical presentations and enhances the transferability of the findings. This inclusivity may support wider applicability of the DBBT across chronic musculoskeletal conditions. Additionally, the piloting stage was not completed with individuals living with CKP, which meant that opportunities to identify and address any population-specific

considerations regarding usability, technical aspects, or acceptability prior to the main data collection phase were limited.

The intervention period was limited to two weeks, which was appropriate for assessing initial acceptability and usability. However, this duration may not capture long-term engagement, sustain behaviour change, or evolve user experiences over time. Future studies should consider extended follow-up to examine continued use and adherence beyond the early implementation phase. Also, the toolkit was not evaluated within a routine clinical environment or service pathway, which may limit ecological validity and understanding of real-world implementation factors (e.g., workflow integration, time, staffing, governance). This limitation is partially mitigated by the toolkit's intended use in home settings; however, pragmatic evaluation across clinic-to-home pathways remains necessary to establish clinical relevance and scalability. In addition, the success of the intervention is contingent upon expert interpretation of kinematic outputs. While physiotherapists typically have foundational knowledge of kinematics as part of their professional education, specific training on interpreting the outputs from this system would be required to ensure data are translated into clinical decision-making. Such training was provided to the researcher (M.S.) who is delivering the intervention in this study and would need to be incorporated into implementation protocols for future clinical use.

Further, while kinematic assessment tools have become more accessible, the acquisition and interpretation of kinematic data still require technical knowledge (e.g., calibration procedures and data processing). Providing standardised training protocols would facilitate broader clinical adoption and ensure consistent data quality across users. Also, exercise descriptions currently use medical terminology that may not be readily understood by patients. Terminology should be adapted to lay language to optimise accessibility and engagement. Although the Xsens MVN system has been validated in previous research (Al-Amri et al. 2018; Kobsar et al. 2020), this study did not independently assess the reliability of sensor placement procedures applied to the specific participants in this cohort. Future work could include a focused reliability check to further ensure accuracy in individual cases, particularly when applied to clinical populations.

Moreover, while small angular changes could theoretically be influenced by measurement error in some systems, the Xsens MVN system uses validated inertial sensors rather than optical markers, minimising such errors. Nevertheless, caution should be applied when interpreting very small kinematic changes observed in this study, as their clinical relevance remains to be fully established. Future research with larger sample sizes and longer follow-up periods could further investigate the clinical significance and functional impact of such changes.

Lastly, technical challenges were also noted. The DBBT's reliance on internet connectivity for processing gait data through MotionCloud resulted in few processing delays or temporary interruptions. Additionally, gait reports could not be generated for two participants due to technical failures. While these issues were infrequent, they underscore the importance of optimising system performance and ensuring technological robustness for real-world deployment.

8.6. Recommendations

For future research

The positive acceptability and usability findings support progression to a larger-scale feasibility study comparing the DBBT with standard care or other digital interventions to explore its implementation potential and prepare for future effectiveness trials Recent evidence demonstrates that web-based exercise interventions can improve adherence and outcomes in musculoskeletal conditions, supporting the potential for technology-enhanced approaches (Bennell et al. 2019).

Extended follow-up studies

Research with longer intervention periods (3-6 months) and extended follow-up (12+ months) is needed to assess sustained engagement, behaviour change, and long-term clinical outcomes. Systematic reviews emphasise the importance of longer-term follow-up to assess sustained adherence to exercise interventions in musculoskeletal conditions (Holden et al. 2014).

For technology development

Improved gait reporting: Implementation of participant recommendations such as simplified technical language and merged before/after comparisons into one report would facilitate the future use of the DBBT.

For clinical practice

Professional training: Development of training programmes for physiotherapists in biomechanical biofeedback interpretation and technology-enhanced exercise prescription. Professional development in healthcare technology requires structured approaches to ensure competency and confidence in new tools and techniques.

Implementation guidelines: Creation of clinical practice guidelines for incorporating biomechanical biofeedback into standard physiotherapy workflows. Evidence-based guideline development requires systematic methodology and stakeholder engagement to ensure practical implementation.

8.7. Clinical implications

For physiotherapy practice

Enhanced assessment capabilities: The DBBT provides physiotherapists with objective, quantifiable data on patient movement patterns that can supplement traditional clinical assessment methods. This biomechanical information can inform more targeted exercise prescription and enable more precise monitoring of progress.

Improved patient education: Biomechanical biofeedback offers a powerful educational tool, enabling physiotherapists to show patients exactly how their movement patterns contribute to symptoms and how exercises can address specific impairments. This visual feedback can enhance patient understanding and motivation.

Remote monitoring: The toolkit enables physiotherapists to monitor patient progress and adherence between sessions, potentially improving the continuity of care and enabling more responsive treatment adjustments.

For patient self-management

Increased self-awareness: Participants reported enhanced understanding of their condition and movement patterns, potentially supporting more effective self-management strategies and adherence to exercise programmes.

Objective progress tracking: The ability to track objective improvements in movement quality alongside symptom changes may provide additional motivation for sustained engagement with rehabilitation.

Personalised exercise experience: The data-driven approach to exercise prescription may improve the relevance and effectiveness of home exercise programmes compared to generic prescriptions.

For healthcare services

Efficiency gains: Technology-enhanced physiotherapy may enable more efficient use of healthcare resources by supporting effective home-based rehabilitation with reduced need for frequent in-person appointments.

Standardisation: Biomechanical biofeedback tools could contribute to more standardised assessment and treatment approaches across different practitioners and settings.

Quality improvement: Objective movement data could support quality improvement initiatives and enable more evidence-based evaluation of physiotherapy interventions.

8.8. Final reflection

This research represents an important step toward integrating objective biomechanical assessment and biofeedback into routine physiotherapy practice for CKP management. The overwhelmingly positive acceptability and usability findings provide confidence that technology-enhanced physiotherapy approaches can be successfully implemented in community settings.

The study has demonstrated that individuals with CKP are ready and willing to engage with digital health tools when they provide clear value and are designed with user needs in mind. The combination of objective assessment, personalised feedback and exercise programmes, and convenient mobile access addresses many of the limitations identified in current digital health interventions for musculoskeletal conditions.

However, the journey from acceptability and usability evaluation to routine clinical implementation requires continued research, particularly around long-term effectiveness, cost-effectiveness, and optimal integration into existing healthcare systems. The foundation established by this research provides a roadmap for future development and evaluation efforts.

Ultimately, this PhD project contributes to the growing evidence base supporting technology-enhanced physiotherapy and provides a practical example of how advanced biomechanical assessment can be made accessible and acceptable to patients in community settings. As healthcare systems continue to evolve toward more personalised, data-driven approaches, tools like the DBBT may play an increasingly important role in optimising outcomes for individuals with chronic musculoskeletal conditions.

The positive reception of biomechanical biofeedback by participants suggests a readiness for innovation in physiotherapy practice. With continued development and evaluation, such tools have the potential to transform how we assess, treat, and monitor individuals with CKP, ultimately leading to more effective, efficient, and engaging rehabilitation experiences. Lastly, the current PhD project process is summarised in the following timeline to facilitate identifying the process taken including project development, ethical approval, data collection, and the end of the study.

Figure 19 PhD timeline

Chapter 9

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Appendices

Appendix (1) Critical Appraisal Skills Programme Checklists

CASP Checklist:

For Qualitative Research

Section A Are the results valid?	
1. Was there a clear statement of the aims of the research?	☐Yes ☐ No ☐ Can't Tell

CONSIDER: • what was the goal of the research? • why was it thought important? • its relevance	
2. Is a qualitative methodology appropriate?	☐Yes ☐ No ☐ Can't Tell
CONSIDER: • If the research seeks to interpret or illuminate the actions and/or subjective experiences of research participants • Is qualitative research the right methodology for addressing the research goal?	
3. Was the research design appropriate to address the aims of the research?	☐Yes ☐ No ☐ Can't Tell

CONSIDER: • if the researcher has justified the research design (e.g., have they discussed how they decided which method to use)	
4. Was the recruitment strategy appropriate to the aims of the research?	☐Yes ☐ No ☐ Can't Tell
CONSIDER: • If the researcher has explained how the participants were selected • If they explained why the participants they selected were the most appropriate to provide access to the type of knowledge sought by the study • If there are any discussions around recruitment (e.g. why some people chose not to take part)	
5. Was the data collected in a way that addressed the research issue?	☐Yes ☐ No ☐ Can't Tell

CONSIDER: • If the setting for the data collection was justified • If it is clear how data were collected (e.g. focus group, semi-structured interview etc.) • If the researcher has justified the methods chosen • If the researcher has made the methods explicit (e.g. for interview method, is there an indication of how interviews are conducted, or did they use a topic guide) • If methods were modified during the study. If so, has the researcher explained how and why • If the form of data is clear (e.g. tape recordings, video material, notes etc.) • If the researcher has discussed saturation of data	
6. Has the relationship between researcher and participants been adequately considered?	☐Yes ☐ No ☐ Can't Tell
CONSIDER: • If the researcher critically examined their own role, potential bias and influence during (a) formulation of the research questions (b) data collection, including sample recruitment and choice of location • How the researcher responded to events during the study and whether they considered the implications of any changes in the research design	
Section B: What are the results?	

7. Have ethical issues been taken into consideration?	☐Yes ☐ No ☐ Can't Tell
CONSIDER: • If there are sufficient details of how the research was explained to participants for the reader to assess whether ethical standards were maintained • If the researcher has discussed issues raised by the study (e.g. issues around informed consent or confidentiality or how they have handled the effects of the study on the participants during and after the study) • If approval has been sought from the ethics committee	
8. Was the data analysis sufficiently rigorous?	☐Yes ☐ No ☐ Can't Tell
CONSIDER: • If there is an in-depth description of the analysis process • If thematic analysis is used. If so, is it clear how the categories/themes were derived from the data • Whether the researcher explains how the data presented were selected from the original sample to demonstrate the analysis process	

• If sufficient data are presented to support the findings • To what extent contradictory data are taken into account • Whether the researcher critically examined their own role, potential bias and influence during analysis and selection of data for presentation	
9. Is there a clear statement of findings?	☐Yes ☐ No ☐ Can't Tell
CONSIDER: • If the findings are explicit • If there is adequate discussion of the evidence both for and against the researcher's arguments • If the researcher has discussed the credibility of their findings (e.g. triangulation, respondent validation, more than one analyst) • If the findings are discussed in relation to the original research question	
Section C: Will the results help locally?	
10. How valuable is the research?	☐Yes ☐ No ☐ Can't Tell
CONSIDER: • If the researcher discusses the contribution the study makes to existing	

knowledge or understanding (e.g., do they consider the findings in relation to current practice or policy, or relevant research-based literature

- If they identify new areas where research is necessary
- If the researchers have discussed whether or how the findings can be transferred to other populations or considered other ways the research may be used

APPRAISAL SUMMARY: List key points from your critical appraisal that need to be considered when assessing the validity of the results and their usefulness in decision-making.		
Positive/Methodologically sound	Negative/Relatively poor methodology	Unknowns

Critical Appraisal Skills Programme

CASP Checklist:

Section A: Is the basic study design valid for a systematic review?	
1. Did the systematic review address a clearly formulated research question?	☐ Yes ☐ No ☐ Can't Tell
CONSIDER: Did the researchers state a research question and a null hypothesis? For a systematic review of RCTs, a research question can be 'formulated' in terms of the PICOT(S) framework: • Population • Intervention • Comparator • Outcome/s and Outcome measures	

• Time, e.g., study timeframe, or follow-up intervals • Setting	
2. Did the researchers search for appropriate study design(s) to answer the research question?	☐Yes ☐ No ☐ Can't Tell
CONSIDER: If the research question is concerned with the efficacy of an intervention, the RCT is the appropriate study design for a systematic review. The most common type of RCT is the parallel RCT in which individuals are randomised to study groups; other methods of randomisation, however, could be relevant depending on the research question.	
Notes to support interpretation of Section A, Questions 1 and 2: If you answered "No" to both these questions: • It is likely that the researchers did not clearly formulate the fundamental aspects of the research question, and the most appropriate way of answering it. If this is the case, it is likely other problems will arise during the conduct of the systematic review • Consider whether it would be useful to continue with the critical appraisal process	
Section B: Is the systematic review methodologically sound?	
3. Were all the relevant primary	☐Yes ☐ No ☐ Can't Tell

research studies likely to have been included in the systematic review? a) Searching for primary research studies	
CONSIDER: • Was the search strategy comprehensive and clearly reported? • Did the search include 1 or more of the major bibliographic databases, e.g., MEDLINE/PubMed, and Embase? • Did the researchers provide MESH terms for MEDLINE, or their equivalent for other databases? • Were relevant subject-specific bibliographic databases searched? • Did the search include non-English language studies? • Did the researchers undertake citation searching, including hand-searching of reference lists from primary research studies included in the systematic review? • Did the search include unpublished studies? For instance, did the search include registers of ongoing trials or preprint repositories? • Did the researchers consult experts in the field about potential primary research studies or ongoing trials that could be included?	
b) Screening primary research studies from the search	☐Yes ☐ No ☐ Can't Tell

CONSIDER: • Did the researchers define appropriate eligibility or inclusion and exclusion criteria? • Did the researchers design and implement a robust process to screen the primary research studies? For instance, two researchers working independently with a third independent researcher to resolve any disagreements. • Was screening based on the title and abstract of primary research studies found during the search? • Did the researchers adhere to the eligibility criteria?	
c) Selecting primary research studies to include in the systematic review	☐Yes ☐ No ☐ Can't Tell
CONSIDER: • Did the researchers design and implement a robust process to select the primary research studies according to the eligibility criteria? For instance, two researchers working independently with a third independent researcher to resolve any disagreements. • Were decisions to include or exclude primary research studies based on full-text analysis? • Did the researchers adhere to the eligibility criteria? • Was the level of agreement between the researchers responsible for selecting the primary research studies calculated and reported? For instance, by calculating the kappa statistic of inter-rate reliability.	
d) Summarising the search and its outputs	☐Yes ☐ No ☐ Can't Tell

CONSIDER: Did the researchers present a PRISMA-type flow diagram, including the numbers of primary research studies that were: • Duplicates? • Screened out? • Excluded, with the reasons for exclusion? • Included in the systematic review? • Included in the meta-analysis (data may not have been complete in some of the primary research studies)?	
4. Did the researchers assess the validity or methodological rigour of the primary research studies included in the systematic review?	☐Yes ☐ No ☐ Can't Tell
CONSIDER: Lack of methodological rigour in the individual primary research studies can affect the validity and interpretation of the findings of the systematic review with meta-analysis. • Did the researchers use a validated tool to assess the methodological rigour of the primary research studies included in the systematic review? • Was the tool appropriate to assess the type(s) of study design(s) included in the systematic review? For example, the Cochrane Risk of Bias tool specifically for RCTs or the McMaster EPHPP tool for any quantitative study design, including RCTs.	

• Did the researchers present the findings from their quality assessment, and interpret them accurately?	
5. Did the researchers extract, and present information from the individual primary research studies appropriately and transparently? (a) Extraction of data	☐Yes ☐ No ☐ Can't Tell
CONSIDER: • Did the researchers design and implement a robust process for the extraction of data from the individual primary research studies? • Did the researchers follow guidance on data extraction? • Did the researchers use a standardised form or software programme to record the data to ensure completeness and accuracy? • Did the researchers extract the relevant data for the study-level characteristics and the results of each primary research study?	
(b) Presentation of data	☐Yes ☐ No ☐ Can't Tell
CONSIDER: • Did the researchers present the key characteristics of the individual primary research studies, e.g., in a table? For instance, the number of participants, the profile of participants (age, sex), the intervention, the comparator, the outcome/s	

evaluated, and the study timeframe.

- Did the researchers present the results of the individual primary research studies in a Forest plot or combination of table and Forest plot? For instance, the effect size/s, the confidence-interval ranges, and the P values. NB: The Forest plot should also show the overall result from the meta-analysis.

Notes to support the interpretation of Section B, Questions 3-5:

If you answered "No" to these questions, it is likely that there is a lack of methodological rigour in the conduct of the systematic review, which means it is best to interpret the results with caution, and to assess how those aspects of poor methodology will have an impact on the results of the systematic review.

- For Question 3, a "No" response indicates that this systematic review may have missed primary research studies that could have contributed to answering the research question; in a systematic review with meta-analysis, the results of any missing primary research studies could have altered the effect estimate for the systematic review.
- For Question 4, a "No" response indicates that the researchers did not identify any systematic bias or confounding factors in the primary research studies that could have affected the results of the systematic review; in the absence of this information, it is not possible for you to assess in what ways the results of the systematic review could have been affected, and it is best to be cautious when interpreting the results.
- For Question 5, a "No" response indicates that the researchers did not organise the data from the primary research studies in a coherent way such that it could analysed appropriately, and thereby reliable conclusions drawn from it.

If you answered "No" to all three questions in Section B, consider whether it would be useful to continue with the critical appraisal process.

Section C: Are the results of the systematic review trustworthy?

6. Did the researchers analyse the pooled results of the individual primary research studies	☐Yes ☐ No ☐ Can't Tell

appropriately?	

CONSIDER:

- Did the researchers undertake a power calculation and sample-size estimation during the design and planning of the systematic review?
- Did the number of participants whose outcomes were entered into the analysis meet the power calculation, i.e., was the meta-analysis sufficiently powered to detect any effect on the outcomes of interest?
- Did the researchers use an appropriate effect measure?
- Did the researchers provide confidence-interval ranges for the effect estimates in the systematic review?
- Did the researchers provide p values for the effect estimates in the systematic review?
- Did the researchers provide a minimal important difference, that is the smallest possible difference that a person would perceive as a beneficial effect of intervention?
- Did the researchers assess the level of statistical heterogeneity (variability) among the primary research studies? For example, using the I^2 statistic.
- Did the researchers use an appropriate model of meta-analysis for the level of heterogeneity among the primary research studies (a random-effects model if there was heterogeneity or a fixed-effects model if the primary research studies were all investigating the same underlying effect)?
- Did the researchers perform any sensitivity analyses?
- Did the researchers analyse the reasons for heterogeneity using subgroup analysis or meta-regression? For subgroup analysis, see Question 6.1, and for meta-regression see Question 6.2.
- Did the researchers investigate the small-study effect, and assess the potential

for publication bias in the systematic review (e.g., using a funnel plot)?	
6.1 Subgroup analysis	☐Yes ☐ No ☐ Can't Tell
CONSIDER: Were the characteristics or effect modifiers for investigation: • Specified in the study protocol, with the direction of effect, and statistical tests to be used? • Clearly defined, with a rationale for selection? • Not closely related to other characteristics, i.e., differentiation is possible? • Analysed in relation to the primary outcome? If continuous data were allocated to categories, were the thresholds or cut-off points specified in the study protocol together with a rationale? If a large number of characteristics or effect modifiers were investigated, or subgroup analyses conducted, did the researchers adjust for multiple testing? Was a test for interaction undertaken to determine whether any subgroup effects were statistically significant? Was the analysis of effect modification based on comparison within rather than between studies?	
6.2 Meta-regression	☐Yes ☐ No ☐ Can't Tell

CONSIDER:

Were the characteristics or effect modifiers for investigation:

- Specified in the study protocol, with the direction of effect?
- Continuous data? If continuous data were allocated to categories, were the thresholds or cut-off points specified in the study protocol with a rationale for selection?

If a large number of characteristics or effect modifiers were investigated, or meta-regression analyses performed, did the researchers adjust for multiple testing?

Was a test for interaction undertaken to determine whether any effects were statistically significant?

Was a random-effects model used for the meta-regression analyses?

Was the analysis of effect modification based on comparison within rather than between studies?

7. Did the researchers report any limitations of the systematic review and, if so, do the limitations discussed cover all the issues you identified during critical appraisal?	☐Yes ☐ No ☐ Can't Tell

CONSIDER:

- Did the researchers discuss whether the meta-analysis was sufficiently powered to detect an effect of intervention?
- Did the researchers consider the appropriateness of the effect measure or measures they used?
- Did the researchers reflect on the precision of the effect estimate, i.e., the confidence-interval range? The smaller the range, the narrower the confidence intervals, meaning the result is more precise, and closer to the true effect size.
- If relevant, did the researchers note whether the confidence-interval range

included the “line of no effect” (0 for a difference, 1 for a ratio, where the null hypothesis holds true), or whether the lower limit of the confidence-interval range was close to the “line of no effect”, and discuss the implications for the results of the meta-analysis? • If the results were statistically significant (i.e., they were less likely to be due to chance), did the researchers discuss whether the results would be important or meaningful for the outcomes experienced by individuals and/or populations using a minimal important difference specific to the research question? Did the researchers consider whether relevant primary research studies could have been missed? • Did the researchers mention any systematic bias identified during the risk-of-bias/quality assessment of the primary research studies, and explain how it might have influenced the effect estimate in the meta-analysis? • Did the researchers mention any potential sources of confounding that could have influenced the effect estimate in the meta-analysis? • Did the researchers discuss the implications of any sensitivity analyses? • Did the researchers discuss the impact of the level of heterogeneity on the results of the meta-analysis? • Did the researchers investigate the reasons for any heterogeneity across the primary research studies and discuss the implications? For subgroup analysis, see Question 7.1, and for meta-regression, see Question 7.2. • Did the researchers discuss the effect of any publication bias on the results of the meta-analysis?	
7.1 Subgroup-analysis	☐Yes ☐ No ☐ Can’t Tell
CONSIDER:	

• If characteristics or effect modifiers were not pre-specified, did the researchers address whether bias was introduced into the analysis? • Did the researchers reflect on whether the characteristics or effect modifiers selected were well-defined to ensure clarity about the effect being investigated? • If no rationale was given for the selection of specific characteristics or effect modifiers, or the rationale was not supported by evidence or a plausible argument of meaningfulness, did the researchers discuss whether this affected the validity or relevance of the subgroup analysis? • If characteristics or effect modifiers were closely related to other characteristics, did the researchers mention the potential for confounding? • Did the researchers outline whether the subgroup analyses were sufficiently powered to detect an effect on the primary outcome? • If continuous data were allocated to categories, did the researchers address whether the thresholds or cut-off points could have introduced bias into the subgroup analysis or were not meaningful either clinically or in terms of public or population health? If more than three characteristics or effect modifiers were investigated, or subgroup analyses performed, did the researchers adjust for multiple testing and consider the potential to generate Type I errors? • Did the researchers explain the results of any tests for interaction and whether they were statistically significant? • Did the researchers discuss the implications of whether the results of tests for interaction were quantitative or qualitative? • If the analysis of effect modification was based on a comparison between studies, did the researchers reflect on whether the number of studies in the smallest subgroups was large enough for the results to be credible?	
7.2 Meta-regression	☐Yes ☐ No ☐ Can't Tell

CONSIDER: • If characteristics or effect modifiers were not pre-specified, did the researchers address whether bias was introduced into the analysis? • If continuous data were allocated into categories, did the researchers address whether any thresholds or cut-off points for categorisation were arbitrary and could have introduced bias into the meta-regression or were not meaningful clinically or in terms of public or population health? • If more than three characteristics or effect modifiers were investigated, or meta-regression analyses performed, did the researchers adjust for multiple testing and consider the potential to generate Type I errors? • Did the researchers discuss the implications of any tests for interaction and whether they were statistically significant? • If a random-effects model was not used to account for residual heterogeneity and/or mixed effects, which would have allowed for both within-study and between-study variation, did the researchers outline the implications for the results? • If the analysis of effect modification was based on a between-study comparison, did the researchers reflect on whether the number of primary research studies in the meta-regression was sufficient for the results to be credible?	
8. Would the benefits of intervention outweigh any potential disadvantages, harms and/or additional demand for resources associated with acting on the results?	☐Yes ☐ No ☐ Can't Tell

CONSIDER:

- Are you clear about the likely benefits of the intervention, bearing in mind the potential impacts of any study limitations?
- Did the researchers identify any potential disadvantages or harms associated with the intervention?
- If so, did the researchers assess any benefits of the intervention against the disadvantages or harms, and discuss the overall balance between benefit and harm?
- Did the researchers report any information on the potential demand for resources (e.g. cost, workforce, time, skills level/skills mix, training needs, data collection and analysis, IT requirements) that might be associated with acting on the results of the systematic review?

- Notes to support interpretation of Section C, Questions 6, 7 & 8: If you answered “No” to these questions, it is likely that the researchers did not analyse and interpret the information from the primary research studies appropriately, nor did they discuss the limitations of the systematic review as fully as possible so it is not possible for you to assess the trustworthiness (validity and credibility) of the results of the systematic review. Finally, if there is no information on the likely resource demands of intervention, it is not possible for you to judge whether you have the resource capacity to act upon the results.

If you answered “No” to all three questions in Section C, consider whether it would be useful to continue with the critical appraisal process.

Section D: Are the results of the systematic review relevant locally?

9. Can the results of the systematic review be applied to your local population/in your local setting or context?	☐Yes ☐ No ☐ Can’t Tell

CONSIDER: • Are there differences between your local population and the participants in the primary research studies in the systematic review that would influence whether you would act upon the results? • Are there differences between your local setting and the settings or contexts in the primary research studies in the systematic review that would influence whether you would act upon the results? • Are there any outcomes or other factors that the researchers could have studied that would have been useful to you bearing in mind the needs of your local population and/or setting?	
Notes to support interpretation of Section D, Question 9: • If you answered “No” to this question, it is not necessary to answer Question 10 because, irrespective of a systematic review’s methodological rigour, the results are not applicable to the individuals or populations for whom you are responsible. • If you answered “Yes” to Question 9, answer Question 10	
Section E: Will the implementation of the results represent greater value for your service users or population?	
10. If actioned, would the findings from the systematic review represent greater or additional value for the individuals or populations for whom you are responsible?	☐Yes ☐ No ☐ Can’t Tell

CONSIDER:

Value equals the Outcome/s (Benefit minus Harm) divided by the Resources required for implementation.

- What resources would be needed to take action on the findings of the systematic review? Take account of various types of resource, not only costs, but also time, skills mix, skills development or training needs, IT requirements, and other material resources.
- If necessary, are you able to disinvest resources from other activities to be able to re-invest in actioning the findings from the systematic review?

Notes to support interpretation of Section E, Question 10:

- If you answered “No” to this question, it is likely that the findings of the systematic review will not confer greater or additional benefit or value on the individuals and/or populations for whom you are responsible, despite the systematic review’s applicability to your local setting.
- If you answered “Yes” it is likely that the findings of the systematic review will confer greater or additional benefit or value on the individuals and/or populations for whom you are responsible, and you need to discuss with colleagues whether it would be appropriate to implement the findings in your local setting.

What is your conclusion about the systematic review – can it be used to support evidence-based decision-making?	☐Yes ☐ No ☐ Can’t Tell

CONSIDER:
• Would you use it to change practice or to recommend changes to care policy and procedures in your organisation? • Could you judiciously implement the intervention without delay?

CASP General SR Checklist: Collation of critical appraisal responses

Yes	Checklist question	Can't tell	No
	A. Is the basic study design valid for a systematic review?		
	1. Did the systematic review address a clearly formulated research question?		
	2. Did the researchers search for appropriate study designs to answer the research question?		
	B. Is the systematic review methodologically sound?		
	3. Were all relevant primary research studies likely to have been included in the systematic review?		
	4. Did the researchers assess the validity or methodological rigour of the primary research studies included in the systematic review?		
	5. Did the researchers extract, and present information on the individual primary research studies appropriately and transparently?		
	C. Are the results of the systematic review trustworthy?		
	6. Did the researchers analyse the pooled results of the individual primary research studies appropriately?		
	7. Did the researchers report any limitations of the systematic review and, if so, do the limitations discussed cover all the issues in your critical appraisal?		
	8. Would the benefits of intervention outweigh any potential		

	disadvantages, harms and/or additional demand for resources associated with acting on the results?		

D. Are the results of the systematic review relevant locally?

	9. Can the results of the systematic review be applied to your local population/in your local setting or context?		

E. Will the implementation of the results represent greater value for your service users or population?

	10. If actioned, would the findings from the systematic review represent greater or additional value for the individuals or populations for whom you are responsible?		

APPRAISAL SUMMARY: List key points from your critical appraisal that need to be considered when assessing the validity of the results and their usefulness in decision-making.		
Positive/Methodologically sound	Negative/Relatively poor methodology	Unknowns

CASP Checklist:

Section A Is the basic study design valid for a randomised controlled trial?	
11. Did the study address a clearly formulated research question?	☐Yes ☐ No ☐ Can't Tell
CONSIDER: Was the study designed to assess the outcomes of an intervention? Is the research question 'formulated' in terms of: • Population studied • Intervention given • Comparator chosen • Outcomes measured?	
12. Was the assignment of participants to interventions randomised?	☐Yes ☐ No ☐ Can't Tell

CONSIDER: • How was randomisation carried out? Was the method appropriate? • Was randomisation sufficient to eliminate systematic bias? • Was the allocation sequence concealed from investigators and participants?	
13. Were all participants who entered the study accounted for at its conclusion?	☐Yes ☐ No ☐ Can't Tell
CONSIDER: • Were losses to follow-up and exclusions after randomisation accounted for? • Were participants analysed in the study groups to which they were randomised (intention-to-treat analysis)? • Was the study stopped early? If so, what was the reason?	
Section B Was the study methodologically sound?	
14. (a) Were the participants 'blind' to intervention they were given?	☐Yes ☐ No ☐ Can't Tell
(b) Were the investigators 'blind' to	☐Yes ☐ No ☐ Can't Tell

the intervention they were giving to participants?	
(c) Were the people assessing/analysing outcome/s 'blinded'?	☐Yes ☐ No ☐ Can't Tell
15. Were the study groups similar at the start of the randomised controlled trial?	☐Yes ☐ No ☐ Can't Tell
CONSIDER: • Were the baseline characteristics of each study group (e.g. age, sex, socio-economic group) clearly set out? • Were there any differences between the study groups that could affect the outcome/s?	
16. Apart from the experimental intervention, did each study group	☐Yes ☐ No ☐ Can't Tell

receive the same level of care (that is, were they treated equally)?	
CONSIDER: • Was there a clearly defined study protocol? • If any additional interventions were given (e.g. tests or treatments), were they similar between the study groups? • Were the follow-up intervals the same for each study group?	
Section C: What are the results?	
17. Were the effects of intervention reported comprehensively?	☐Yes ☐ No ☐ Can't Tell
CONSIDER: • Was a power calculation undertaken? • What outcomes were measured, and were they clearly specified? • How were the results expressed? For binary outcomes, were relative and absolute effects reported? • Were the results reported for each outcome in each study group at each	

follow-up interval? • Was there any missing or incomplete data? • Was there differential drop-out between the study groups that could affect the results? • Were potential sources of bias identified? • Which statistical tests were used? • Were p values reported?	
18. Was the precision of the estimate of the intervention or treatment effect reported?	☐Yes ☐ No ☐ Can't Tell
CONSIDER: • Were confidence intervals (CIs) reported?	
19. Do the benefits of the experimental intervention outweigh the harms and costs?	☐Yes ☐ No ☐ Can't Tell

CONSIDER: • What was the size of the intervention or treatment effect? • Were harms or unintended effects reported for each study group? • Was a cost-effectiveness analysis undertaken? (Cost-effectiveness analysis allows a comparison to be made between different interventions used in the care of the same condition or problem.)	
Section D: Will the results help locally?	
20. Can the results be applied to your local population/in your context?	☐Yes ☐ No ☐ Can't Tell
CONSIDER: • Are the study participants similar to the people in your care? • Would any differences between your population and the study participants alter the outcomes reported in the study? • Are the outcomes important to your population? • Are there any outcomes you would have wanted information on that have not been studied or reported? • Are there any limitations of the study that would affect your decision?	
21. Would the experimental intervention provide greater value to the people in your care than any of the existing interventions?	☐Yes ☐ No ☐ Can't Tell

CONSIDER: • What resources are needed to introduce this intervention taking into account time, finances, and skills development or training needs? • Are you able to disinvest resources in one or more existing interventions in order to be able to re-invest in the new intervention?	

APPRAISAL SUMMARY: List key points from your critical appraisal that need to be considered when assessing the validity of the results and their usefulness in decision-making.		
Positive/Methodologically sound	Negative/Relatively poor methodology	Unknowns

Appendix (2) Literature Searching Strategy

Several databases were utilised to identify the relevant research articles exploring the impact of CKP and biomechanical biofeedback on biomechanical with digital health interventions, the table below highlights the keywords used in this search. The research engines used were as follows, Medline, Ovid Emcare, CINAHL, Cochrane library, Scopus, and Web of Science. The searched keywords were important to focus the search on the desired topic.

Osteoarthritis	Biomechanics	Feedback	Self-management	Digital health	Exercise	Pain assessment
OR	OR	OR	OR	OR	OR	OR
Knee osteoarthritis	Biomechanical	Biofeedback	Self-monitoring	Digital intervention	Exercise prescription	Pain evaluation
OR	OR	OR	OR	OR	OR	OR
Knee OA	Gait analysis	Haptic	Self-monitoring	e-health	Exercise program	Pain outcomes
OR	OR	OR	OR	OR	OR	OR
Degenerative knee	Kinematic	Visual		Telehealth		
OR	OR	OR		OR		
Degeneration of the knee	Kinematics	auditory		Tele Rahab		
OR				OR		
Arthritis	Joint angles			telerehabilitation		
OR	OR					
Knee pain	Joint range of motion					
	OR					
	ROM					

The search using this strategy was not successful and did not reveal the desired articles. Thus, the researcher (M.S) utilised another strategy in which there were two searching processes that took place. The first search was conducted to identify the impact of CKP on gait biomechanical parameters. The second search was conducted to identify the use of digital health with CKP population. The keywords for the first and the second search are highlighted below,

Search 1

The aim of this search was to identify studies that utilised digital health interventions for individuals with CKP conditions. The search was restricted to studies that were

open access, published in English, and included experimental studies, review articles, and qualitative research articles.

All search results were imported into Mendeley reference manager, where duplicate records were removed. The inclusion and exclusion criteria were applied to determine the relevant studies for the literature review. Studies were included if they:

1. Assessed digital health interventions.
2. Included participants with CKP.
3. Evaluated acceptability and usability of digital health interventions.

Following this process, 18 studies (n = 18) were deemed appropriate for inclusion.

PICO Framework

- P (Population): Individuals with CKP conditions.
- I (Intervention): Digital health interventions, including telehealth, telerehabilitation, e-health, and digital interventions.
- C (Comparison): Studies comparing digital health interventions to traditional care, in-person rehabilitation, or no intervention.
- O (Outcome): Acceptability and usability of digital health interventions.

Search Terms and Synonyms

(digital health OR digital intervention OR e-health OR telehealth OR telerehabilitation)
AND
(CKP OR knee pain OR knee OA OR knee osteoarthritis OR degenerative knee OR arthritic knee OR arthritis)
AND
(acceptable OR acceptability OR usable OR usability)

Databases Searched

- PubMed
- Scopus

- Web of Science
- CINAHL (Cumulative Index to Nursing and Allied Health Literature)
- Ovid Emcare
- Cochrane library

Search 2

This search aimed to identify studies that highlighted the impact of CKP on gait. The search was limited to research that was open access, published in English, and included experimental studies, review articles, or other relevant studies related to gait analysis.

All search results were imported into Mendeley reference manager, where duplicate records were removed. The inclusion and exclusion criteria were set to identify relevant studies for inclusion in the literature review. The criteria were as follows:

1. Studies that included information on biomechanical variables.
2. Studies that clearly stated the analysis settings, including gait phase and analysis plane.
3. Studies that focused on the lower limb, particularly the knee joint.
4. Studies where the task being analysed was gait and was clearly reported.

After applying these criteria and removing irrelevant research and duplicates, 18 studies (n = 18) were selected for inclusion in the review.

PICO Framework

- P (Population): Individuals with CKP.
- I (Intervention): Studies that involve the impact of CKP on gait analysis.
- C (Comparison): Not explicitly defined but generally compares biomechanical parameters between individuals with CKP and healthy controls or other conditions.

- O (Outcome): Studies assessing biomechanical variables related to gait analysis, including kinematics, kinetics, spatiotemporal parameters, muscle activity, and force measurement.

Search Terms and Synonyms

(CKP OR knee pain OR knee OA OR knee osteoarthritis OR degenerative knee OR arthritic knee OR arthritis)
AND
(biomech* OR kinematics OR kinetics OR ST OR spatiotemporal OR muscle activity)
AND
(gait OR gait analysis OR movement analysis OR walking)
AND
(wearable sensors OR Xsens OR sensor technology OR worn sensors OR EMG OR electromyography OR kinetic OR ground reaction force)

Databases Searched

- PubMed
- Scopus
- Web of Science
- CINAHL (Cumulative Index to Nursing and Allied Health Literature)
- Ovid Emcare
- Cochrane library

Both literature findings were summarised and presented in Table (2.1) and Table (2.3) in chapter 2 “Integrated background and literature review”.

Appendix (3) Cochrane handbook guidance for qualitative research data extraction.

Example of qualitative data extraction template, Cochrane handbook guidance: Cochrane library: https://methods.cochrane.org/qi/supplemental-handbook-guidance.

Additional Box 1: Examples of items included in data extraction forms
1.1: Standard data extraction form (Munro et al. 2007)
1- Country 2- Aims of study 3- Ethics – how ethical issues were addressed 4- Study setting 5- Theoretical background of study 6- Sampling approach 7- Participant characteristics 8- Data collection methods 9- Data analysis approach 10- Key themes identified in the study (1st order interpretations) 11- Data extracts related to the key themes (I have to read the themes to pick the related information) 12- Author explanations of the key themes (2nd order interpretations) (Written before and within each theme {Authors own words}. 13- Recommendations made by authors (Can be found in the end of the study). 14- Assessment of study quality {Critical appraisal}.

Appendix (4) Quantitative data extraction template and the definitions

Variable	Definition
Authors	The researchers who conducted the study.
Year of Publication	The year that the study was published in.
Study Aims	The aim that researchers trying to achieve by conducting the study.
Study Location	The country that the study took place in.
Study Design	The design is referred to the strategy or the framework that authors chose to answer their research question and to explain the type of their research.
Functional Task	The task that is performed by participants who took place in the study.
Type of Wearable Technology	The type of worn technology attached to each participant to provide feedback.
Place of attachement of the sensor	
Sample Size	The number of participants in the study.
Population	Participants classified by their condition, or disease.
Participants	Participants classified by their gender (male/female).
Intervention description	The tested intervention used by researchers.
Comparator	The comparator factor used by researchers against the intervention.
Study Settings	Is where the study took place (laboratory, clinic, home, or free-living settings).
Site of OA	The location of Osteoarthritis (Ankle, Knee, or Hip).
Study Outcome Measures	The tool used by the researchers to measure their phenomenon of interest.

Principle Findings	The main results of the study.
Quality Assessment	The assessment of the study in which an identification of its limitation will be presented.

Appendix (5) Participants Information Sheet (PIS)

PARTICIPANT INFORMATION SHEET

Evaluation of the Acceptability and Usability of a Digital Biomechanical Biofeedback Toolkit for the Physiotherapy Management of CKP

You are being invited to take part in a research project. Before you decide whether or not to take part, it is important for you to understand why the research is being undertaken and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. You can also contact the researcher directly to discuss any point and /or have an explanation for any unclarity you find in this document,

Additionally, since you've received this document, you are encouraged to contact the researcher with your decision within 5 working days to facilitate the booking of your preferred time slot.

Thank you for reading this.

Researcher's contact information:

Mr. Mohammad Subahi
[redacted]

1. What is the purpose of this research project?

The purpose of this study is to test a physiotherapy treatment toolkit for adults diagnosed with general knee pain or pain due to osteoarthritis. This is a PhD project that investigates several aspects when using the toolkit. But first, let's know the toolkit components. This treatment toolkit includes a mobile application, a motion cloud system, and wearable sensors technology. These components will help us to understand the movement by generating reports that will be used as a feedback tool about your biomechanical aspects (e.g. your joint range of motion, and your walking speed, etc..) This, in turn, will help us to identify what are the best exercises that can be prescribed. In addition, the mobile app will include surveys about the level of pain you feel and the efforts you put. Those surveys will also be used as feedback that we can share. Lastly, the mobile app will provide you with your personalised exercise program and videos on how to perform the exercise from home.

2. Why have I been invited to take part?

You have been invited because you are a volunteer adult diagnosed with knee osteoarthritis, or having knee pain, physically active, feeling pain on your knees with physical activities on most days of the week, able to understand English, able to provide informed consent, willing to avoid commencing other intervention for knee pain during the duration of the trial, able to come for two visits to Cardiff University lab in the Heath Campus, willing to have a face-to-face interview, and interested in receiving specific physiotherapeutic exercises prescribed based on your needs. On the other hand, you are not eligible to take part in the study if you have musculoskeletal pain whereby the knee is not its main source, you have any contraindication to exercises (e.g. high risk of falling), have Pain caused by malignancy, fractures, or inflammatory arthritis, received a surgery on the knee in the last 12 months, commencing knee pain treatments like intra-articular injection in the last 12 weeks, have underwent a knee replacement surgery, and morning stiffness in the knee joint that lasts no longer than 30 minutes.

3. 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. If you decide to take part, we will discuss the research project with you [and 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. If you are a Cardiff University student or staff member, your involvement in this project will have no effect on your education or your job duties. In addition, you are free to withdraw your consent to participate in the research project at any time, without giving a reason, even after signing the consent form.

4. What will taking part involve?

The overall duration of this project is going to be 2 weeks. You will be required to attend the university lab only for two times (once on the first week, and another time for reassessment on the second week). On both lab visits the researcher will place wearable sensors on you, which require wearing shorts to facilitate the sensors placements on lower limbs. Lastly, you will be asked to perform functional tasks (e.g walking for 10 meters, sit to stand, etc…).

On the second visit, you will be reassessed by doing the same process of the first visit. Each visit will take up to 2 hours. Additionally, on the second visit, you will take part in an audio recorded interview with the researcher asking you about the acceptability of the toolkit (takes up to 15 minutes).

5. Will I be paid for taking part?

The participation in this study is completely voluntary (see section 3). Your travel or other costs associated with attending the university are your own responsibility. However, we will issue you £20 Amazon voucher upon completion of your participation.

6. What are the possible benefits of taking part?

One of the major aspects of this project is the assessment and prescribing physiotherapeutic exercises for adults diagnosed with knee osteoarthritis. Therefore, you will get benefits like being assessed and becoming more aware of your

condition, and you will have a physiotherapy exercise program that you will apply from home, which is highly likely to benefit your range of motion, muscle strength, pain levels, and your function and general fitness. Also, you will be introduced to one of the newest assessment, monitor, and treatment techniques, which is the use of wearable sensor technology and receiving of biofeedback about your own condition, which will make you more involved/engaged in the whole process of managing and treating your condition.

7. What are the possible risks of taking part?

Since you will be performing exercises and functional tasks, and wearable sensors will be placed on your body, there will be some minor risks that you might have. More specifically, you might have skin irritation from the wearable sensors, and dehydration and fatiguability for the task performance. However, you will be offered water, and rest intervals to make you feel more comfortable. Also, to avoid any itchiness, you will be asked to wear shorts or sportswear. Additionally, during the interview, you might feel distressed or uncomfortable, but you will be offered to have a break as you wish, drink water, and feel free to ask for any clarification or assistance. Furthermore, we remind you that you have the right to withdraw from the study without providing any explanation. In case of any concern, you can contact the researcher or the supervisors (contact details are at the end of this document).

8. Will my taking part in this research project be kept confidential?

All information collected from (or about) you during the research project will be kept 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.

9. What will happen to my Personal Data?

You will provide personal information like your name, date of birth, email address, but those personal information will only be used for research purposes. However, in our project we reassure you that your data will be anonymised and remain confidential according to Cardiff University Data Protection Act (2018). Your personal information will be kept in a passworded and encrypted database that only the researcher will have access to. While using your data, for instance, in the data analysis, your details will be changed into codes and numbers that only the researcher will identify who you are. The study data including your personal information will be stored for 5 years and then will be destroyed.

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. Also, the above mentioned information will be printed and provided for you once you decide to take part in this project. Moreover, in case the researcher decided to publish any part of this project, your information will also be anonymised, and the researcher will do his best to maintain your confidentiality.

10. What happens to the data at the end of the research project?

The data that will be collected during this project will be used as part of the researcher's PhD studies. Additionally, the data might be published in scientific research papers, conferences, or workshops. However, we, the researcher and his supervisors, reassure you that all of your personal data will not be used directly and in case it was used, it is going to be anonymised with codes and no one will be able

to identify you as an individual who participated and took part in the current research project.

11. What will happen to the results of the research project?

The results of the current study are likely to be published in scientific journals and conferences. If you wish to know the results of this project, you can simply speak to the researcher and show your interest in knowing the results, so he can assist you and contact with you regarding any results update (i.e. send you a link of a published paper that has the results). It is the researcher's intention to use verbatim quotes from you, gained form the interview, but we reassure you that if these quotes were used, they will be anonymised.

12. What if there is a problem?

Your complain will be respected and taken seriously because we trust that you, as a participant, are coming and expecting to be highly respected and valued.

If you wish to complain or have grounds for concerns about any aspect of the manner in which you have been approached or treated during the course of this research, please contact [Mohammad Subahi at Subahim1@cardiff.ac.uk]. If your complaint is not managed to your satisfaction, please contact [Dr Kate Button at buttonk@cardiff.ac.uk , or Dr Mohammed Alamri at al-amrim@cardiff.ac.uk]

If you are harmed by taking part in this research project, there are no special compensation arrangements. If you are harmed due to someone's negligence, you may have grounds for legal action, but you may have to pay for it.

13. Who is organising and funding this research project?

The research is organised by Mohammad Subahi, Dr. Kate Button, and Dr. Mohammad Al-Amri, and the school of healthcare sciences in Cardiff University.

14. Who has reviewed this research project?

This research project has been reviewed and given a favourable opinion by the school of healthcare sciences ethics committee at Cardiff University.

15. Further information and contact details

Should you have any questions/concern relating to this research project, you may contact us during normal working hours:

Mr. Mohmmad Subahi
School of healthcare sciences.
[redacted]

Dr. Kate Button
School of healthcare sciences
[redacted]

Dr. Mohammad Al-Amri
School of healthcare sciences
[redacted]

Room [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 (6) Standardised terminology and temple for interpretation of kinematic waveforms.

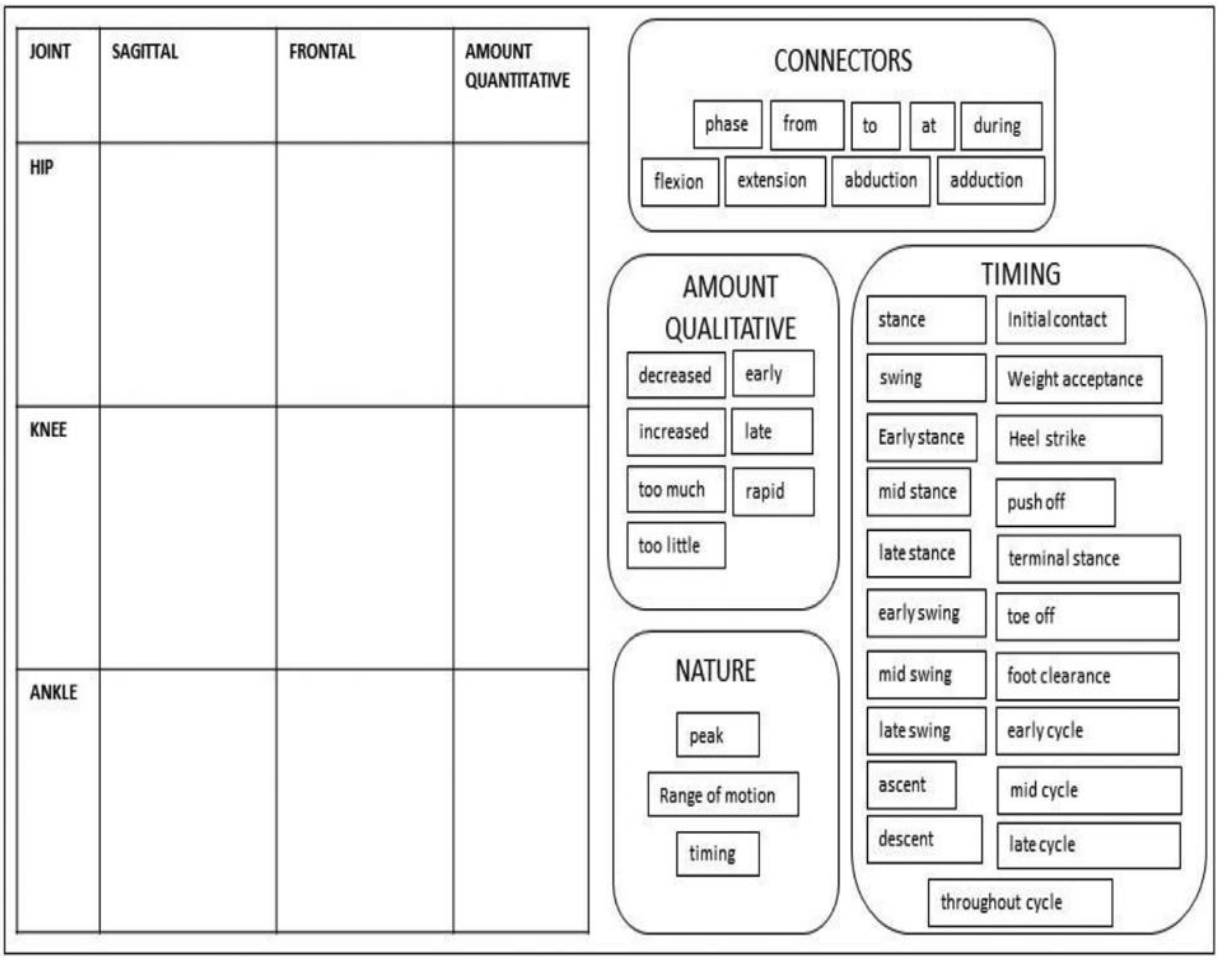


Fig. 3. Standardised terminology and temple for interpretation of kinematic waveforms.

Appendix (7) Interview Guide

Opening questions:

1. Can you tell me about exercises. Sports, or activities you do regularly?

· How long do you spend daily?

2. Can you tell me about your knee problem?

· How long have you had this problem?

· How does this affect your everyday life?

- "Intervention coherence: The extent to which the participant understands the intervention and how it works" (Sekhon et al., 2017)

Based on your understanding, can you tell me about how this toolkit and the provided biomechanical biofeedback incorporated into your physiotherapy plan of exercise prescription?

- "Affective attitude: How an individual feels about the Intervention" (Sekhon et al., 2017)

What was your impression when you were introduced to this toolkit and how do you feel about using this toolkit including the assessment using the wearable sensors, receiving the biomechanical biofeedback, and using the mobile application from home?

- "Burden: The perceived amount of effort that is required to participate in the intervention" (Sekhon et al., 2017)

How easy or difficult was it to use this purpose of this toolkit and the use of the mobile app?

- How the biomechanical biofeedback could be improved?
- How would you prefer the gait report to be presented to you?
- Have you experienced any challenges that need to take into account? (Any risk).
    - How these challenges could be encountered?

- "Perceived effectiveness: The extent to which the intervention is perceived as likely to achieve its purpose" (Sekhon et al., 2017) (modify)
    1. In your opinion, how toolkit and the biomechanical biofeedback report could assist with your physiotherapy care plan (Prompt: motivation, monitoring, personalising, targeting, engagement, etc)
        - Do you think the toolkit changed how you understand your movement and made the exercise more reliable? To what extent? How did it help? (i.e. personalised, tailored, objective)
    2. What do you think about using this technology in the future?

- "Self-efficacy: The participant's confidence that they can perform the behaviour(s) required to participate in the intervention" (Sekhon et al., 2017)

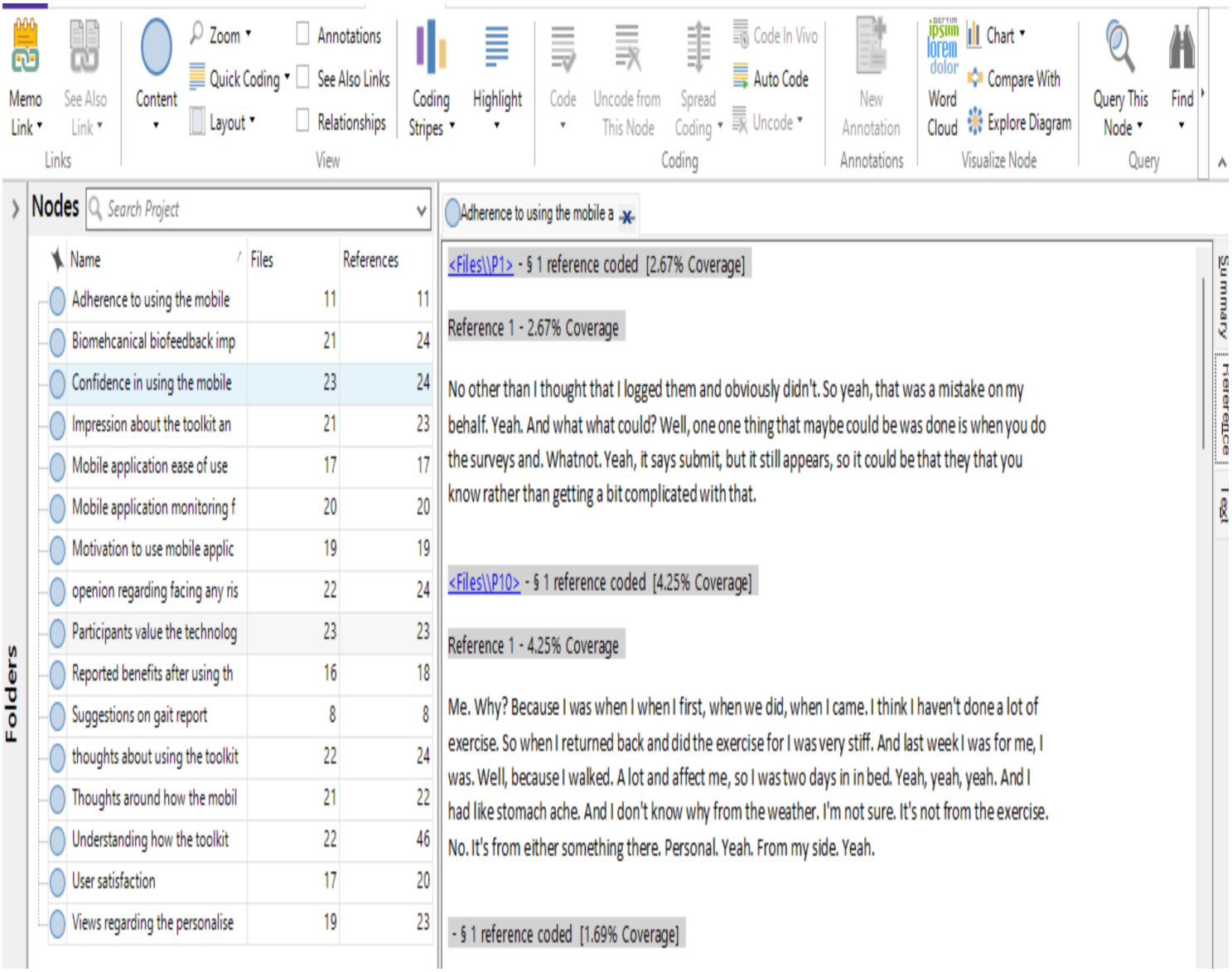
How confident you were when you started using the mobile app in terms of accessing the components, following the exercise program, answering the questionnaires questions, logging into the app?

- Closing questions
    3. What would be your take-home message from the experience of this toolkit?

    4. Is there anything you want to add concerning the toolkit, mobile app, report, or the data collection session?

    5. Why you haven't completed logging all of the exercises?

Appendix (8) Example / NVivo front page with created themes



Appendix (9) Interview transcript (Example)

Speaker 1

Thank you very much for taking part in this study. And I'll start the interview by asking you about what are your exercises and sports or activities that you do regularly.

Speaker 2

OK, so I I I can tell you about the exercises I I've done as part of. The programme you've yeah, yeah.

Speaker 1

No, no, no. Before before we start the programme, what are the exercises or the daily activities that you do?

Speaker 2

OK. Well, I'm. I'm. I'm I'm based at home, so I'm not working at the moment, but over the summer months I'm a I'm a sportsman so I I I play cricket weekly. So there's a lot to do in, in on on a Saturday in a competitive match, so so so I'm a bowler, so there's a need for me to perform for about an hour each game as as a bowler and and to field and to bat as well. I I try and walk as much as I can. UM and. That's probably. That's probably probably it. Yeah, from from the housework. I do gardening that I do. Yeah. Typical typical activities for someone my age. Really.

Speaker 1

And how long they spend daily in terms of spending time doing those activities?

Speaker 2

Garden gardening and housework is probably about maybe half an hour a day, and then when it comes to the sports activities, that's most of a Saturday afternoon, yeah.

Speaker 1

So in total does it reach to one hour, one hour and a half? Two hours of being active?

Speaker 2

Oh, half for it. I would say it's less than I would say that, say half an hour. That perhaps. Four to five hours a week, altogether, yeah.

Speaker 1

OK, OK. Can you tell me about your knee problem?

Speaker 2

OK I have. In general, pain in in in my left knee, it was particularly bad when I was playing sport, I wasn't able to run to, to feel the ball. It was difficult for me to to play matches. I bought absorbent insoles for for for my shoes in order to to lessen the effect of of pain and and and impact. When I was when I was when I was playing. Slowly that that also I had a supportive knee, a near pre knee strap which had supporting straps on it. Yeah which I used to wear when I was playing so I was able to play through, overcome some of the pain, take some of the strain off my knee when I was playing, yeah. By by wearing by wearing the knee strap and and and the shoe supports.

Speaker 1

And how long have you had this problem?

Speaker 2

I've had the problem about six months, yeah. So yeah.

Speaker 1

And was it was it decreasing by any chance or was fluctuating?

Speaker 2

It got it was at its worst in in in April and it's it's been. It's slowly. I've as I've sort of got got used to the pain and learned how to sort of play through it, sometimes the worst pain is at the beginning, and the more you play through it, the more you're you're used to living with the pain and and it actually does lessen. So I've I've learned over time to to, to continue and to not and not to avoid certain movements, because it's it's simply, is, is best just to to live to, to keep on exercising with it. I really believe in that.

Speaker 1

And how does this affect your everyday life? So away from your activities.

Speaker 2

Thankfully, thankfully not too bad. I do. I do. Sometimes need to drive my son to university in Yorkshire and so that's somebody obviously driving. I don't drive an automatic car, I drive a manual car. So there's a lot of work, clutch work on my, but I actually find that quite quite straightforward. I find that quite easy. It doesn't strain me too much and I think that's the only thing that I have to be slightly careful with. I also am a sportsman as well. I used to do a lot

of yoga. Yeah. And I found that I I simply couldn't do some of the exercises because of that I I can't kneel. For example, I can't kneel properly. So any any there are some things I can't quite do like I used to but but I mean most things I can do with a with an adapt adaptation sometimes if I need to get up and the knee is painful, I can hold onto a surface to to help myself move up. So I kind of found ways of living. We're working with it really.

Speaker 1

OK, perfect. So my next question is that based on your understanding, can you tell me about how the toolkit and the provided biomechanical biofeedback incorporated into the physiotherapy plan of exercise prescription?

Speaker 2

I I thought this was this was really informative because the what the the toolkit was able to show through the through the diagrams and the figures, it was telling me that my my stride length was uneven between my left or left side and my right so it showed that the flexion in my in my in my ankle was not as good on the left as it was on the right, and that some of the pain that I had been feeling in the leg has been more on on walking was was a combination of of of movement from the hip and the ankle together, although I was feeling the pain in the knee. So that that then led to prescription of of exercises to improve the abduction in the in the hip and the flexibility in the ankles. So being aware of that. But even before I was tested today I I knew that I was improving my flexion because when I was walking with better flexibility on my left side on my left heel and being aware of of of, of trying to to match how I was, how my heel strike was working between my left and my right. But I was able. I knew I was walking faster. I knew, and it was almost effortless. So even before the testing, I had a suspicion that that things were improving.

Speaker 1

Perfect. OK. What was your impression when you were introduced to this toolkit? How did you feel about using it and receiving of the biofeedback from the report and using the mobile application from home.

Speaker 2

I I thought it was it was really, really interesting. I I used to be a scientist. So. So I'm. I'm really interested in the mechanics of how certain things work, but but the the the exercise programme was it was really clear in the app, the, the, the videos in the were were were short and were well presented. So it was really clear. Sometimes I could look and see exactly where a foot was placed or a knee was placed so and how far to. That was all very

good. Uh also for example, if you've only do one of the three sets, just being able to press that to to to log the set to know that you did one. So it helped in the time management during the day, means I can't always do the session in one sitting, so being able to just know where I stopped after one or two sets yeah, it was, it was really interesting actually.

Speaker 1

OK, how easy or difficult was it to use this toolkit and the mobile app?

Speaker 2

I'd say it was mostly very easy the the only thing that I needed to be kept aware of is the is the updating. There's a a need to refresh, I sometimes I'd I'd looked at the app and it seemed that. The exercises I'd already done had turned up into the into the folder called missed. And I had to then go back, refresh the app and there was a little bit of a time period while it was doing that then the correct exercises came up for the day. Yeah. This cause a bit of confusing, so I initially I thought that some of my record had been lost but once I got used to that feature it was it was quite easy to work with really. I was understandable anyway.

Speaker 1

OK, so I'll ask you now about your thoughts, I shared with you the biomechanical biofeedback in the form of a report and you saw the report that has graphs and tables.

Speaker

Right.

Speaker 1

How could this be improved from your opinion?

Speaker 2

It seems absolutely fine. When I don't understand what the graphs mean and the physiotherapist interpreting them, so I'd know for sure. Uh I don't know what for example, the graph reach a maximum point, but I don't know what what is on the X axis on the Y axis so so all I can presume is that is that is that you're interested in in the shape and the value it reaches that. It seems it seems as because you were able to explain everything back in terms of what was happening. That's fine. That that, yeah, that's not really a problem, you know? Yeah.

Speaker 1

Ok, what if I sent you this for example the report and asked you to have a look by yourself? Would you be able to understand anything?

Speaker 2

I might be able to understand about half of it. I I think the stride length thing is really clear. Yeah. And. And given that how how they were, it was clear. That given that stride lengths were were almost identical left to right, that's me. Even as a layperson suggests that that's that's correct. You you would imagine that a perfectly balanced, uninjured person will walk with an equal stride length left to right, so that bit was really clear. Yeah. Other things about the angle of abduction. Or adduction, it's difficult to know what that means exactly.

Speaker 1

So you. Yeah. So you think that? There is a need for a physiotherapist to interpret that.

Speaker 2

Yeah, yeah.

Speaker 1

Or you have an idea that we can add some text to this report to make it look easier for you to read.

Speaker 2

That's possible. I mean it was if the abduction concept was harder to understand because I couldn't relate it to anything. I know it is something I'm doing but uh I I can't see however when it came to my heel strike and and the flexion in the in in the in the heel, that was something I I could understand because it was was a thing I can see I was doing. So it was. And that was, to me was more understandable because I I I kind of could control control that when I was walking anyway. In short, the abduction is a bit of an abstract idea. Yeah, for for someone who's not a a not physiologically trained or not a physiotherapist it could be unclear.

Speaker 1

So this leads to another question which is about how would you prefer this gate report to be presented to you? Yeah.

Speaker 2

That's interesting. Well, the diagram is always a good way of of expressing something, so I suppose and also I I personally quite like as well as a diagram that everything goes on. In

one presentation, so on one slide or on one sheet of a four. So yeah, it's if I have a a really good report summary might be something along the lines of a, a, a graphic showing. What the relative stride lengths were left and right, what the angle was between the feet, relatively speaking. And maybe just one or two of the abduction charts just and with with the highlighting areas saying that this this is what that means perhaps, yeah.

Speaker 1

Yeah, yeah. That’s brilliant suggestions. Thank you. OK. The next question, uh So have you experienced any challenges that needs to take into account any risks, for instance. When you use the the mobile app from home.

Speaker 2

Not really. They sometimes the the the very first exercise of the day. I was a bit stiff. That's that. And that's natural. But once I got through the first couple of motions, particularly the first exercise, I don't know if I can. Sorry, I forgot what it was called. It was the MHM. Sorry if I could demonstrate for you. It was this exercise. Yeah, that one was particularly the the earlier exercises were quite hard for me to to. Yeah, to get my full range. There was only once I've done several that I was able to get the full extent of the stretch. Yeah.

Speaker 1

Yeah, yeah, yeah, yeah. The stretching. That's why I put it as the first exercise because it has this. Yeah, stretching thing, yeah.

Speaker 2

Yeah, yeah. Yeah, also the one. Here this, this one sometimes in the morning, the very first, yeah. Say I I got better at this, but the very first one could be very difficult, yeah. And then I I would find. Once, so it was. They weren't dangerous. But I felt that I. I wasn't. All my technique wasn't always easy to get right. First time. Yeah, I needed to warm up to do the exercises. Well, if if that makes any sense. Yeah.

Speaker 1

OK. Yeah. Yes, but you know. The purpose for those exercises is not is not always just to to make you feel better. It's instead to make you feel better after you feel you were challenged, and then you overcame the challenge. So if in the beginning you you, you're finding some difficulties in doing this. Exercise and then with the time as you redo this exercise over the time you're becoming better and better and better, so you think. Think like in two weeks. I'm like today you have achieved something instead of just doing things that are easy and we

don't know if they're going to work for you or not. This is also a very important part because I haven't demonstrated those exercises to you. It was completely dependent on the video. Yeah. So you had this experience by yourself and you're the right person to evaluate it, not me. So I understand what you are saying, but luckily that you got used to those exercises and you had the chance to practice them and. On real life when when we did the second report, we saw that there were few. And as I told you, my recommendation is to continue doing that.

Speaker 2

Great. Great now.

Speaker 1

Yeah. Perfect. OK. So. The following question is. In your opinion, how the toolkit and the report could assist with your physiotherapy care plan? So for example you could think about being motivated.

Speaker 2

Definitely yes, yes. Seeing the report helped me knowing more and the app motivated me uhm to exercise.

Speaker 1

Great, do you think that this toolkit provided you with personalised or targeted exercises?

Speaker 2

Yes. Yeah. Definitely, yeah. I knew particularly after I did the the the exercise myself that that they’re they were for me to to to help my condition.

Speaker 1

So you know I used this toolkit with you including the sensors, the report, the mobile app. Have you found this toolkit engaging?

Speaker 2

Yes. Yeah. well. The sensor is a great technology and the app demonstrated my my exercise aa and the the yeah report was clear as you’ve explained it so I’d definitely say I I was found it engaging.

Speaker 1

report

Speaker 1

Perfect. And do you think that the toolkit changed how you understand your movement and made your exercises more reliable? And to what extent? Perfect.

Speaker 2

It definitely it improved my understanding of of what was happening when I was walking and and and that the particularly what was highlighted was it was like my sense of of pain. Umm in a certain area was perhaps due to things happening elsewhere. It's just that I could feel it there. So I'm trying to think what? Else I can add.

Speaker 1

Yeah. The second part was did the toolkit made the the exercise more reliable.

Speaker 2

Yeah, yeah, yeah.

Speaker 1

So I could explained this part for your you. You know I have prescribed home exercises.

Speaker 1

So do you know now why you were doing each one of those exercises?

Speaker 2

Each each of the exercises was. Was it. Was clear that I I. Was either strengthening the hip. The ankle flexion, flexion, or the knee and there was and and in most cases there was more than one exercise for those, and there were certainly different ones for the for the two different ones for. The hip. And two different ones for the ankle are the only one for the knee, so I I think it was. I I could see how that how those exercises are related to the findings that we discussed in the first session, yes from. From what was happening between my hip and my and my ankle and my knee, all three together, really.

Speaker 1

Yeah, Yeah. So you could say that the exercises were more reliable?

Speaker 2

Yes, yes, I think so, yes, yes.

Speaker 1

The exercises, yeah. All right. What do you think about using this technology in the future?

Speaker 2

I think it's it's. It's really interesting and it's really interesting for a a patient or or somebody like me who's quite determined to to do all they can to, to engage with improving themselves. I I I think that someone who's motivated to to want to do it and to be active in their own recovery, that's brilliant. So and and and is able to as well and is is able to find the time. In their in their schedule to to be able to and the space. To to to exercise comfortably in in private that their family lives mean that they they they can. They can escape for a few minutes to do that sort of thing. Little techniques also that that that I I found I mean it was quite it was quite difficult sometimes to do some exercises where there was carpet better on a hard surface than on than on carpet for example. So on on the whole, yeah, I think it's it's a really good really good direction. So that medicine moves in. It's moving in really.

Speaker 1

Yeah. OK. So this is a little bit long question. So I'd like to ask you about the confidence, so how confident you were when you started using the mobile app in terms of accessing the components following the exercise programmes, answering the questionnaire questions. And log in into the app?

Speaker 2

Yeah. Yeah, well, initially I. Just use it as a as a means of getting to the exercises, but it was quite clever because when there was a survey, it didn't pop the survey questions up until the date that it was scheduled to. So by which time I was used to how the other parts of the app worked. Yeah. So when something new came up. On there, it wasn't like I was swamped. I could see this is an extra feature that that needs to be responded to as a questionnaire. I again, I I spoke well of the of the, of the interlinking of the video and that was that that worked very well because the videos didn't go on for too long and you could actually just look at them. You know, sometimes there was a need for me to assess the position of of one foot relative to sort of another. And what how? Where I could put my hands to rest. And it was it was. Very good. And it did that.

Speaker 1

Yeah. All right. So what would be your take home message from this experience of using this tool?

Speaker 2

Well, I would say to anyone who's. Anyone who's who's who's been diagnosed with with having any kind of issue around knee pain actively to consider. Trying something personalised like this to tackle that problem. If nothing else, they'll learn a great deal about about what the what, what's what is wrong exactly, and what, what, what and what can be done to manage the the situation. So I I you know, I I can't really see much against, yeah, against at least trying trying an individualised assessment. You know, I've learned a lot. And and I, you know, I've learned, you know, to, to, to you know about. But when I start to feel pain and and I know I can, sometimes I can just go through the pain because the pain is just just telling me something at that particular moment. It doesn't mean and I can't move on and do it. To do an exercise. I'll put weight here and and you know, it's helped me to challenge myself a bit and I feel a bit, I feel a bit stronger today. Today I felt very good on the. Assessments and and. You know.

Speaker 1

Yes. And is there anything you want to add concerning the toolkit, the mobile app, the report, the data and the data collection session?

Speaker 2

That showed. No, it all seemed you explained it really well. Mohammed. Thank you. The you know, it was. It was clear when when the software had to get a a starting position to initialise. Yeah, it was. It was quite clear what to do. It was clear when you were using sensors and collected the data.

Speaker 1

Perfect.

Speaker 2

On the on the whole, it was. It was a really interesting thing to be part of. Really perfect. Yeah. Yeah. Thank you.

Speaker 1

My pleasure. Alright, thank you very much. It was a pleasure having you on this project. OK. Thank you.

Appendix (10) Matlab Code

```
clc; clear; close all;

[File, Dir] = uigetfile('*.xlsx','Select File: ','MultiSelect','On');


% Catch to ensure File is a cell structure even if 1 file is selected

if iscell(File)

    N = length(File);

else

    N = 1;

    File = cellstr(File);

end


for PatientNum=1:N

FileName=[Dir File{PatientNum}];

DataIn = importfile1(FileName, "timecurves", [2, Inf]);


JA=DataIn(DataIn.set=='JOINT_ANGLES',:);

RH=JA(JA.subset=="RightHip",:);
```

```
LH=JA(JA.subset=="LeftHip",:);


figure('Renderer', 'painters','Units','pixels','Position',[99 225 1122 663])
max_cycle=max(RH.cycle);


subplot(231)
for i=0:max_cycle
plot(RH.index(RH.cycle==i),RH.z(RH.cycle==i),'Color',"#D95319",'LineWidth',1)
hold on
plot(LH.index(LH.cycle==i),LH.z(LH.cycle==i),'Color',"#0072BD",'LineWidth',1)
RH_Z(i+1,:)=RH.z(RH.cycle==i);
LH_Z(i+1,:)=LH.z(LH.cycle==i);
end
grid on


title('Sagital: Flexion(+)/Extension(-)')
xlabel('% Gait Cycle')
ylabel('Joint Angle (deg)')
% keyboard
subplot(232)
for i=0:max_cycle
plot(RH.index(RH.cycle==i),RH.x(RH.cycle==i),'Color',"#D95319",'LineWidth',1)
hold on
plot(LH.index(LH.cycle==i),LH.x(LH.cycle==i),'Color',"#0072BD",'LineWidth',1)
```

```
RH_X(i+1,:)=RH.x(RH.cycle==i);
LH_X(i+1,:)=LH.x(LH.cycle==i);
end
title('Frontal: Abduction(+)/Adduction(-)')
xlabel('% Gait Cycle')
ylabel('Joint Angle (deg)')
grid on
subplot(233)
for i=0:max_cycle
plot(RH.index(RH.cycle==i),RH.y(RH.cycle==i),'Color',"#D95319",'LineWidth',1)
hold on
plot(LH.index(LH.cycle==i),LH.y(LH.cycle==i),'Color',"#0072BD",'LineWidth',1)
RH_Y(i+1,:)=RH.y(RH.cycle==i);
LH_Y(i+1,:)=LH.y(LH.cycle==i);
end
title('Transvers: Internal(+)/External(-)')
xlabel('% Gait Cycle')
ylabel('Joint Angle (deg)')
grid on
legend('Right','Left','Location','bestoutside')

%% Plot the means
subplot(234)
plot(RH.index(RH.cycle==i),mean(RH_Z),'Color',"#D95319",'LineWidth',1.5,'LineStyle','--')
```

```
hold on

plot(RH.index(RH.cycle==i),mean(LH_Z),'Color',"#0072BD",'LineWidth',1.5,'LineStyle','--')

title('Mean: Flexion(+)/Extension(-)')

% legend('Right','Left','Location','best')

xlabel('% Gait Cycle')

ylabel('Joint Angle (deg)')

grid on


subplot(235)

plot(RH.index(RH.cycle==i),mean(RH_X),'Color',"#D95319",'LineWidth',1.5,'LineStyle','--')

hold on

plot(RH.index(RH.cycle==i),mean(LH_X),'Color',"#0072BD",'LineWidth',1.5,'LineStyle','--')

title('Mean: Abduction(+)/Adduction(-)')

% legend('Right','Left','Location','best')

xlabel('% Gait Cycle')

ylabel('Joint Angle (deg)')

grid on


subplot(236)

plot(RH.index(RH.cycle==i),mean(RH_Y),'Color',"#D95319",'LineWidth',1.5,'LineStyle','--')

hold on
```

```
plot(RH.index(RH.cycle==i),mean(LH_Y),'Color',"#0072BD",'LineWidth',1.5,'LineStyl
e','--')

title('Mean: Internal(+)/External(-)')

legend('Right','Left','Location','bestoutside')

xlabel('% Gait Cycle')

ylabel('Joint Angle (deg)')

grid on


sgtitle(sprintf('Hip Joint Angles\n %s',File{PatientNum}))


%% Collect some numbers max and min for each file


Max_All{PatientNum,1}=[max(max(RH_Z)) max(max(RH_X)) max(max(RH_Y))];

Max_All{PatientNum,2}=[max(max(LH_Z)) max(max(LH_X)) max(max(LH_Y))];


Min_All{PatientNum,1}=[min(min(RH_Z)) min(min(RH_X)) min(min(RH_Y))];

Min_All{PatientNum,2}=[min(min(LH_Z)) min(min(LH_X)) min(min(LH_Y))];


%% Now we start to work on Overall data

All_Means_X{PatientNum,1}=mean(RH_X);

All_Means_X{PatientNum,2}=mean(LH_X);


All_Means_Y{PatientNum,1}=mean(RH_Y);

All_Means_Y{PatientNum,2}=mean(LH_Y);
```

```
All_Means_Z{PatientNum,1}=mean(RH_Z);

All_Means_Z{PatientNum,2}=mean(LH_Z);

index=RH.index(RH.cycle==i);

%keyboard

end


%% Now take the means of all files' means

for i=1:N

Make_R_X_mean(i,:)=All_Means_X{i,1};

Make_L_X_mean(i,:)=All_Means_X{i,2};


Make_R_Y_mean(i,:)=All_Means_Y{i,1};

Make_L_Y_mean(i,:)=All_Means_Y{i,2};


Make_R_Z_mean(i,:)=All_Means_Z{i,1};

Make_L_Z_mean(i,:)=All_Means_Z{i,2};

end


%% Find the Ranges based on plans (x,y,z) and phases (stance, swing)

for i=1:N

    % Find the range for stance phase Right foot in X plan

Ranges_R_X(i,1)=abs(max(Make_R_X_mean(i,[1:61]))-
min(Make_R_X_mean(i,[1:61])));

  % Find the range for swing phase Right foot in X plan
```

```
Ranges_R_X(i,2)=abs(max(Make_R_X_mean(i,[62:end]))-
min(Make_R_X_mean(i,[62:end])));

    % Find the range for stance phase left foot in X plan

Ranges_L_X(i,1)=abs(max(Make_L_X_mean(i,[1:61]))-
min(Make_L_X_mean(i,[1:61])));

    % Find the range for swing phase left foot in X plan

Ranges_L_X(i,2)=abs(max(Make_L_X_mean(i,[62:end]))-
min(Make_L_X_mean(i,[62:end])));



Ranges_R_Y(i,1)=abs(max(Make_R_Y_mean(i,[1:61]))-
min(Make_R_Y_mean(i,[1:61])));

Ranges_R_Y(i,2)=abs(max(Make_R_Y_mean(i,[62:end]))-
min(Make_R_Y_mean(i,[62:end])));


Ranges_L_Y(i,1)=abs(max(Make_L_Y_mean(i,[1:61]))-
min(Make_L_Y_mean(i,[1:61])));

Ranges_L_Y(i,2)=abs(max(Make_L_Y_mean(i,[62:end]))-
min(Make_L_Y_mean(i,[62:end])));



Ranges_R_Z(i,1)=abs(max(Make_R_Z_mean(i,[1:61]))-
min(Make_R_Z_mean(i,[1:61])));

Ranges_R_Z(i,2)=abs(max(Make_R_Z_mean(i,[62:end]))-
min(Make_R_Z_mean(i,[62:end])));
```

```
Ranges_L_Z(i,1)=abs(max(Make_L_Z_mean(i,[1:61]))-
min(Make_L_Z_mean(i,[1:61])));

Ranges_L_Z(i,2)=abs(max(Make_L_Z_mean(i,[62:end]))-
min(Make_L_Z_mean(i,[62:end])));

end


%% Open and save these data.

% These 4 var are the ranges for stance and swing phases for right and left

% foot. Each varible is 3x2 matrix. Row 1 is X, Row 2 is Y, Row 3 is Z. Col

% 1 is mean and col 2 is s.d

%**********************************************************************

Ranges_table_stancePhase_Right=[mean(Ranges_R_X(:,1)),
std(Ranges_R_X(:,1));...

   mean(Ranges_R_Y(:,1)), std(Ranges_R_Y(:,1));...

   mean(Ranges_R_Z(:,1)), std(Ranges_R_Z(:,1))];


Ranges_table_stancePhase_Left=[mean(Ranges_L_X(:,1)), std(Ranges_L_X(:,1));...

   mean(Ranges_L_Y(:,1)), std(Ranges_L_Y(:,1));...

   mean(Ranges_L_Z(:,1)), std(Ranges_L_Z(:,1))];


Ranges_table_swingPhase_Right=[mean(Ranges_R_X(:,2)),
std(Ranges_R_X(:,2));...

   mean(Ranges_R_Y(:,2)), std(Ranges_R_Y(:,2));...

   mean(Ranges_R_Z(:,2)), std(Ranges_R_Z(:,2))];
```

```
Ranges_table_swingPhase_Left=[mean(Ranges_L_X(:,2)), std(Ranges_L_X(:,2));...
    mean(Ranges_L_Y(:,2)), std(Ranges_L_Y(:,2));...
    mean(Ranges_L_Z(:,2)), std(Ranges_L_Z(:,2))];
%% ********************************************************************
%%
Date_R_X=[mean(Make_R_X_mean)' std(Make_R_X_mean)'];
Date_L_X=[mean(Make_L_X_mean)' std(Make_L_X_mean)'];

Date_R_Y=[mean(Make_R_Y_mean)' std(Make_R_Y_mean)'];
Date_L_Y=[mean(Make_L_Y_mean)' std(Make_L_Y_mean)'];

Date_R_Z=[mean(Make_R_Z_mean)' std(Make_R_Z_mean)'];
Date_L_Z=[mean(Make_L_Z_mean)' std(Make_L_Z_mean)'];



% keyboard
close all
figure('Renderer', 'painters','Units','pixels','Position',[2135 55 1.0433e+03 500.6667])
subplot(231)
for i=1:N
plot(index,All_Means_Z{i,1},'Color',"#D95319",'LineWidth',1.5)
hold on
plot(index,All_Means_Z{i,2},'Color',"#0072BD",'LineWidth',1.5)
```

```
end

title(sprintf('Means of Cycles'' Files'))
% legend('Right','Left','Location','best')
xlabel('% Gait Cycle')
ylabel('Joint Angle (deg)')
grid on

subplot(234)
plot(index,Date_R_Z(:,1),'Color',"#D95319",'LineWidth',1.5,'LineStyle','-')
% plot(index,All_Means_Z{i,1})
hold on
plot(index,Date_L_Z(:,1),'Color',"#0072BD",'LineWidth',1.5,'LineStyle','-')
title(sprintf('Flexion(+)/Extension(-)'))
% legend('Right','Left','Location','best')
xlabel('% Gait Cycle')
ylabel('Joint Angle (deg)')
grid on


% keyboard
subplot(232)
for i=1:N
plot(index,All_Means_X{i,1},'Color',"#D95319",'LineWidth',1.5)
```

```
hold on
plot(index,All_Means_X{i,2},'Color',"#0072BD",'LineWidth',1.5)
end
title(sprintf('Means of Cycles" Files'))
% legend('Right','Left','Location','best')
xlabel('% Gait Cycle')
ylabel('Joint Angle (deg)')
grid on

subplot(235)

plot(index,Date_R_X(:,1),'Color',"#D95319",'LineWidth',1.5,'LineStyle','-')
% plot(index,All_Means_Z{i,1})
hold on
plot(index,Date_L_X(:,1),'Color',"#0072BD",'LineWidth',1.5,'LineStyle','-')
title(sprintf('Abduction(+)/Adduction(-)'))
% legend('Right','Left','Location','best')
xlabel('% Gait Cycle')
ylabel('Joint Angle (deg)')
grid on

subplot(233)
for i=1:N
```

```
plot(index,All_Means_Y{i,1},'Color',"#D95319",'LineWidth',1.5)
hold on
plot(index,All_Means_Y{i,2},'Color',"#0072BD",'LineWidth',1.5)

end
title(sprintf('Means of Cycles" Files'))
legend('Right','Left','Location','bestoutside')
xlabel('% Gait Cycle')
ylabel('Joint Angle (deg)')
grid on
sgtitle(sprintf('All Files Hip Joint Angles\n N=%d',N))

subplot(236)

plot(index,Date_R_Y(:,1),'Color',"#D95319",'LineWidth',1.5,'LineStyle','-')
% plot(index,All_Means_Z{i,1})
hold on
plot(index,Date_L_Y(:,1),'Color',"#0072BD",'LineWidth',1.5,'LineStyle','-')

title(sprintf('Internal(+)/External(-)'))
legend('Right','Left','Location','bestoutside')
xlabel('% Gait Cycle')
ylabel('Joint Angle (deg)')
grid on
```

```
keyboard

% save(gcf,sprint)

%% Ok, now take the mean of all pationts and them find max and min


[Flexion_R,I]=max(Date_R_Z(:,1));

Flexion_R_sd=Date_R_Z(I,2);


[Flexion_L,I]=max(Date_L_Z(:,1));

Flexion_L_sd=Date_L_Z(I,2);


[Extension_R,I]=min(Date_R_Z(:,1));

Extension_R_sd=Date_R_Z(I,2);


[Extension_L,I]=min(Date_L_Z(:,1));

Extension_L_sd=Date_L_Z(I,2);


[Abduction_R,I]=max(Date_R_X(:,1));

Abduction_R_sd=Date_R_X(I,2);


[Abduction_L,I]=max(Date_L_X(:,1));

Abduction_L_sd=Date_L_X(I,2);


[Adduction_R,I]=min(Date_R_X(:,1));
```

```
Adduction_R_sd=Date_R_X(I,2);

[Adduction_L,I]=min(Date_L_X(:,1));
Adduction_L_sd=Date_L_X(I,2);

[Internal_R,I]=max(Date_R_Y(:,1));
Internal_R_sd=Date_R_Y(I,2);
[Internal_L,I]=max(Date_L_Y(:,1));
Internal_L_sd=Date_L_Y(I,2);

[External_R,I]=min(Date_R_Y(:,1));
External_R_sd=Date_R_Y(I,2);
[External_L,I]=min(Date_L_Y(:,1));
External_L_sd=Date_L_Y(I,2);

Right_All=[Flexion_R Flexion_R_sd;...
    Extension_R Extension_R_sd;...
    Abduction_R, Abduction_R_sd;...
    Adduction_R,Adduction_R_sd;...
    Internal_R,Internal_R_sd;...
    External_R,External_R_sd];

Left_All=[Flexion_L Flexion_L_sd;...
    Extension_L Extension_L_sd;...
```

```
    Abduction_L, Abduction_L_sd;...
    Adduction_L,Adduction_L_sd;...
    Internal_L,Internal_L_sd;...
    External_L,External_L_sd];
% TTable2=[Right_All;Left_All];
Table2means=[Right_All(:,1) Left_All(:,1)];
Table3sd=[Right_All(:,2) Left_All(:,2)];
%% Finding Range of Motions based on Stence and Sweing phases
% Stence phase for gait from 0 to 60
% sweing from 61 to 100
% starting with stence
Phase=[1:61];

[Flexion_R,I]=max(Date_R_Z(Phase,1));
Flexion_R_sd=Date_R_Z(I,2);

[Flexion_L,I]=max(Date_L_Z(Phase,1));
Flexion_L_sd=Date_L_Z(I,2);

[Extension_R,I]=min(Date_R_Z(Phase,1));
Extension_R_sd=Date_R_Z(I,2);

[Extension_L,I]=min(Date_L_Z(Phase,1));
Extension_L_sd=Date_L_Z(I,2);
```

```
[Abduction_R,I]=max(Date_R_X(Phase,1));
Abduction_R_sd=Date_R_X(I,2);

[Abduction_L,I]=max(Date_L_X(Phase,1));
Abduction_L_sd=Date_L_X(I,2);

[Adduction_R,I]=min(Date_R_X(Phase,1));
Adduction_R_sd=Date_R_X(I,2);

[Adduction_L,I]=min(Date_L_X(Phase,1));
Adduction_L_sd=Date_L_X(I,2);

[Internal_R,I]=max(Date_R_Y(Phase,1));
Internal_R_sd=Date_R_Y(I,2);
[Internal_L,I]=max(Date_L_Y(Phase,1));
Internal_L_sd=Date_L_Y(I,2);

[External_R,I]=min(Date_R_Y(Phase,1));
External_R_sd=Date_R_Y(I,2);
[External_L,I]=min(Date_L_Y(Phase,1));
External_L_sd=Date_L_Y(I,2);

Right_All=[Flexion_R Flexion_R_sd;...
```

```
    Extension_R Extension_R_sd;...
    Abduction_R, Abduction_R_sd;...
    Adduction_R,Adduction_R_sd;...
    Internal_R,Internal_R_sd;...
    External_R,External_R_sd];

Left_All=[Flexion_L Flexion_L_sd;...
    Extension_L Extension_L_sd;...
    Abduction_L, Abduction_L_sd;...
    Adduction_L,Adduction_L_sd;...
    Internal_L,Internal_L_sd;...
    External_L,External_L_sd];
% TTable2=[Right_All;Left_All];
Stence_phase_Table2means=[Right_All(:,1) Left_All(:,1)];
Stence_phase_Table3sd=[Right_All(:,2) Left_All(:,2)];


% Now sweing phase
Phase=[62:101];

[Flexion_R,I]=max(Date_R_Z(Phase,1));
Flexion_R_sd=Date_R_Z(I,2);

[Flexion_L,I]=max(Date_L_Z(Phase,1));
```

```
Flexion_L_sd=Date_L_Z(I,2);

[Extension_R,I]=min(Date_R_Z(Phase,1));
Extension_R_sd=Date_R_Z(I,2);

[Extension_L,I]=min(Date_L_Z(Phase,1));
Extension_L_sd=Date_L_Z(I,2);

[Abduction_R,I]=max(Date_R_X(Phase,1));
Abduction_R_sd=Date_R_X(I,2);

[Abduction_L,I]=max(Date_L_X(Phase,1));
Abduction_L_sd=Date_L_X(I,2);

[Adduction_R,I]=min(Date_R_X(Phase,1));
Adduction_R_sd=Date_R_X(I,2);

[Adduction_L,I]=min(Date_L_X(Phase,1));
Adduction_L_sd=Date_L_X(I,2);

[Internal_R,I]=max(Date_R_Y(Phase,1));
Internal_R_sd=Date_R_Y(I,2);
[Internal_L,I]=max(Date_L_Y(Phase,1));
Internal_L_sd=Date_L_Y(I,2);
```

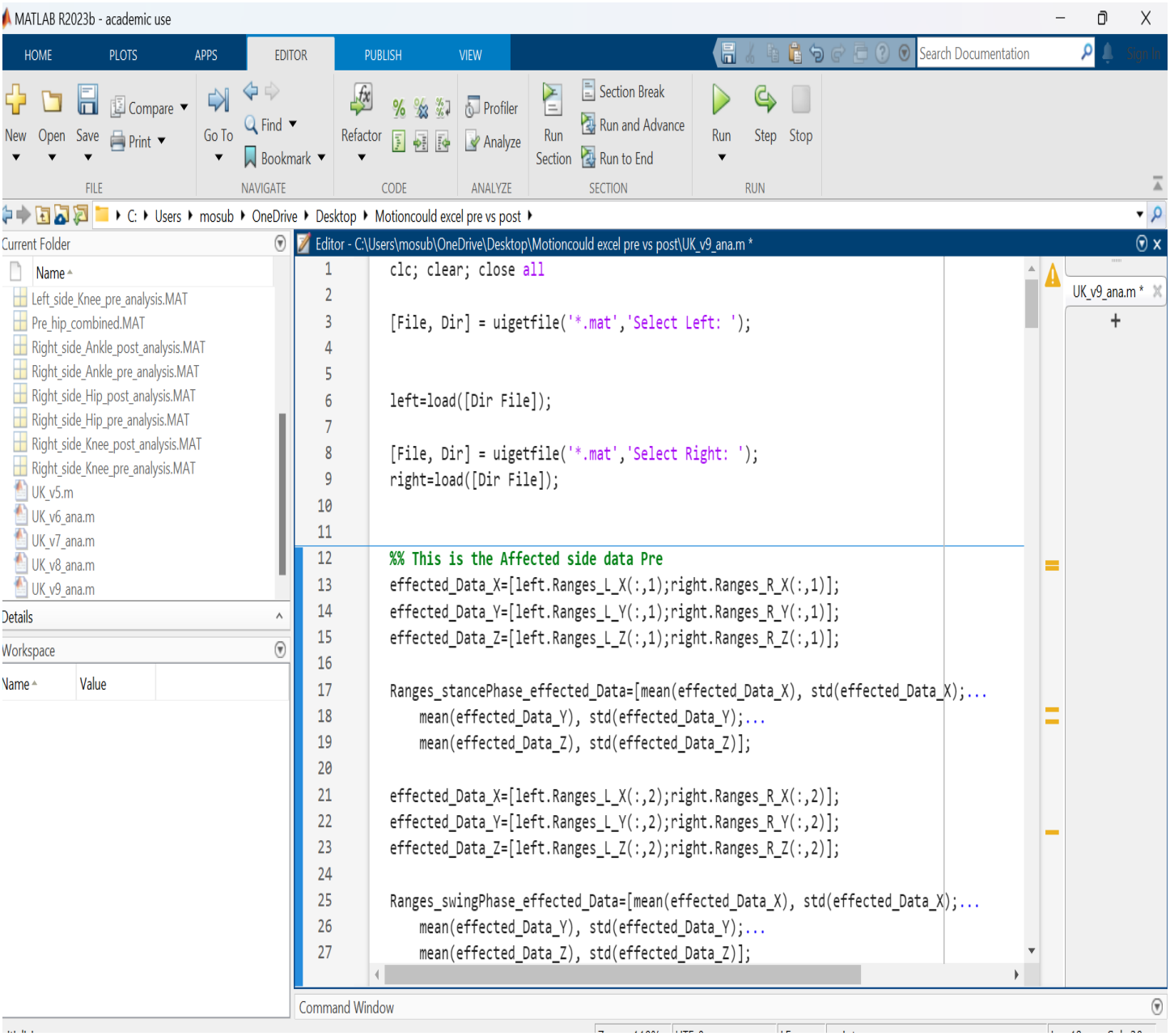
```
[External_R,I]=min(Date_R_Y(Phase,1));
External_R_sd=Date_R_Y(I,2);
[External_L,I]=min(Date_L_Y(Phase,1));
External_L_sd=Date_L_Y(I,2);

Right_All=[Flexion_R Flexion_R_sd;...
    Extension_R Extension_R_sd;...
    Abduction_R, Abduction_R_sd;...
    Adduction_R,Adduction_R_sd;...
    Internal_R,Internal_R_sd;...
    External_R,External_R_sd];

Left_All=[Flexion_L Flexion_L_sd;...
    Extension_L Extension_L_sd;...
    Abduction_L, Abduction_L_sd;...
    Adduction_L,Adduction_L_sd;...
    Internal_L,Internal_L_sd;...
    External_L,External_L_sd];
% TTable2=[Right_All;Left_All];
Sweing_phase_Table2means=[Right_All(:,1) Left_All(:,1)];
Sweing_phase_Table3sd=[Right_All(:,2) Left_All(:,2)];

%% Make Bar graph
```

```
model_series = Table2means; %[TTable2(1,1:2);
TTable2(3,1:2);TTable2(5,1:2);TTable2(7,1:2);TTable2(9,1:2);TTable2(11,1:2)];

model_error = Table3sd;% [TTable2(2,1:2);
TTable2(4,1:2);TTable2(6,1:2);TTable2(8,1:2);TTable2(10,1:2);TTable2(12,1:2)];

figure

b = bar(model_series, 'grouped');

hold on

% Calculate the number of groups and number of bars in each group

[ngroups,nbars] = size(model_series);

% Get the x coordinate of the bars

x = nan(nbars, ngroups);

for i = 1:nbars

    x(i,:) = b(i).XEndPoints;

end

% Plot the errorbars

errorbar(x',model_series,model_error,'k','linestyle','none');

hold off

x_label =
categorical({'Flexion';'Extension';'Abduction';'Adduction';'Internal';'External'}); %The
Group Label

set(gca,'xticklabel',x_label)

ylabel('Overall: Joint Angle (deg)')

title('Hip Joint Angle')

legend('Right','Left','Location','southoutside','Orientation','horizontal')
```

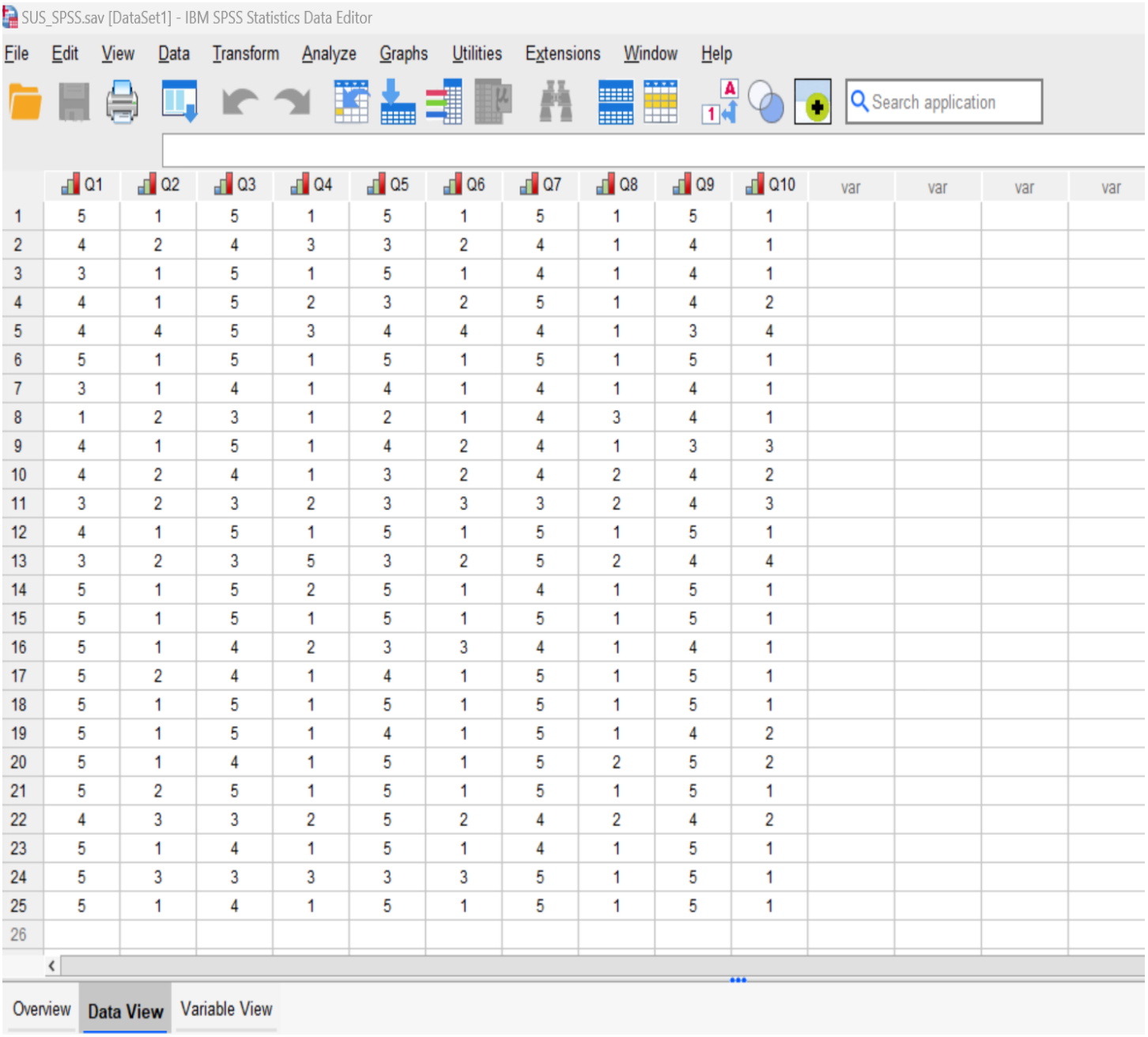
```
%%

close all

figure

subplot(121)

model_series = Stence_phase_Table2means; %[TTable2(1,1:2);
TTable2(3,1:2);TTable2(5,1:2);TTable2(7,1:2);TTable2(9,1:2);TTable2(11,1:2)];

model_error = Stence_phase_Table3sd;


b = bar(model_series, 'grouped');

hold on

% Calculate the number of groups and number of bars in each group

[ngroups,nbars] = size(model_series);

% Get the x coordinate of the bars

x = nan(nbars, ngroups);

for i = 1:nbars

    x(i,:) = b(i).XEndPoints;

end

% Plot the errorbars

errorbar(x',model_series,model_error,'k','linestyle','none');

hold off

x_label =
categorical({'Flexion';'Extension';'Abduction';'Adduction';'Internal';'External'}); %The
Group Label

set(gca,'xticklabel',x_label)
```

```
ylabel('Joint Angle (deg)')

title('Stance: Hip Joint Angle ')

legend('Right','Left','Location','southoutside','Orientation','horizontal')


subplot(122)

model_series = Sweing_phase_Table2means; %[TTable2(1,1:2);
TTable2(3,1:2);TTable2(5,1:2);TTable2(7,1:2);TTable2(9,1:2);TTable2(11,1:2)];

model_error = Sweing_phase_Table3sd;


b = bar(model_series, 'grouped');

hold on

% Calculate the number of groups and number of bars in each group

[ngroups,nbars] = size(model_series);

% Get the x coordinate of the bars

x = nan(nbars, ngroups);

for i = 1:nbars

    x(i,:) = b(i).XEndPoints;

end

% Plot the errorbars

errorbar(x',model_series,model_error,'k','linestyle','none');

hold off

x_label =
categorical({'Flexion';'Extension';'Abduction';'Adduction';'Internal';'External'}); %The
Group Label

set(gca,'xticklabel',x_label)
```

```
ylabel('Joint Angle (deg)')

title('Swing: Hip Joint Angle ')

legend('Right','Left','Location','southoutside','Orientation','horizontal')


%% Save or copy these varibles for the peak range of motions as we talked about.

% Each of the following matrices is 6x2, where each row is a motion in the

% following order

% Row 1 is Flexion

% Row 2 is Extension

% Row 3 is Abduction

% Row 4 is Adduction

% Row 5 is Internal

% Row 6 is External

% Col 1 is the Right Foot and Col 2 is the left foot

% As the var nams stand, the s.d vars are in the same way

Stence_phase_Table2means;

Stence_phase_Table3sd;

Sweing_phase_Table2means;

Sweing_phase_Table3sd;
```


MATLAB R2023b - academic use
HOME
PLOTS
APPS
EDITOR
PUBLISH
VIEW
Search Documentation
New
Open
Save
Compare
Print
Go To
Find
Bookmark
Refactor
Profiler
Analyze
Run Section
Section Break
Run and Advance
Run to End
Run
Step
Stop
FILE
NAVIGATE
CODE
ANALYZE
SECTION
RUN
C: Users mosub OneDrive Desktop Motioncould excel pre vs post
Current Folder
Name
Left_side_Knee_pre_analysis.MAT
Pre_hip_combined.MAT
Right_side_Ankle_post_analysis.MAT
Right_side_Ankle_pre_analysis.MAT
Right_side_Hip_post_analysis.MAT
Right_side_Hip_pre_analysis.MAT
Right_side_Knee_post_analysis.MAT
Right_side_Knee_pre_analysis.MAT
UK_v5.m
UK_v6_ana.m
UK_v7_ana.m
UK_v8_ana.m
UK_v9_ana.m
Details
Workspace
Name
Value
Editor - C:\Users\mosub\OneDrive\Desktop\Motioncould excel pre vs post\UK_v9_ana.m *
UK_v9_ana.m *
1 clc; clear; close all
2
3 [File, Dir] = uigetfile('*.mat','Select Left: ');
4
5
6 left=load([Dir File]);
7
8 [File, Dir] = uigetfile('*.mat','Select Right: ');
9 right=load([Dir File]);
10
11
12 %% This is the Affected side data Pre
13 effected_Data_X=[left.Ranges_L_X(:,1);right.Ranges_R_X(:,1)];
14 effected_Data_Y=[left.Ranges_L_Y(:,1);right.Ranges_R_Y(:,1)];
15 effected_Data_Z=[left.Ranges_L_Z(:,1);right.Ranges_R_Z(:,1)];
16
17 Ranges_stancePhase_effected_Data=[mean(effected_Data_X), std(effected_Data_X);...
18 mean(effected_Data_Y), std(effected_Data_Y);...
19 mean(effected_Data_Z), std(effected_Data_Z)];
20
21 effected_Data_X=[left.Ranges_L_X(:,2);right.Ranges_R_X(:,2)];
22 effected_Data_Y=[left.Ranges_L_Y(:,2);right.Ranges_R_Y(:,2)];
23 effected_Data_Z=[left.Ranges_L_Z(:,2);right.Ranges_R_Z(:,2)];
24
25 Ranges_swingPhase_effected_Data=[mean(effected_Data_X), std(effected_Data_X);...
26 mean(effected_Data_Y), std(effected_Data_Y);...
27 mean(effected_Data_Z), std(effected_Data_Z)];
Command Window

Appendix (11) SPSS example



	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	var	var	var	var
1	5	1	5	1	5	1	5	1	5	1				
2	4	2	4	3	3	2	4	1	4	1				
3	3	1	5	1	5	1	4	1	4	1				
4	4	1	5	2	3	2	5	1	4	2				
5	4	4	5	3	4	4	4	1	3	4				
6	5	1	5	1	5	1	5	1	5	1				
7	3	1	4	1	4	1	4	1	4	1				
8	1	2	3	1	2	1	4	3	4	1				
9	4	1	5	1	4	2	4	1	3	3				
10	4	2	4	1	3	2	4	2	4	2				
11	3	2	3	2	3	3	3	2	4	3				
12	4	1	5	1	5	1	5	1	5	1				
13	3	2	3	5	3	2	5	2	4	4				
14	5	1	5	2	5	1	4	1	5	1				
15	5	1	5	1	5	1	5	1	5	1				
16	5	1	4	2	3	3	4	1	4	1				
17	5	2	4	1	4	1	5	1	5	1				
18	5	1	5	1	5	1	5	1	5	1				
19	5	1	5	1	4	1	5	1	4	2				
20	5	1	4	1	5	1	5	2	5	2				
21	5	2	5	1	5	1	5	1	5	1				
22	4	3	3	2	5	2	4	2	4	2				
23	5	1	4	1	5	1	4	1	5	1				
24	5	3	3	3	3	3	5	1	5	1				
25	5	1	4	1	5	1	5	1	5	1				
26														

Overview Data View Variable View

Appendix (12) Invitation Flyer

DIGITAL BIOMECHANICAL BIOFEEDBACK TOOLKIT FOR THE PHYSIOTHERAPY MANAGEMENT OF PEOPLE WITH KNEE OSTEOARTHRITIS

If you are an adult experiencing general knee pain or knee pain because of osteoarthritis during activity for most days in the last 3 months, then this project is perfectly designed for you

CARDIFF UNIVERSITY · SCHOOL OF HEALTHCARE SCIENCES ·

YOU WILL GET

FREE EXERCISE PROGRAM +

amazon VOUCHER

1- Scan the QR code or contact the researcher "Mohammad Subahi" directly at Subahim1@cardiff.ac.uk to take part in a study that aims to develop a biomechanical biofeedback toolkit.

2- In this study, you will get the chance to be assessed and learn about the way you walk.

3- A personalised exercise program will be prescribed for you.

4- You will have the opportunity to use a mobile app for your tailored exercises from home.

5- Wearable sensor technology will be used for movement analysis and EMG sensors will be used to measure your muscle activity. Thus, you need to wear shorts/sportswear.

6- Once you contact the researcher, participant information sheet, lab booking form, and consent form will be sent to you.

7- This study is ethically approved by the ethics committee in Cardiff University, School of Healthcare Sciences.

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

SPIN

Movella

Appendix (13) Ethical Approval

Cardiff

Email hcareethics @cf.ac.uk

Head of School and Dean /Pennaeth yr Ysgol Dros Dro a Deon Professor David Whitaker

www.cardiff.ac.uk 3 October 2022 Prifysgol Caerdydd

Mohammad Subahi Ty Eastgate

Cardiff University 35 – 43 Heol Casnewydd

School of Healthcare Sciences Caerdydd

Email hcareethics@cf.ac.uk www.caerdydd.ac.uk [redacted]

Dear Mohammad

Research project title: Physiotherapy Treatment Toolkit for Individuals with Knee Osteoarthritis

SREC reference: REC905

The School of Healthcare Sciences Research Ethics Committee reviewed the above application via its proportionate review process.

Ethical Opinion the Committe e 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 hcareethics@cardiff.ac.uk 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 hcarewthics@cardiff.ac.uk for its records.

Periodic reports from and/or visits to the Chief/Principal Investigator;
Oral updates to the Committee (by the Chief/Principal Investigator ;
Establishing a project -specific monitoring provision.

Monitoring requirements

The Committee must be informed of any unexpected ethical issues or unexpected adverse events that arise during the research project e.g.

- End of project report ONLY;
- Annual reports;
-
-

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.

Complaints/Appeals

If you are dissatisfied with the decision made by the Committee, please contact Dr Kate Button 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,

Dr Becci Hemming
School of Healthcare Sciences Ethics Committee

Cc Dr Kate Button, Dr Mohammad Al Amri

Appendix (14) Consent Form

CONSENT FORM

Evaluation of the Acceptability and Usability of a Digital Biomechanical Biofeedback Toolkit for the Physiotherapy Management of CKP

Name of Chief/Principal Investigator: Mr. Mohammad M. Subahi

initial box

I confirm that I have read the information sheet dated 28/09/2022 version 2 for the above research project.	
I confirm that I have understood the information sheet dated 28/09/2022 version 2 for the above research project and that I have had the opportunity to ask questions and that these have been answered satisfactorily.	
I understand that my participation is voluntary and I am free to withdraw at any time without giving a reason and without any adverse consequences (e.g. to medical care or legal rights, if relevant). I understand that if I withdraw, information about me that has already been obtained may be kept by Cardiff	

University.	
I understand that data collected during the research project may be looked at by individuals from Cardiff University or from regulatory authorities, where it is relevant to my taking part in the research project. I give permission for these individuals to have access to my data.	
I consent to the processing of my personal information name, age, email address, and telephone number to be collected for the purposes explained to me. I understand that such information will be held in accordance with all applicable data protection legislation and in strict confidence, unless disclosure is required by law or professional obligation.	
I understand who will have access to personal information provided, how the data will be stored and what will happen to the data at the end of the research project.	
I understand that after the research project, anonymised data may be used in international conferences, teaching sessions, and scientific discussion, which would make it publicly available via a data repository and may be used for purposes not related to this research project. I understand that it will not be possible to identify me from this data that is seen and used by other researchers, for ethically approved research projects, on the understanding that confidentiality will be maintained.	
I consent to being audio recorded/ video recorded/ having my photograph taken for the purposes of the research project and I understand how it will be used in the research.	
I understand that anonymised excerpts and/or verbatim quotes from my interview may be used as part of the research publication.	
I understand how the findings and results of the research project will be written up and published.	

I agree to take part in this research project.	

Name of participant (print)	Date	Signature
Name of person taking consent (print)	Date	Signature

Role of person taking consent

(print)

Contact information:

Mohammad Subahi

Dr. Mohammad Al-Amri

[redacted]

Dr. Kate Button

[redacted]

THANK YOU FOR PARTICIPATING IN OUR RESEARCH

YOU WILL BE GIVEN A COPY OF THIS CONSENT FORM TO KEEP

Appendix (15) Thank you from my participant

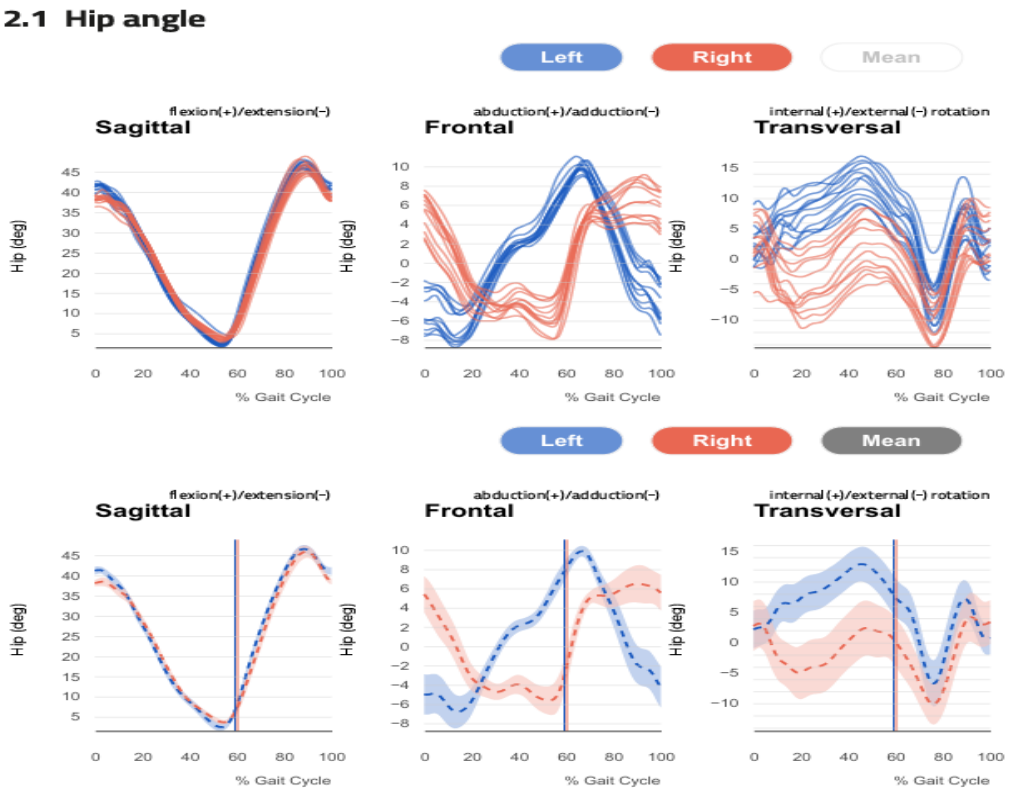
Dear Kate

Please could I write you a brief note to give my thanks to the recent efforts of PhD student Mohammad Subahi? I had the pleasure of assisting him in assessing the strength and performance in my arthritic knee in the past few weeks.

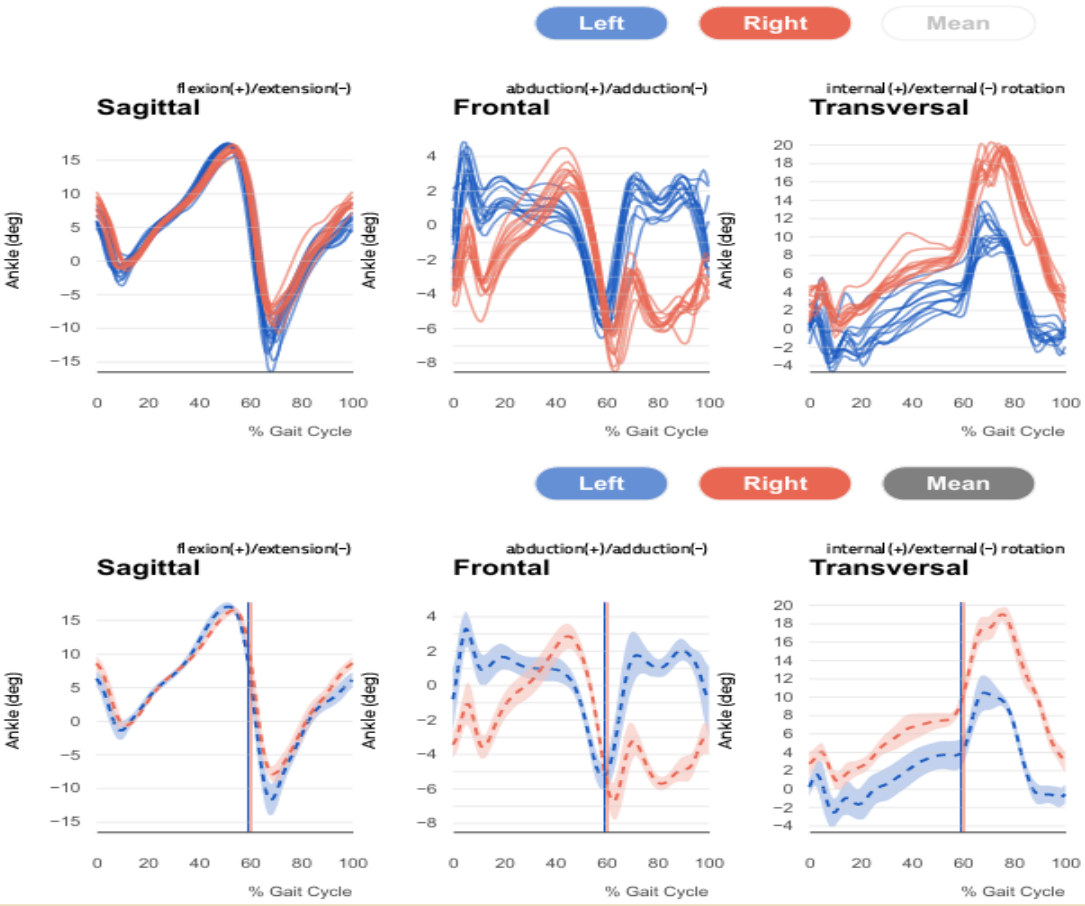
Not only did the «Kinduct» exercise programme given improve my strength and flexibility, I learnt a lot from the analysis done about my gait and found Mohammad to be a very polite and mature young man. I am really glad that I participated in the trial and hope that his PhD is successful.

Please extend my thanks to him for the great work he has done already!

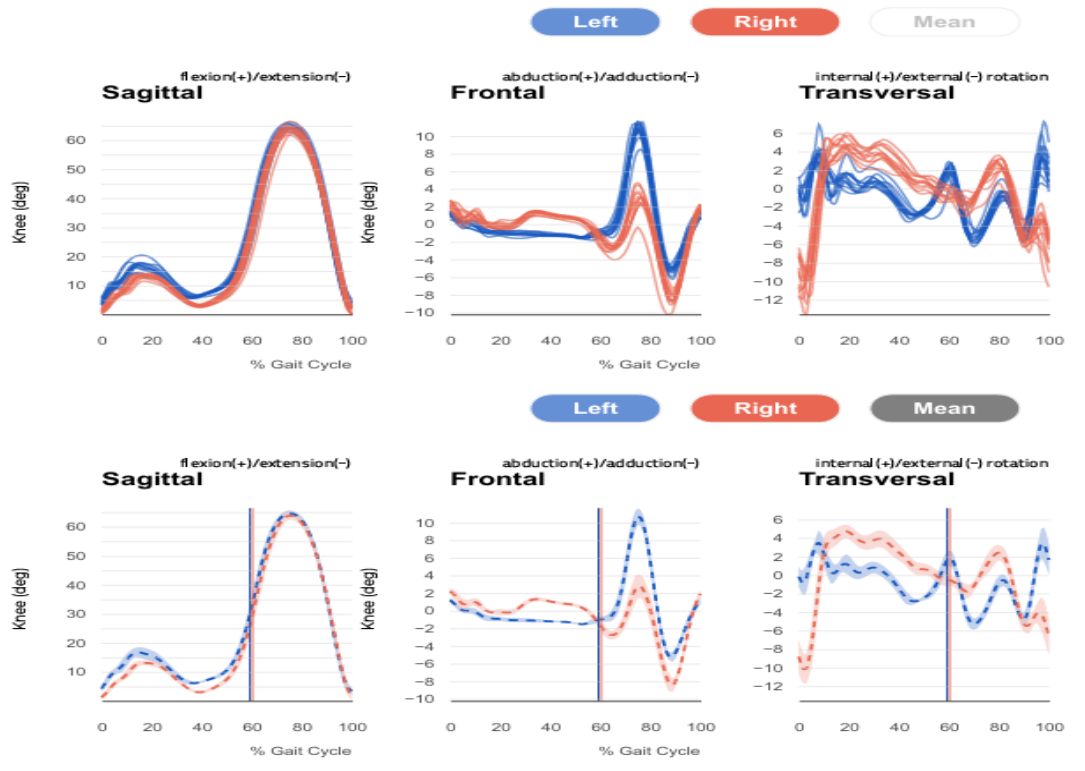
Appendix (16) Example of the gait report Waveforms



2.3 Ankle angle



2.2 Knee angle



Appendix (17) Lab Workflow sheet

Data Collection Lab Workflow

"Lab Workflow"

Step 1: Participants' arrival

- Once a participant arrives, they will be greeted and welcomed, and if they need to change, they will be guided to a screened off area where they can wear their sportswear.
- Water and snack will be offered to all participants.

Step 2: participant and session details

(Fill the boxes below)

Participant Details	
Participant Initial	
Visit Number	
Participant Group	
Chief complaints / affected side	
Pt history	

Session Details	
Date	
Time	
Researchers Present (Initials)	

Step 3: Questionnaires

Questionnaire (completed by email/completed on arrival)		
Consent form (only visit 1)		

WOMAC		(Tick when completed)
PHQ-9		
NPRS		
TAMPA		
Self-efficacy for managing chronic disease		
system useability scale (SUS) Note: SUS will be completed only on the second lab visit "post-trial stage".		

Step 4: Anthropometric details

Anthropometric Data Collection (Used to measure BMI, to identify EMG sensor placement, and to create Xsens avatar)	
Dominant side/leg Ask the participant	
Weight Using SECA scales	
Height (without shoes) Using stadiometer	
Height (with shoes) Using stadiometer	
Foot length With shoes on	
Shoulder height Floor to acromion	
Shoulder width Acromion to acromion	
Elbow span Left to right olecranon in T-pose	

Wrist span Left to right ulnar styloid in T-pose	
Arm span In T-Pose, measure from middle fingertip to fingertip	
Hip height From floor to the greater trochanter	
Hip width From the left ASIS to the right ASIS	
Knee height From the floor to the lateral epicondyle	
Ankle height From the floor to the centre lateral malleolus	

Step 5: Sensor placement

MVN (XSENS) sensors will be placed. All sensor placements will be based on Xsens sensor placement guidance.

Step 6.: Xsens sensor placement

Special Xsens vest, straps, head band, and gloves will be used to place the sensors based on Xsens sensor placement guidance.

Step 7: Xsens sensors calibration

Calibration task will be performed before starting the trial to make sure that all sensors are properly working and linked to the system.

Step 8: Performed tasks

Walking down the corridor.

Step 9: Sensors' removal:

On this step, all the sensors that were attached to the participant body will be removed.

Step 10: Report generation

Based on the data that were collected from the walk trial, gait report will be generated from the motion cloud.

Step 11: Providing feedback & exercise prescription

Using the report, a biomechanical biofeedback will be provided to participants about their spatiotemporal, and joint kinematic variable. Accordingly, exercises program will be created.

Step 12: Participant education:

All the prescribed exercises will be presented on the participant profile on the digital online platform (Kinduct). At this step, the researcher will teach the participant how to use the digital platform and access their profile to find the exercise program.

Second lab visit

Step 13: participants second lab visit

All the above-mentioned procedures will be applied again on this step.

Step 14: system useability scale (SUS)

Participants will fill the system usability scale for the toolkit usability testing.

Step 15: Semi-structured interview

Participants will be interviewed the developed interview guide to explore the acceptability of the digital toolkit.

Step 16: Thanking participants for participation

This is the final step of the trial. Sharing the results of the study with participants will be offered and offering participants any further assistance or answering any further question they might have.

Appendix (18) Study risk assessment

Risk Assessment

RISK RATING MATRIX

Likelihood	Severity 1 (No injury)	Severity 2 (First Aid)	Severity 3 (Minor Injury)	Severity 4 (Major Injury)	Severity 5 (Death)
5 - Almost Certain	5	10	15	20	25
4 - Very Likely	4	8	12	16	20
3 - Likely	3	6	9	12	15
2 - Unlikely	2	4	6	8	10
1 - Very Unlikely	1	2	3	4	5

Risk Rating Categories:

- **1-3 = LOW RISK** (Green) - Acceptable with current controls
- **4-9 = MEDIUM RISK** (Yellow) - Additional controls should be considered
- **10-16 = HIGH RISK** (Orange) - Priority action required
- **20-25 = CRITICAL RISK** (Red) - Immediate action required

Current Study's RISK ASSESSMENT TABLE

No.	Hazard/Risk	Who Might Be Harmed	Likelihood (1-5)	Severity (1-5)	Risk Score	Risk Rating	Control Measures in Place
QUANTITATIVE COMPONENT - Physical Risks							
1	Temporary increase in existing knee discomfort during brief walk	Participants	2	2	4	**LOW**	• Only participants with MILD chronic knee pain included • Medical clearance obtained prior to participation Single short walk only (approx. 25 steps, not repetitive) Participants informed they can stop at any time Brief baseline pain assessment before walk Researcher accompanies participant throughout

No.	Hazard/Risk	Who Might Be Harmed	Likelihood (1-5)	Severity (1-5)	Risk Score	Risk Rating	Control Measures in Place
							Any temporary discomfort expected to resolve with rest Participants already accustomed to managing their knee pain
2	Trip or stumble during corridor walk	Participants	1	2	2	**LOW**	Only independently mobile participants included Corridor pre-checked, cleared, and confirmed empty Short distance (single 25-step walk) Researcher walks alongside participant

No.	Hazard/Risk	Who Might Be Harmed	Likelihood (1-5)	Severity (1-5)	Risk Score	Risk Rating	Control Measures in Place
							Participants wear their own comfortable sports footwear Walking aid permitted if normally used Corridor wall available for support if needed Same floor as lab (no stairs/elevators) Well-lit, even surface verified
3	Minor skin irritation from sensor straps/vest	Participants	1	1	1	**LOW**	All sensors placed OVER sports clothing (no direct skin contact) Straps adjusted to comfortable, non-restrictive fit

No.	Hazard/Risk	Who Might Be Harmed	Likelihood (1-5)	Severity (1-5)	Risk Score	Risk Rating	Control Measures in Place
							Pre-screening for known skin sensitivities/allergies Equipment sanitized between uses Hypoallergenic materials used Short wear duration (less than 30 minutes) Participants can request adjustment at any time
4	Mild dehydration or fatigue	Participants	1	1	1	**LOW**	Minimal physical exertion (single 25-step walk) Total session duration brief (under 1 hour)

No.	Hazard/Risk	Who Might Be Harmed	Likelihood (1-5)	Severity (1-5)	Risk Score	Risk Rating	Control Measures in Place
							Water freely available in lab Participants advised to arrive hydrated Comfortable room temperature maintained Rest breaks offered between activities Seating available throughout session
5	Mild anxiety from wearing sensors or being observed	Participants	2	1	2	**LOW**	Full explanation and demonstration of equipment beforehand Sensors are wireless (no restrictive cables)

No.	Hazard/Risk	Who Might Be Harmed	Likelihood (1-5)	Severity (1-5)	Risk Score	Risk Rating	Control Measures in Place
							Participants can familiarize themselves with equipment Non-invasive, external sensors only Worn over regular sports clothing Voluntary participation with right to withdraw Comfortable, private lab environment Researcher provides reassurance and support
QUALITATIVE COMPONENT - Psychological/Emotional Risks							

No.	Hazard/Risk	Who Might Be Harmed	Likelihood (1-5)	Severity (1-5)	Risk Score	Risk Rating	Control Measures in Place
6	Mild discomfort discussing technology acceptability	Participants	1	1	1	**LOW**	Interview questions focus ONLY on technology/toolkit acceptability No personal, sensitive, or intrusive questions asked Questions about usability, feasibility, and perceptions only Non-clinical, non-therapeutic interview Participants can decline to answer any question Participants can stop interview at any time No questions

No.	Hazard/Risk	Who Might Be Harmed	Likelihood (1-5)	Severity (1-5)	Risk Score	Risk Rating	Control Measures in Place
							about personal life, trauma, or difficult experiences Professional, respectful interview environment
7	Fatigue from interview duration	Participants	1	1	1	**LOW**	Interview kept brief and focused (20-30 minutes) Comfortable seating provided Breaks offered if needed Participants can request to pause or stop Refreshments available Flexible pacing based on participant comfort

No.	Hazard/Risk	Who Might Be Harmed	Likelihood (1-5)	Severity (1-5)	Risk Score	Risk Rating	Control Measures in Place
8	Anxiety about being audio/video recorded	Participants	1	1	1	**LOW**	Recording explained clearly in consent process Participants can decline recording (notes taken instead) Recordings stored securely and confidentially Only used for research purposes Will be destroyed after specified analysis period Participants reassured about confidentiality Camera positioned non-intrusively if video used

- **OVERALL STUDY RISK CLASSIFICATION:** LOW RISK

JUSTIFICATION FOR LOW-RISK CLASSIFICATION

Quantitative Component:

- Minimal physical demand (single 25-step walk)
- Participant selection criteria ensure only chronic knee pain, independently mobile individuals
- Non-invasive external sensors worn over clothing
- Brief session duration (around 1 hour total including breaks)
- Controlled, supervised environment
- Temporary discomfort manageable with existing pain strategies

Qualitative Component:

- Non-sensitive interview topics (technology acceptability only)
- No psychological distress expected
- Brief interview duration (20-30 minutes)
- Voluntary participation with right to decline or withdraw
- No vulnerable or intrusive topics discussed

Overall Study:

- Low-risk adult population
- Standard research safeguards in place
- Appropriate data protection measures
- University oversight and ethics approval obtained