Evaluation of an Early-Stage Prototype of a Virtual Reality-Based Physiotherapy Toolkit for Individuals with Chronic Knee Pain

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Abstract

Background: Chronic knee pain (CKP) affects quality of life and poses significant challenges for healthcare delivery, with low treatment adherence outside clinical settings. Therapeutic exercise remains a cornerstone intervention for managing CKP, with evidence supporting its effectiveness in improving function and reducing pain. Virtual reality (VR) has emerged as a promising tool for delivering therapeutic exercises in a more engaging and motivating format. However, there remains a paucity of evidence regarding the biomechanical challenges and usability of VR applications for home-based knee rehabilitation. This thesis aimed to evaluate an early-stage prototype of a VR-based physiotherapy toolkit designed for people with CKP with the aim of facilitating therapeutic exercises within a home setting.

Method and findings: A total of 40 participants with CKP (52.5% male, 47.5% female, age range 18–56+ years) underwent a single laboratory session during which both kinematic performance and system usability were assessed. The study design was informed by the Medical Research Council (MRC) framework for developing complex interventions and was structured across three parts: part 1 comprised an umbrella review of eight systematic reviews examining the applications of VR-based physiotherapy. This part aimed to identify, synthesise and critically evaluate existing evidence on the application of VR in therapeutic interventions. The findings suggested that while VR demonstrates potential to improve physical function, significant gaps persist in understanding its biomechanics and its usability for home-based physiotherapy settings. The methodological quality of the reviewed research was low, highlighting the need for rigorous and high-quality research in this area. Part 2 evaluated whether an in-house VR-based physiotherapy toolkit can accurately replicate therapeutic movements and provide appropriate challenges across different difficulty levels. Participants performed five VR-based physiotherapy exercise scenarios, during which joint range of motion (ROM) and key muscles' activity were recorded concurrently. The results demonstrated that progressive increases in exercise difficulty led to enhanced movement demands while preserving symmetrical lower-limb muscle activation. These findings indicate that the system can deliver individualised exercise interventions that adapt to personal movement characteristics following physiotherapy best practices. Part 3 focused on evaluating the usability and acceptability of the VR-based physiotherapy prototype among participants with CKP. Usability was quantitatively established using the System Usability Scale (SUS), yielding a mean score of 76, which is indicative of good overall usability. Qualitative feedback was also collected and exposed to content analysis, which revealed a positive user experience: 389 positive codes were recorded, compared to 62 negative codes. However, specific areas for improvement were identified, including frequent technical challenges (307 codes) and the need for clearer instructional guidance (84 codes).

Conclusion: This research demonstrates that VR can offer a promising, engaging, and biomechanically relevant system to deliver therapeutic exercises. However, challenges related to technical reliability and clarity of instructional content require further development to ensure successful long-term implementation. This research contributes to a growing body of evidence supporting the integration of VR into musculoskeletal physiotherapy and provides valuable insights to inform future development and successful implementation in both home and clinical settings.

Contents

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- Almutairi, A., Sabbagh, D., Button, K. and Al-Amri, M. 2024. Exploring the potential of virtual reality in knee therapeutic exercises: An umbrella review. Poster presented at the 2024 OARSI World Congress on Osteoarthritis. doi: 10.1016/j.joca.2024.02.839

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Professional Contributions:

- Contributed to the development of the Knee and Hip Osteoarthritis Exercise Toolkit for Clinicians, created by the Osteoarthritis Research Society International Rehabilitation Discussion Group. (2025). Available at: https://blogs.unimelb.edu.au/exercisetoolkit/

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Glossary of Abbreviations

3D	Three dimensional
ACLR	Anterior cruciate ligament reconstruction
ADL	Activities of daily living
AMSTAR	A Measurement Tool to Assess Systematic Reviews
CCA	Corrected Covered Area
CI	Confidence Interval
CKP	Chronic knee pain
cm	Centimetres
COM	Centre of Mass
COP	Centre of Pressure
df	Degrees of Freedom
EMG	Electromyography
IMU	Inertial Measurements Unit
IQR	Interquartile Range
Kg	Kilograms
m	Metres
MRC	Medical Research Council
MTw	Wireless motion trackers
MVN	Motion Analysis Capture
OA	Osteoarthritis
OARSI	Osteoarthritis Research Society International
PFPS	Patellofemoral pain syndrome
PHQ-9	Patient Health Questionnaire-9
PIS	Participant Information Sheets
PROMs	Patient Reported Outcome Measures
PT	Physiotherapy
QoL	Quality of Life
RCT	Randomised Control Trial
ROM	Range of Motion

SD	Standard Deviation
SI	Symmetry Index
SMD	Standardized Mean Difference
SR	Systematic Review
SUS	System Usability Scale
TAM	Technology Acceptance Model
TFA	Theoretical Framework of Acceptability
TKR	Total Knee Replacement
TSK	Tampa Scale for Kinesiophobia
UTAUT	Unified Theory of Acceptance and Use of Technology
μV	Microvolts
VR	Virtual Reality
WOMAC	Western Ontario and McMaster Universities Osteoarthritis Index

CHAPTER 1: Introduction

1.1 Background

Chronic knee pain (CKP) represents a significant global health challenge that impacts individuals' quality of life and healthcare systems worldwide. Despite its prevalence, there is no universally agreed-upon definition for CKP. While often linked to conditions such as osteoarthritis (OA), debate continues about whether CKP should be considered a distinct disease entity (Treede et al. 2019). The condition typically refers to persistent or recurrent knee joint pain lasting for an extended period, usually three months or longer, significantly affecting daily activities and mobility.

The definition of CKP has varied in the literature, with some resources characterising it as recurring pain lasting at least a month, while others describe it as longer-term manifestations (O'Reilly et al. 1996; Ingham et al. 2011). In individuals aged 40 and older, CKP is often associated with knee OA or other related disorders, although it can affect adults of all ages (Altman et al. 1986; Versus Arthritis 2024). The pathophysiology of CKP is complex, involving multiple mechanisms, such as changes in pain modulatory pathways, inflammation, nerve sensitisation, and the release of pain mediators (Neogi 2013). In the case of knee OA, structural changes such as cartilage degradation, bone remodelling, and synovial inflammation contribute to pain generation (Felson 2009).

While there is no definitive cure for CKP, therapeutic exercise has emerged as the cornerstone of pain management to improve quality of life. A Cochrane review provided foundational evidence, demonstrating significant improvements in physical function and pain reduction through therapeutic exercise (Fransen et al. 2015). Building on this evidence, the American College of Rheumatology/Arthritis Foundation guidelines, developed by Kolasinski et al. (2020), recommended a combination of low-impact aerobic exercise and strength training as an effective management approach for CKP. Most recently, the National Institute for Health and Care Excellence (NICE 2023) has reinforced these findings, strongly recommending exercise as a core management strategy for knee OA, with a focus on local muscle strengthening and general aerobic fitness.

Despite the evidence-based guidelines, implementation of physiotherapy in clinical practice faces significant challenges. Recent reports highlight substantial barriers within the NHS, including extended waiting times, resource limitations, and workforce shortages (Health Foundation 2023). The COVID-19 pandemic has worsened these systemic issues, with a 2023 Health Foundation report indicating that over 30% of patients wait more than 18 weeks for musculoskeletal physiotherapy services (Bagenal 2022; Health Foundation 2023).

Home-based physiotherapy programmes offer a potential solution to access barriers but come with their own set of challenges. These include limited accessibility to supervision, particularly for individuals in remote areas (Kolasinski et al. 2020). Without proper supervision, patients often struggle to maintain correct exercise form, which is crucial because improper technique can reduce effectiveness or even cause injury (Koh et al. 2017). Adherence rates in unsupervised programmes frequently fall below 50% (Aitken et al. 2010), highlighting the difficulty in maintaining patient commitment.

Another major challenge is the lack of real-time feedback on performance, which prevents patients from making immediate corrections and understanding their progress (Brennan et al. 2020). This feedback gap is particularly problematic because patients need to know if they are performing exercises correctly to gain the full therapeutic benefit. Additionally, home-based programmes have limited ability to monitor progress systematically, which affects both patient motivation and the healthcare provider's capability to optimise treatment plans over time (Ley and Putz 2024). These challenges highlight a fundamental issue: while home-based physiotherapy offers accessibility, the lack of connection between objective assessment and clinical practice makes it difficult to ensure that patients are following their treatment plans effectively and experiencing optimal outcomes.

VR technology has shown promise in addressing these limitations for various clinical conditions, such as stroke rehabilitation and cerebral palsy (Dockx et al. 2016; Laver et al. 2017). By creating immersive, interactive environments, VR can enhance patient engagement, potentially improving the low adherence rates seen in traditional home programmes. Furthermore, VR systems can provide the real-time feedback that is notably absent in conventional home-based approaches, allowing patients to correct their exercise form immediately. However, the effectiveness and feasibility of VR interventions specifically for CKP remain unexplored, presenting an important gap in the literature that warrants further investigation.

1.2 Research Gap

A critical gap exists in current physiotherapy practice regarding the development of home-based exercise solutions for individuals with CKP that effectively address the barriers and limitations identified earlier: limited supervision, difficulty maintaining proper form, low adherence rates, lack of real-time feedback, and inadequate progress monitoring. While VR technology has shown promise in various rehabilitation contexts (Dockx et al. 2016; Laver et al. 2017), several significant gaps remain in the research literature.

First, there is limited evidence regarding the usability and acceptability of VR-based systems designed for home-based therapeutic exercise delivery for CKP patients. Studies by Gumaa and Rehan Youssef (2019) have shown promising results for VR applications in knee rehabilitation, while Rutkowski et al. (2020) demonstrated positive user experiences with VR-based exercise systems among older adults.

However, these studies primarily focused on clinical settings rather than home environments, and few specifically targeted the CKP population. Jin et al. (2018) conducted one of the few studies examining home-based VR for knee conditions, but their research focused primarily on post-surgical rehabilitation rather than chronic pain management. Understanding these usability and acceptability factors is essential because they directly affect whether patients engage with and continue using these technologies in their everyday environments, particularly given the unique challenges CKP patients face regarding pain management during exercise.

Second, research is limited in determining appropriate challenge levels in VR-based rehabilitation exercises that balance difficulty with achievability to maintain patient motivation. For the purposes of addressing this gap, 'biomechanically challenging' is defined as VR exercises that demonstrate progressive increases in movement demands, measured through joint range of motion and muscle activation patterns. This ensures exercises provide sufficient stimulus for therapeutic benefit while remaining achievable for individuals with CKP. However, current research lacks an evaluation of how VR systems can deliver such progressive, measurable challenges that appropriately stress the musculoskeletal system without exceeding individual capabilities. Third, the evidence base is insufficient regarding the reliability and accuracy of VR systems in monitoring exercise performance and providing feedback that ensures correct execution: a crucial factor, given that proper form directly affects therapeutic outcomes (Brennan et al. 2020).

Additionally, safety considerations regarding the setup and operation of VR toolkits within home environments remain underexplored, particularly for older adults or those with mobility limitations, who comprise a significant portion of the CKP population. These gaps collectively highlight the need for physiotherapists to adopt new technological approaches that can help CKP patients to adhere to their exercise programmes and engage effectively from home while ensuring that the biomechanical quality of exercises matches what would be achieved under direct clinical supervision (Koh et al. 2017).

1.3 Thesis Aim and Structure

The primary aim of this thesis was to evaluate an in-house purpose-built VR-based physiotherapy toolkit for individuals with CKP. The VR toolkit consists of a structured exercise programme delivered through five VR-based physiotherapy scenarios. Participants engage in guided movements, which are captured by a Microsoft Kinect v2 sensor. This sensor employs infrared depth camera technology to track full-body skeletal movements with a resolution of 512 × 424 pixels at 30 frames per second. It can track up to 25 anatomical landmarks simultaneously, allowing for precise measurement of joint angles, movement velocity, and ROM during therapeutic exercises, all without requiring participants to wear markers or additional equipment (Wang et al. 2015).

The evaluation of this VR-based physiotherapy system was structured around three key objectives, which define the framework of this thesis into three parts:

Part 1: Systematically identifying, summarising, and evaluating the quality of literature investigated the potential of VR in therapeutic exercises (Chapter 3).

Part 2: Exploring whether the VR games are ‘fit-for-purpose' by providing an appropriate level of challenge and accurately mirroring exercises, assessed through joint ROM and muscle activities to ensure that they meet the physical therapy needs (Chapter 5).

Part 3: Evaluating the usability and acceptability of the VR prototype toolkit among participants with CKP (Chapter 5).

The three parts of this thesis are linked to provide a comprehensive evaluation of the VR toolkit. Part 1 (umbrella review) identifies evidence gaps regarding VR's biomechanical accuracy and usability in knee rehabilitation. Despite promising results, the review revealed a lack of evidence on whether virtual exercises produce the same joint movements and muscle activity as traditional therapy exercises. The review also found limited research on user acceptance and usability factors that determine whether patients will successfully use VR systems at home, establishing the literature-based foundation and research priorities that directly inform Parts 2 and 3. Part 2 measures whether VR exercises can provide movement challenges by examining joint movement and muscle activity as the exercises progress to more difficult levels, resulting in higher activation patterns and greater ROM. Part 3 tests whether people with CKP find the VR toolkit easy to use and acceptable for their rehabilitation.

1.4 Research Approach

The evaluation of the VR-based physiotherapy toolkit in this study was primarily guided by the Medical Research Council (MRC) framework for complex interventions, with the Technology Acceptance Model (TAM) applied as a complementary framework during the development phase (Davis 2014; Skivington et al. 2021). The MRC framework was selected to provide a methodologically robust and evidence-informed approach for intervention development.

The MRC framework structures the development and evaluation of complex interventions through four phases: development, feasibility, evaluation, and implementation (Figure 1). It identifies six core elements to consider throughout: context, programme theory, stakeholder engagement, key uncertainties, intervention refinement, and economic considerations (Skivington et al. 2021). This PhD thesis specifically focused on the development stage of the framework, incorporating most of the six elements outlined in Table 1. The development work has produced a structured exercise toolkit for individuals with CKP, delivered through five VR scenarios. Future research beyond this PhD may progress to the feasibility, evaluation, and implementation phases of the MRC framework.

Table 1: MRC Framework Core Elements aligned with the Current PhD Thesis.

MRC Framework Stages	Core Elements	How it aligned with this PhD Thesis
Development Stage	Consider context	A comprehensive literature review was conducted to explore the gaps in the current evidence concerning using VR-based physiotherapy intervention for individuals with CKP.
	Develop, refine, or (re) test programme theory	The discussion chapter addressed the programme theory's development, refinement, and testing. The VR toolkit testing findings informed our understanding of how and why the toolkit will work in practice.
	Engage stakeholders	- Engaging the end-users of the VR-toolkit (patients with CKP) to evaluate the biomechanical challenges of the system. - Understanding and evaluating user acceptance of VR technology.
	Identify key uncertainties	Identifying the key uncertainties involved reviewing published research evidence related to VR-based physiotherapy interventions. This helped in exploring the potential of using VR in physiotherapy intervention for people with knee pain, and

		this was covered in the umbrella review (Chapter 3)
	Refine intervention	This element has not been covered in this thesis, but it would be part of the future recommendation based on the suggestions collected from the participants during the Think Aloud session in the Usability study.
	Economic considerations	This element is beyond the scope of this thesis.

Within the development phase of the MRC framework, specifically in the stakeholder engagement element, the TAM is integrated to address specific aspects of user acceptance. The TAM provided a structured approach to understanding and evaluating how users interacted with and accepted the VR technology (Taherdoost 2018). This model focuses on two key factors influencing user behaviour: perceived usefulness (the degree to which a person believes that using the technology will enhance their performance) and perceived ease of use (the extent to which a person believes that using the technology will be easy) (Davis 1987). These perceptions directly influence users' attitudes toward and intentions to use the VR-based physiotherapy system (Taherdoost 2018).

By incorporating TAM into the development phase, this study adopted a user-centred approach to guide refinements to the VR toolkit. This ensured that modifications were informed by user needs and experiences, rather than solely technical factors. The TAM's constructs offered targeted, actionable insights into both the technical and therapeutic aspects of the toolkit. This phase addressed the third part of the thesis: to evaluate the usability and acceptability of the VR prototype toolkit among participants with CKP. This was achieved using a think-aloud methodology and the System Usability Scale (SUS), allowing participants to verbalise their thoughts and experiences during the VR use. The resulting data was analysed through quantitative content analysis, providing a systematic approach to evaluating user acceptance and usability within the TAM's key constructs of perceived usefulness and ease of use.

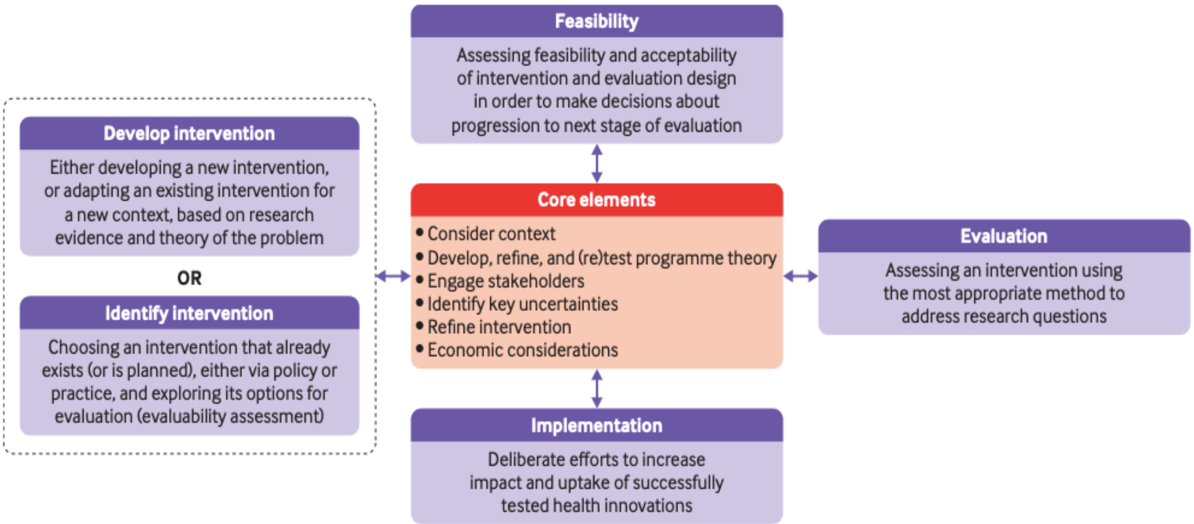


Figure 1: Stages of the MRC Framework.

1.5 The Contribution of this Work

This project makes specific contributions to VR therapy research by evaluating a novel toolkit aligned with the development phase of the MRC framework. The integration of biomechanical analysis and think-aloud feedback, combined with systematic evidence synthesis, has produced a theoretically informed VR toolkit that can now progress toward the feasibility and evaluation phases of the MRC framework. This structured developmental approach establishes a foundation for future clinical testing of VR applications in physiotherapy settings.

More specifically, this project addresses the management challenges of CKP by creating an evidence-based, user-tested VR exergaming solution designed for home use. CKP typically requires ongoing rehabilitation exercises; however, traditional home exercise programmes encounter significant challenges related to adherence and proper technique. The VR toolkit developed in this research merges therapeutic exercises with game elements to potentially enhance both exercise accuracy and programme adherence.

The home-based nature of this VR toolkit directly addresses accessibility barriers, including transportation difficulties, time constraints, and financial costs associated with frequent in-person therapy appointments. This approach may allow patients to perform guided exercises more consistently while receiving visual feedback on their performance, potentially extending the reach of effective rehabilitation to populations with limited access to physical therapy services.

1.6 Structure of the Thesis

This thesis comprises seven chapters, systematically structured to address the research aims and objectives:

Chapter 1 presents a brief background to CKP, highlighting it as a significant health challenge. It outlines the primary methodological frameworks guiding the research and explains how each informs the study's aim and evaluation parts. The chapter concludes with an overview of the thesis structure to guide the reader through the subsequent chapters.

Chapter 2 provides a narrative review of existing literature on the prevalence and impact of CKP. It critically examines current physiotherapy approaches and their limitations, alongside the evolving role of VR in healthcare. The chapter identifies inconsistencies in existing studies due to varying technologies, outcome measures, and populations, establishing the need for a higher-level synthesis.

Chapter 3 presents an umbrella review using JBI methodology to synthesise evidence on VR interventions for knee pain (Aromataris and Munn 2020). This approach addresses the study's first objective by comprehensively evaluating current evidence through a rigorous search strategy across multiple databases. The chapter details the screening process and quality assessment using the AMSTAR-2 tool, while examining review overlap with the Corrected Covered Area (CCA) index (Pieper et al. 2015; Shea et al. 2017). The findings synthesise key outcomes, including pain, physical function, and quality of life. The review identifies important knowledge gaps, limited research on home-based VR applications, insufficient exercise parameters, and a lack of standardised protocols which inform subsequent research objectives on kinematic evaluation and usability assessment of home-based VR exercise toolkits.

Chapter 4 presents the methodological framework and research design, highlighting the role of Patient and Public Involvement (PPI) and its impact on the delivery of the toolkit. This study answers the second and third objectives, providing an overview of the Virtual Reality-based toolkit and technical equipment used.

The chapter details the study design, sampling methods, recruitment process, participant characteristics, study setting, and data collection tools. It describes the outcome measures employed and outlines the research process, which began with a pilot study, followed by ethical amendments, and then the refined data collection phase. The chapter concludes with an explanation of the data processing and analysis methods, as well as the ethical considerations and approvals obtained to ensure adherence to necessary ethical standards.

Chapter 5 presents the study results, beginning with participant demographics and characteristics. It provides detailed findings from both kinematic and usability analyses. The chapter thoroughly examines movement patterns across different VR exercise scenarios and investigates muscle activation patterns during these VR-guided exercises. The chapter includes quantitative content analysis of think-aloud data, showing the frequency distribution of identified codes and categories. It presents SUS scores with corresponding statistical analyses to evaluate user experience. User feedback undergoes quantitative analysis, creating a deeper understanding of participant experiences. Through statistical analysis of the coded data, key themes emerge regarding user interactions and system acceptance. The chapter concludes by synthesising these findings to provide a comprehensive evaluation of system usability and user acceptance of the VR-based physiotherapy toolkit.

Chapter 6 synthesises the findings across research parts, providing a comprehensive overview of the outcomes and their relevance. This chapter discusses the implications for clinical practice and home-based rehabilitation, highlighting how the results can influence patient care and rehabilitation strategies. Concludes by acknowledging the study limitations and their impact on the findings and future recommendations.

Chapter 7 The final chapter summarises the key conclusions drawn from this research.

CHAPTER 2: Literature Review

2.1 Introduction

This chapter provides an overview and background about the prevalence and physical impact of CKP on individuals. It presents a narrative literature review on current approaches in managing CKP, highlighting challenges such as adherence and barriers to exercise. The review further explores physiotherapy treatment using feedback modalities, types of feedback in rehabilitation, and the various motion capture technologies used for movement analysis. The chapter also discusses the use of VR in healthcare, focusing on its potential benefits for managing CKP.

An extensive literature search was conducted to identify gaps in the evidence. The chapter concludes by summarising these research gaps, which led to the need for the umbrella review presented in Chapter 3 and the subsequent development of the thesis's specific aims and objectives.

2.2 Search Strategy

This narrative review began with a thorough search for relevant studies using specific keywords that align with the project's aim. The literature search was organised using three databases: PubMed, Scopus, and CINAHL. It employed a structured approach based on the Population, Intervention, Comparator, and Outcomes (PICO) framework (Table 2). The goal was to identify studies exploring VR use in therapeutic exercises and the impact of feedback modalities on managing CKP.

Keywords related to the population were included, such as "Anterior Knee Pain Syndrome," "Pain Syndrome," "Patellofemoral Pain," "Patellofemoral Syndrome," "Knee Osteoarthritis," "Osteoarthritis of the Knee," "Chronic Knee Pain," "Patella Pain," and "Kneecap Pain." For the intervention, VR-related terms such as "Virtual Reality," "Virtual Reality Therapy," "Virtual Rehabilitation," "Non-immersive VR," "Exergaming", and "User-Computer Interface" were focused upon.

The outcomes considered included measures relevant to exercise adherence and therapeutic effects, such as "Kinematics," "Joint Angle," "Range of Motion (ROM)," "Electromyography (EMG),", "Motion capture”, “Motion analysis", "Pain," "Physical

Function," "Physical Fitness," and "Biomechanics." Additional keywords related to feedback modalities were also incorporated to assess their influence on exercise adherence and performance, including "Feedback," "Biofeedback," "Real-time Feedback," and "Visual Feedback."

To ensure comprehensive coverage while maintaining relevance, the search terms were combined using the Boolean operators "AND" and "OR." Each database's advanced search features were used to refine and filter the results. This systematic approach facilitated the identification of studies that addressed the role of VR in therapeutic exercises and the influence of feedback modalities on outcomes such as biomechanics, ROM, pain, physical function, and exercise adherence in CKP. Additionally, the reference lists of all reviewed publications were examined to identify further relevant material.

Table 2: Search Strategy following PICO Framework

Population	Intervention	Comparator	Outcome
Anterior Knee Pain Syndrome OR Pain Syndrome OR Patellofemoral OR Patellofemoral Pain OR Patellofemoral Pains OR Patellofemoral Syndrome OR Osteoarthritis of the Knee OR Knee Osteoarthritis OR OA OR Chronic knee pain OR patella pain OR kneecap pain.	Virtual Reality OR Virtual Reality Therapy OR Virtual Rehabilitation OR Non-immersive VR OR Exergaming, User-Computer Interface.	Usual care	Kinematics OR joint angle OR joint angles OR ROM OR range of motion OR EMG OR Electromyography OR centre of OR pain OR physical function OR physical fitness OR biomechanics.
			Feedback OR Biofeedback OR Real-time Feedback OR Visual Feedback

Specific inclusion and exclusion criteria were applied to ensure that articles were relevant to the project's scope (Figure 2). This involved focusing on studies that included individuals aged 18 and older experiencing CKP. Only articles written in English and available in full text were considered.

After an initial selection, the titles and abstracts of the identified publications were reviewed for final eligibility. Ultimately, 36 studies were included that best addressed the areas of interest in this project.

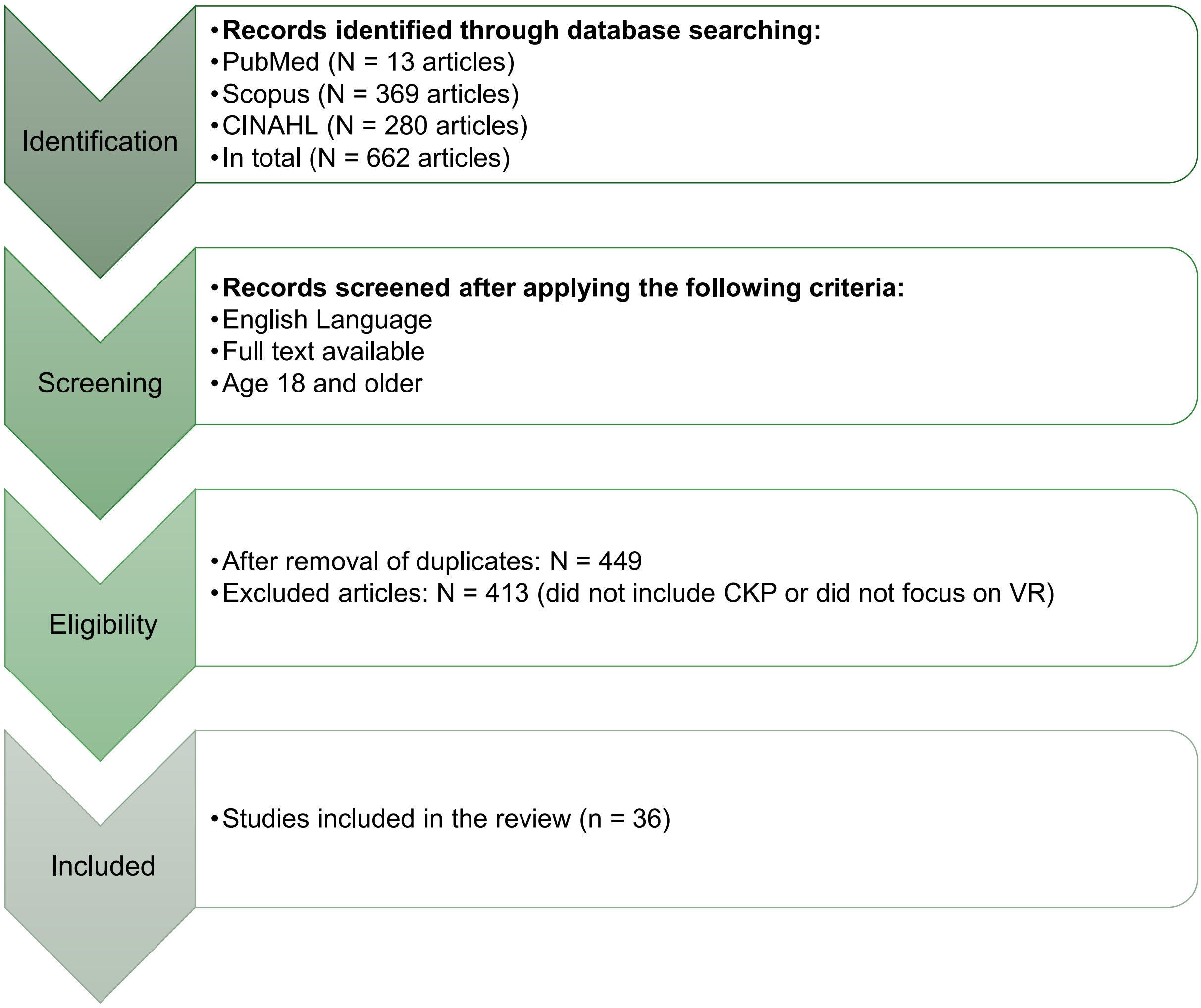


Figure 2: Search Strategy Flowchart

2.3 Overview of CKP

CKP is a common issue among middle-aged and older adults, often leading to significant disability. CKP can result from various causes, including injuries, mechanical problems, different types of arthritis, and other underlying conditions (Yasen 2023). Injuries to the knee can affect the ligaments, tendons, and bursae (fluid-filled sacs), as well as the bones, cartilage, and other structures within the joint (Yasen 2023).

Clinical assessment of CKP involves distinguishing between mechanical and inflammatory patterns of pain. Mechanical pain typically worsens with activity and improves with rest, while inflammatory pain often presents with morning stiffness lasting over 30 minutes and improves with movement (Heidari 2011). This distinction has important implications for treatment planning and prognosis. CKP's impact extends beyond physical limitations and significantly affects psychosocial well-being.

Research indicates that 30–50% of individuals with CKP report symptoms of anxiety or depression (Stubbs et al. 2016), which can create a bidirectional relationship where psychological distress amplifies pain perception, while persistent pain worsens mental health. This complex relationship necessitates multidimensional assessment approaches that capture both physical and psychological domains. The economic burden of CKP is substantial, with direct healthcare costs estimated at £300 million annually in the UK alone, while indirect costs from productivity loss and informal caregiving exceed £3.2 billion (Hunter and Bierma-Zeinstra 2019).

2.4 Prevalence of CKP

The prevalence of CKP varies significantly across studies due to inconsistencies in categorising underlying causes, differing definitions of chronic pain, and variations in study populations and methodologies. Recent data suggest that CKP affects approximately 10–20% of adults globally, with rates increasing markedly with age, particularly among individuals over 50 (Sammito et al. 2021). A systematic review by Pal et al. (2016) reported a 25–30% rise in the global prevalence of knee OA, a major contributor to CKP, over the past decade. This increase may be underestimated due to individuals' tendency to pursue self-management strategies, mainly through over-the-counter pain relievers, rather than seeking formal medical care.

UK epidemiological studies further highlight the significant burden of knee pain in specific populations (NICE 2022). Among adults aged 16 years and older, 19% report experiencing knee pain lasting more than one week, with a notably higher prevalence among older adults (Templeton 2020). Sex-specific differences become apparent in those aged 75 years or older, where prevalence reaches 36% in women compared to 27% in men (Tschon et al. 2021). The impact of severe knee pain extends beyond prevalence alone, with 12% of the population experiencing severe symptoms and 6% reporting associated disability (Overstreet et al. 2023). While OA is the predominant cause of knee pain in adults over 45, patellofemoral pain syndrome demonstrates a higher prevalence among adolescents and females, with an annual prevalence of 22.7% in the general population (Smith et al. 2018).

The significant variability in CKP prevalence aligns with earlier findings by Fejer and Ruhe (2012), who observed prevalence estimates ranging from 6% to 63.4% among older adults. These wide-ranging estimates reflect differences in chronic pain definitions and variations in assessment methodologies, population demographics, and cultural factors influencing pain reporting. Such disparities highlight the challenges in establishing comparable epidemiological data across different studies and populations.

Recent literature has emphasised the need to standardise chronic pain diagnostic approaches, recognising CKP as a distinct clinical condition (Neogi 2013; Sluka 2016; Raja et al. 2020). Multiple factors, including mechanical dysfunction, arthritis, and nerve sensitisation, contribute to CKP's persistent and severe nature. Developing uniform diagnostic criteria and implementing comprehensive epidemiological studies are crucial steps toward accurately assessing and managing CKP across diverse populations.

2.5 Management of CKP

2.5.1 Assessment and Diagnosis

The initial management of CKP starts with a comprehensive assessment to determine its underlying cause. The most common cause is OA, especially in individuals over 50 (Jevsevar 2013; Wood et al. 2023). Several other conditions can lead to CKP, including rheumatoid arthritis, post-traumatic arthritis, and patellofemoral pain syndrome (Rixe 2013). Accurate diagnosis is essential and can be achieved through physical examinations, imaging studies, and possibly specialised tests. This diagnosis will help guide the selection of appropriate treatment options (Jevsevar 2013).

2.5.2 Conservative Management Strategies

The comprehensive management of CKP aims to improve joint function, alleviate pain, and address its broader physical and psychosocial impacts. That involves a multimodal approach incorporating behavioural, educational, psychosocial, and physical interventions alongside pharmacological options such as oral, topical, and intra-articular medications (Zhu 2024). Management strategies are tailored to individual patient needs, with interventions applied sequentially or combined based on disease severity, comorbidities, and personal preferences (Hochberg et al. 2012; Kolasinski et al. 2020).

2.5.3 Patient-Centred Management

Effective management plans consider personal preferences, beliefs, and co-existing medical conditions, such as cardiovascular disease, hypertension, or chronic kidney disease, which may influence the suitability of pharmacological treatments (Hochberg et al. 2012). Access to healthcare services has a significant impact on treatment decisions and outcomes. According to Ali et al. (2018), rural patients encounter considerable barriers to care, such as geographic isolation and limited access to community services. Their qualitative study focused on rural patients with OA and revealed that many struggled to maintain a long-term relationship with a general practitioner. Rural participants often turn to emergency departments for their OA needs due to limited access to primary care. Moreover, the study found that while rural patients know about arthritis support organisations, very few use them (Ali et al. 2018). Additionally, rural participants reported travelling long distances to urban centres for specialist care, with one individual stating, "I only get information when I see my doctor in the urban setting once a year" (Ali et al. 2018, p.420). These geographic and systemic barriers significantly impact the treatment options available to patients and must be addressed to ensure that interventions are practical and feasible for everyone.

CKP is often accompanied by anxiety, depression, mood disorders, chronic widespread pain, sleep disturbances, and impaired coping skills (Zeng et al. 2021). Multimodal treatment approaches are essential for managing these complexities, integrating strategies that reduce stress, improve mood, enhance fitness, and address sleep disturbances. Behavioural and mind-body therapies are recommended to optimise outcomes as adjuncts to physical treatments (Kolasinski et al. 2020; Zhu 2024).

2.5.4 Non-Pharmacological Interventions

Non-pharmacological strategies form the foundation of CKP management. These include:

2.5.4.1 Exercise Therapy

Structured exercise therapy is widely recognised as a cornerstone of treatment, with evidence supporting its benefits in reducing pain, improving joint mobility, and enhancing quality of life (Fransen et al. 2015). Supervised exercise programmes, particularly those tailored to patient preferences, are the most effective, and include aerobic, strength-based, and neuromuscular exercises. Importantly, no single exercise type has proven superior, allowing interventions to be individualised (Young et al. 2023). Innovative delivery methods, such as telehealth platforms like GLAD and ESCAPE Pain, have further expanded accessibility (Barber and Jahanbani 2024).

2.5.4.2 Weight Management

Weight loss is particularly beneficial for overweight or obese individuals, with a 5–10% reduction in body weight significantly improving symptoms and physical function (Dantas 2021). Combining dietary interventions with exercise is more effective than either strategy alone.

2.5.4.3 Patient Education

Education empowers patients to self-manage their condition, dispels misconceptions, and encourages treatment adherence. Tailored educational materials, such as digital tools for younger patients and printed guides for older adults, improve accessibility and engagement. Addressing behavioural impacts, such as fear of activity or social isolation, further enhances the effectiveness of educational strategies (Dantas 2021; Barber and Jahanbani 2024).

2.5.4.4 Adjunct Therapies

Complementary interventions, including assistive devices (e.g., braces, orthotics), thermotherapy, Pilates, aquatic therapy, and Kinesio taping, support traditional approaches by improving mobility and reducing pain. These methods are particularly valuable for patients with severe symptoms or mobility limitations (Somaiya 2024).

2.5.5 Pharmacological Interventions

Pharmacological treatments are often used as adjuncts to nonpharmacological strategies. Topical and oral NSAIDs are recommended for their efficacy in pain relief, with oral options reserved for short-term use due to potential side effects. Intra-articular corticosteroid injections provide temporary pain relief for patients who are unresponsive to NSAIDs, though caution is advised for prolonged use due to diminishing efficacy (Zhu 2024). Emerging therapies, such as platelet-rich plasma (PRP) injections, show promise but require further research to establish long-term benefits (Zhu 2024).

2.5.5.1 Surgical Interventions

For patients with advanced-stage knee OA unresponsive to conservative measures, surgical options like total knee replacement (TKR) may be considered. While TKR offers significant pain relief and functional improvement, it carries risks of persistent pain and complications, underscoring the importance of careful patient selection and comprehensive postoperative rehabilitation (Zhu 2024).

In summary, CKP requires a personalised, multimodal management approach that integrates nonpharmacological strategies, pharmacological treatments, and, when necessary, surgical interventions. Exercise therapy, weight management, and patient education form the foundation of treatment, addressing both physical and psychosocial impacts.

2.6 Therapeutic Exercise Types for CKP Management

An effective exercise prescription includes four essential components: cardiorespiratory fitness, muscular strength, flexibility, and body composition. Studies demonstrate a direct relationship between physical activity levels and various health outcomes, including overall mortality (Lee et al. 2012; Yu et al. 2021), cardiorespiratory function (Myers et al. 2019), metabolic health (Colberg et al. 2016), weight management (Swift et al. 2018), bone density (Daly et al. 2019), cancer risk reduction (Patel et al. 2019), and sleep quality (Dolezal et al. 2017).

For individuals with arthritis specifically, regular physical activity has been shown to reduce pain, improve function, and enhance quality of life (Kelley et al. 2018; Versus Arthritis 2022). To ensure optimal results, these prescriptions should be personalised, considering four key adjustable variables: frequency, intensity, duration, and type (FITT) (Piercy et al. 2018). The following sections will provide detailed explanations of types of exercises that can be used to manage patients with CKP, followed by the supporting biomechanical studies.

2.6.1 Strengthening Exercises

Strengthening exercises are the cornerstone of therapeutic exercise programmes for CKP. These interventions specifically target the muscles supporting the knee joint to improve stability and function (Bannuru et al. 2019). Resistance training emphasises the development of the quadriceps, hamstrings, and hip abductor muscle groups, which play crucial roles in stabilising the knee during weight-bearing activities (Kolasinski et al. 2020).

Research indicates that progressive strength training can effectively reduce pain intensity while improving physical function in individuals with CKP (Fransen et al. 2015). Progressive resistance protocols typically start with isometric exercises, which reduce joint stress while building foundational strength (Bannuru et al. 2019). As tolerance improves, the exercises gradually progress to include concentric and eccentric loading patterns (Bannuru et al. 2019). The effectiveness of strengthening exercises appears to be dose-dependent, with programmes lasting 12 weeks or longer showing more substantial clinical benefits compared to shorter interventions (Bannuru et al. 2019).

The efficacy of strengthening exercises is supported by numerous high-quality systematic reviews and randomised controlled trials (RCTs) (Juhl et al. 2014; Fransen et al. 2015). A comprehensive meta-analysis conducted by Juhl et al. (2014) evaluated 48 RCTs to establish the value of strengthening exercises. This study found that programmes focused primarily on strengthening the quadriceps led to greater pain reduction compared to more generalised exercise approaches. Their analysis indicated that the best results were achieved with sessions performed three times a week, highlighting that the frequency of exercise is a crucial factor in treatment outcomes.

Complementing these findings, a significant Cochrane systematic review conducted by Fransen et al. (2015) examined 54 RCTs involving 3,913 participants. The review found moderate-quality evidence that land-based exercise programmes can reduce pain and enhance physical function in patients with knee OA. Specifically, it reported standardised mean differences of -0.49 for pain reduction and -0.52 for improvement in physical function, indicating clinically meaningful benefits.

Despite existing evidence, important questions remain about the optimal implementation of strengthening programmes for OA. These programmes exhibit significant variability in their design. A systematic review by Bartholdy et al. (2017) investigated the relationship between changes in muscle strength and clinical outcomes in patients with knee OA. The authors discovered that higher exercise intensities led to greater improvements in muscle strength; however, the link between strength gains and pain reduction was only moderate. This suggests that other factors may also play a role in clinical improvement.

Programme effectiveness is further complicated by adherence challenges. Bennell et al. (2014) emphasised that while immediate benefits after interventions can be considerable, maintaining long-term adherence poses a significant challenge. A systematic review by Nicolson et al. (2017) specifically explored interventions aimed at increasing adherence to therapeutic exercise among older adults with knee OA. Their findings indicated that strategies such as booster sessions, activity monitoring, and behavioural change techniques show promise, but further investigation is necessary.

There is a significant research gap in understanding how to tailor strengthening protocols to individual needs. A systematic review by Dell'Isola et al. (2016) identified distinct phenotypes of OA that may respond differently to various interventions, including different strengthening methods. However, the authors pointed out that there is a lack of validation studies that confirm improved outcomes through approaches tailored to these phenotypes (Dell'Isola et al. 2016).

The evidence strongly supports the importance of strengthening exercises for managing CKP, while emphasising several critical considerations to optimise their effectiveness. Exercise prescriptions should be tailored based on factors such as sex, body mass, and pain patterns, as different patient populations require specific movement strategies and exercise modifications. Future research should focus on developing comprehensive, individualised approaches that consider patient-specific factors and use technological advancements in assessment and monitoring. Additionally, studies that explore the relationship between short-term exercise adherence and long-term outcomes would offer valuable insights for enhancing rehabilitation programmes.

2.6.2 Aerobic Exercises

Aerobic exercise is a crucial part of therapeutic exercises for CKP, providing benefits that go beyond improving the local joint to enhance overall physical health and quality of life (Tanaka et al. 2013). It increases heart rate and breathing intensity, and encompasses a wide range of activities, including walking, running, cycling, cross-country skiing, swimming, and dancing (Kaya Utlu 2023). A systematic review and meta-analysis conducted by Fransen et al. (2015) revealed that land-based exercise interventions, which included aerobic components, resulted in clinically meaningful improvements in pain (SMD -0.49; 95% CI -0.39 to -0.59) and physical function (SMD -0.52; 95% CI -0.39 to -0.64) for patients suffering from knee OA. These findings are backed by several systematic reviews that consistently demonstrate the effectiveness of regular aerobic activity in reducing pain and enhancing function for individuals with knee OA (Semanik et al. 2012; Tanaka et al. 2013; Juhl et al. 2014).

The physiological mechanisms by which aerobic exercise produces therapeutic effects are complex. Brosseau et al. (2017) noted in their clinical practice guidelines that low-impact aerobics activities such as stationary cycling, water-based exercises, and elliptical training effectively promote cardiovascular conditioning while minimising compressive and shear forces on the knee joint. This protective benefit is important for individuals with moderate to severe joint pathology, where high-impact activities may worsen symptoms (Brosseau et al. 2017).

Aerobic exercise seems to modulate pain through various pathways. A randomised controlled trial by Juhl et al. (2014) revealed that participants who engaged in aerobic exercise three times a week for twelve weeks exhibited significant improvements in pain thresholds compared to non-exercising controls, attributing these changes to enhanced endogenous opioid production and improved descending pain inhibitory mechanisms (Juhl et al. 2014). Furthermore, Bennell et al. (2016) indicated that regular aerobic activity was linked to reductions in systemic inflammatory markers, including C-reactive protein and interleukin-6, suggesting a possible anti-inflammatory mechanism contributing to symptom improvement.

The dosage parameters for optimal aerobic exercises have been examined in several studies (Garber et al. 2011; McAlindon et al. 2014). The ACSM guidelines compiled by Garber et al. (2011) recommend 150 minutes of moderate-intensity aerobic activity weekly, divided into sessions of at least 10 minutes. However, McAlindon et al. (2014) found in their systematic review that significant benefits for knee OA patients could be achieved with modified protocols of 20–30 minutes of low-impact aerobic activity 2–3 times per week. This suggests that even adjusted protocols provide meaningful clinical benefits for this population.

A significant advantage of aerobic exercise lies in its systemic effects (Quicke et al. 2015). While strengthening exercises mainly target local neuromuscular impairments, aerobic training enhances cardiorespiratory fitness, which Brosseau et al. (2017) identified as independently associated with reduced disability and improved function among patients with knee OA. Furthermore, Quicke et al. (2015) demonstrated in their longitudinal analysis that the maintenance of aerobic fitness was linked to slower disease progression and a decreased likelihood of needing surgical intervention over a 5-year follow-up period.

The selection of specific aerobic modalities should consider individual factors, including symptom severity, comorbidities, and preferences (Bartels et al. 2016). Aquatic exercise has shown efficacy for patients experiencing substantial pain or obesity, as documented by Bartels et al. (2016) in their Cochrane review, which presented moderate-quality evidence for pain reduction (SMD −0.31; 95% CI −0.47 to −0.15) and improvement in function (SMD −0.32; 95% CI −0.47 to −0.17) with aquatic interventions.

2.6.3 Neuromuscular Training

Neuromuscular training has gained attention as a standalone intervention for addressing the proprioceptive deficits commonly seen in chronic knee conditions. It aims to improve balance, coordination, and joint position awareness through progressive activities (Piercy et al. 2018). These deficits often result in impaired joint position sense, delayed muscle activation patterns, and reduced dynamic stability (Ageberg and Roos 2015; Hall et al. 2015).

The effectiveness of neuromuscular training as a standalone intervention was investigated by Ageberg et al. (2013) in a study involving patients with moderate knee OA. They implemented a 12-week neuromuscular training programme without additional strength training. This randomised controlled trial (RCT) demonstrated significant improvements in self-reported functional outcomes, particularly on the

KOOS (Knee Injury and Osteoarthritis Outcome Score) activities of daily living (ADL) subscale, which recorded an average increase of 9.8 points ($p < 0.01$).

Additionally, participants experienced a significant reduction in pain during activities, as indicated by a decrease of 2.1 points on the Visual Analogue Scale (VAS) ($p < 0.01$) when compared to a control group that received only patient education. Notably, these improvements were achieved without any concurrent increase in quadriceps strength, indicating that the clinical benefits resulted from neuromuscular mechanisms rather than strength gains.

Bennell et al. (2016) studied the effects of neuromuscular training by comparing a structured programme of balance and proprioceptive exercises with a sham intervention. Their findings revealed that participants in the neuromuscular training group experienced significant improvements in knee joint position sense, with a mean improvement of 2.4 degrees ($p < 0.001$), as well as enhancements in dynamic balance, measured using the Star Excursion Balance Test, with an improvement of 6.7 cm ($p < 0.01$) after 8 weeks. Additionally, these improvements in proprioceptive function were significantly correlated with reductions in pain ($r = -0.64$, $p < 0.001$), providing direct evidence of the link between improved neuromuscular control and symptomatic relief.

Despite promising evidence, there are several limitations in the current research on standalone neuromuscular training. Most studies have employed relatively short intervention periods, typically ranging from 8 to 12 weeks, and data on long-term follow-up remains limited. Liu et al. (2017) noted significant variability in neuromuscular training protocols, which makes direct comparisons between studies challenging. They emphasised the need for standardised assessment protocols and clear guidelines for progression specifically related to neuromuscular interventions.

Future research should focus on several critical areas: determining the optimal progression of neuromuscular challenges, investigating the long-term retention of neuromuscular adaptations, establishing clear dosage parameters (including frequency, intensity, and duration), and identifying patient characteristics that predict the optimal response to standalone neuromuscular training versus combined approaches.

2.7 Supporting Biomechanical Studies

Biomechanics refers to the study of how forces affect the body during movement and how the body's structures respond to these forces (Winter 2009; Neumann 2024). In the context of CKP, biomechanical analysis provides crucial insights into how the knee joint and surrounding tissues function during different activities and how therapeutic exercises modify these mechanics (Powers et al. 2014). While previous sections have established the clinical effectiveness of various exercise types, biomechanical investigations help to clarify the underlying mechanisms by which these exercises produce clinical benefits (Hunt et al. 2011; Andriacchi et al. 2015).

Individuals with CKP often develop altered movement patterns as a protective strategy to reduce pain (Heiden et al. 2009; Felson 2013). However, these compensatory strategies may create additional stress on joint structures and contribute to disease progression (Mills et al. 2013; Andriacchi et al. 2015). Bouchouras et al. (2015) demonstrated that patients with OA exhibit distinct muscle activation patterns and co-contraction strategies that aim to protect the joint during functional movements. These altered patterns, while initially protective, may lead to increased joint loading and accelerated cartilage degeneration over time (Hodges and Tucker 2011; Simic et al. 2011).

Recent studies by Fu et al. (2021) and Pan et al. (2023) have revealed that even in the early stages of knee OA, patients already show altered muscle activation patterns and limitations in their ROM. This finding underscores the importance of early intervention with appropriately designed exercise programmes that address these biomechanical alterations before they become embedded movement habits. The following sections detail how biomechanical factors influence exercise effectiveness and how different types of exercises affect joint mechanics in patients with CKP.

Biomechanical research has identified significant sex-specific differences in movement patterns that greatly influence how individuals respond to exercise interventions. Segal et al. (2013) found that higher-functioning men demonstrated a greater sagittal hip ROM (111.4°) compared to moderate-functioning men (93.6°), suggesting that males tend to enhance functional performance by using increased hip mobility. In contrast, higher-functioning women exhibited a reduced sagittal knee

ROM (82.7°) compared to lower-functioning women (94.3°), with stronger hip abductor muscles contributing to improved functional outcomes. These findings have significant clinical implications for exercise prescription. Rehabilitation programmes should be tailored to address these sex-specific movement patterns, with men probably benefiting more from exercises that enhance hip mobility and women from interventions that strengthen hip abductors while promoting controlled knee motion.

On the other hand, Verlaan et al. (2018) demonstrated that obese patients with knee OA exhibited significantly reduced sagittal knee range of motion (75.9°) compared to lean patients (85.8°) and healthy controls (85.5°) during functional movements. This restriction in movement directly impacts how these individuals perform exercises and may require specific modifications to standard protocols (Verlaan et al. 2018). Increased body mass places a greater mechanical load on the knee joint, altering movement strategies and potentially reducing the effectiveness of exercise if not properly accounted for (Verlaan et al. 2018). These findings highlight the need to adjust strengthening exercise prescriptions based on each individual's body composition profile, as obese patients may require more gradual progression and modifications to decrease joint loading.

Biomechanical studies have provided valuable insights into the safety and effectiveness of specific strengthening exercises. Brenneman et al. (2016) found that pain had minimal impact on muscle activation patterns during lunge exercises, which supports their inclusion in rehabilitation programmes aimed at improving strength and knee function, even for patients with mild to moderate pain.

Wood et al. (2016) conducted a systematic review on squats and lunges for the rehabilitation of patellofemoral pain (PFP). Their biomechanical analysis revealed that the forces on the patellofemoral joint increase with knee flexion, peaking at 90° before decreasing with additional flexion (Wood et al. 2016). These forces exceed those in open-chain exercises, particularly beyond 60° of knee flexion. Based on these findings, they recommended limiting knee flexion to less than 60° during these exercises for patients with PFP and especially avoiding flexion beyond 90° due to significantly heightened joint loading (Wood et al. 2016). These biomechanical insights assist clinicians in creating safer and more effective strengthening programmes by choosing exercises with suitable joint loading profiles tailored to each patient's condition and pain level.

Understanding the biomechanical impact of knee OA on gait mechanics provides critical information for developing effective aerobic exercise interventions. Schmitt and Rudolph (2008) found that individuals with unstable knees exhibited higher levels of medial muscle co-contraction during walking, especially during the preparation and weight acceptance phases. While this increased muscle activation served as a compensatory strategy to manage instability, it proved ineffective in reducing it and was associated with decreased knee motion, potentially contributing to disease progression.

Bennell et al. (2014) demonstrated that aerobic walking programmes can modify these altered gait patterns by reducing excessive co-contraction and improving knee joint kinematics. The normalisation of joint loading patterns may explain the clinical improvements observed with aerobic exercise interventions beyond their systemic effects on pain and inflammation (Bennell et al. 2014). These biomechanical findings have important implications for aerobic exercise prescription, suggesting that interventions should not only focus on cardiovascular benefits but also address specific gait alterations that may contribute to pain and joint deterioration.

Biomechanical research shows clear evidence of how neuromuscular training helps to improve movement and reduce pain. Unlike general strengthening exercises, which mainly boost muscle strength, neuromuscular training focuses on improving movement quality and coordination.

Knoop et al. (2013) found that an 8-week proprioceptive training programme significantly reduced side-to-side knee motion during single-leg standing by 1.8 cm and enhanced knee control while walking, without a significant increase in quadriceps strength. This indicates that the improvements came mainly from better neuromuscular coordination instead of just increased muscle strength (Knoop et al. 2013).

Bennell et al. (2015) provided further evidence using electromyography (EMG) that proprioceptive training led to a 14.3% reduction in co-contraction between the Vastus Lateralis and Biceps Femoris muscles during walking. This reduction in unnecessary muscle activity was linked to decreased pain and improved function, highlighting a distinct mechanism of benefit from neuromuscular interventions.

Ebben's (2008) EMG studies demonstrated that single-leg balance exercises activate important knee stabilising muscles at levels sufficient to induce training effects (over 40% of maximal voluntary contraction) while minimising high joint loads (Ebben et al. 2008). This provides physiological justification for using these exercises, particularly for patients unable to tolerate high-load strength training (Hunt et al. 2010). Hunt et al. (2010) identified that individuals with pronounced baseline proprioceptive deficits showed the strongest response to neuromuscular training ($r = 0.72$, $p < 0.001$), suggesting that targeting these interventions to patients with specific biomechanical impairments may optimise outcomes.

Further research by Marcori et al. (2022) indicated that single-leg balance training resulted in greater improvements in both static and dynamic balance compared to double-leg training, with a 23.4% enhancement in centre of pressure (COP) excursion versus 9.7% in the double-leg group. These biomechanical improvements correlated with increased pain reduction during daily activities (Marcori et al. 2022).

Another line of evidence supporting standalone neuromuscular training comes from studies focusing on centre of mass (COM) control. Hsu et al. (2010) demonstrated that individuals with knee OA tended to adopt conservative COM control strategies during functional activities, prioritising stability over mobility. A follow-up intervention showed that six weeks of COM control training led to improvements in COM–COP control during walking. Specifically, there was a reduction in COM–COP separation by 1.9 cm ($p < 0.01$), and self-reported instability improved by 2.1 points on a 10-point scale ($p < 0.01$).

Lee et al. (2021) expanded on this research by demonstrating that neuromuscular training focused on controlling the COM specifically improved weight transfer during the transition from double-limb to single-limb support while walking. This phase is critical for maintaining dynamic stability. The improvement in COM control was linked to a 35% reduction in self-reported instances of the knee "giving way" ($p < 0.01$), providing strong evidence that neuromuscular mechanisms can significantly enhance knee stability during functional activities.

Sabashi et al. (2022) made significant contributions to understanding the specific neuromuscular adaptations that occur with standalone balance training. They demonstrated that after 10 weeks of balance exercises, patients with knee OA shifted from a hip-dominant to a more ankle-dominant strategy for maintaining a quiet stance. This change in postural control strategy was associated with a reduction in pain, as indicated by a 1.9-point decrease on the VAS ($p < 0.01$), and improved functional performance, with a 2.3-second improvement on the Timed Up and Go test ($p < 0.01$).

The biomechanical studies discussed earlier demonstrate the importance of evaluating movement patterns and individualising exercise interventions to optimise therapeutic outcomes for patients with CKP. These findings emphasise the importance of personalised approaches that consider each patient's individual traits and movement styles. Exercise programmes should be customised according to personal factors such as gender, body composition, and specific movement problems identified through biomechanical assessments. Research by Segal et al. (2013) and Verlaan et al. (2018) shows that men and women have different movement strategies, and body composition greatly affects joint function. Because of these differences, exercise plans need to be tailored instead of using a one-size-fits-all method.

Different types of exercises impact joint function in unique but supportive ways. Strength exercises increase muscle strength, which helps to stabilise joints and lessen excessive strain. Aerobic exercises adjust walking patterns and tackle overall issues like inflammation, while neuromuscular training improves movement coordination and control. Knowing these different effects allows clinicians to choose the right exercises based on each patient's specific biomechanical patterns.

Combining different exercise modalities offers complementary benefits by addressing the complex biomechanical factors contributing to CKP. While strengthening may improve force production, it may not sufficiently address altered movement patterns that contribute to joint degeneration. Similarly, neuromuscular training enhances coordination but may not provide adequate stimulus for strength development. This biomechanical evidence offers a compelling scientific rationale for multimodal exercise approaches that target multiple aspects of joint function simultaneously.

Regular monitoring of movement patterns during exercise is essential to ensure that patients do not reinforce maladaptive movement strategies that could undermine therapeutic benefits. Studies by Knoop et al. (2013) and Bouchouras et al. (2015) indicated that patients with knee pain often develop compensatory movement patterns, which, although initially protective, may accelerate joint degeneration over time. Without proper monitoring, exercises intended to be therapeutic might inadvertently reinforce these harmful patterns.

Providing feedback on movement quality during exercise may enhance outcomes by helping patients develop more optimal joint loading patterns and movement strategies. Biomechanical studies have shown that improving movement quality, rather than merely increasing strength or endurance, is essential for reducing pain and improving function in patients with CKP.

In summary, biomechanical research provides the scientific foundation for understanding how different types of exercise affect knee joint function and why certain interventions are effective for specific patients. By integrating biomechanical assessment and targeted exercise prescription, clinicians can create more personalised and effective rehabilitation programmes for patients with CKP. There is increasing evidence that combining various exercise types may provide additional benefits that exceed what each method can achieve on its own (Knoop et al. 2013). The next section reviews the evidence supporting multimodal exercise interventions for managing CKP, focusing on how different combinations of exercise modalities influence clinical outcomes, patient adherence, and long-term functional improvements.

2.8 Multimodal Exercise Types in CKP Management

Multiple systematic reviews and international guidelines consistently recommend a multi-faceted approach to exercise programming (Fernandes et al. 2013; Juhl et al. 2014; Fransen et al. 2015; Minshull and Gleeson 2017; Arden et al. 2021). The optimal therapeutic exercise programme should incorporate a combination of strength, aerobics, and balance exercises (Tanaka et al. 2013; Zeng et al. 2021; Ceballos-Laita et al. 2023). By integrating these various exercise types, healthcare professionals can comprehensively address different aspects of physical function, ultimately improving outcomes for individuals with CKP (Young et al. 2023).

Exercise dosage optimisation remains critical yet complex in managing CKP. While research supports the importance of individualised exercise prescriptions based on functional capacity, pain tolerance, and overall health status, significant gaps exist in establishing definitive guidelines for optimal exercise parameters across different patient populations (Juhl et al. 2014; de Rooij et al. 2017).

Leading organisations, including the American College of Rheumatology and the European League Against Rheumatism, recommend a comprehensive approach combining range-of-motion, quadriceps strengthening, and aerobic exercises for CKP management (Felson et al. 2011). While moderate-intensity aerobic and strength-based exercises are generally recommended (Fransen et al. 2015), healthcare professionals must carefully consider individual factors when determining exercise frequency, intensity, and duration (Holden et al. 2023).

This personalised approach ensures sufficient challenge for positive outcomes while maintaining safety and manageability (Juhl et al. 2014). Yet, research gaps persist in understanding how to adjust these parameters systematically based on individual progress and response. Implementing behavioural strategies, including goal setting, positive reinforcement, and exercise contracts, has shown promise in improving patient engagement and long-term adherence (Aitken et al. 2010).

Villadsen et al. (2014) developed a comprehensive exercise programme for patients with severe knee OA who were awaiting TKR. Their multimodal programme included neuromuscular exercises aimed at improving alignment and functional stability, strengthening exercises that targeted specific muscle groups around the knee and hip, and functional exercises that mimicked daily activities. The results of their randomised controlled trial indicated that this combined approach led to significant improvements in functional performance, as measured by the 30-second chair stand test, along with enhanced self-reported outcomes when compared to the control group, which received only educational information.

Further evidence supporting this approach can be found in the MEDIC study, which evaluated a 12-week multimodal treatment programme against usual care for individuals with knee OA (Skou et al. 2015). This multimodal programme combined neuromuscular exercise, education, insoles, and pain medication. The neuromuscular exercise component was thorough and aimed at enhancing postural control, functional stability, and muscle strength. At the 12-month follow-up, participants in the multimodal group demonstrated clinically meaningful improvements in pain, symptoms, and overall quality of life compared to the usual care group. The difference in Knee injury and Osteoarthritis Outcome Score pain between the two groups was 10.7 points, exceeding the 10-point threshold regarded as clinically significant (Skou et al. 2015). This study highlights the enduring benefits of a multimodal treatment approach over an extended timeframe.

The benefits of multimodal exercise approaches arise from their capacity to target multiple physiological mechanisms associated with CKP (Shi and Wu 2023). Strengthening exercises primarily enhance joint stability by increasing muscular support (Bannuru et al. 2019). In addition, aerobic exercise offers complementary advantages by improving cardiovascular fitness and potentially reducing inflammation (Brosseau et al. 2017). Neuromuscular training further enhances outcomes by improving proprioception and coordination, which are frequently impaired in those with chronic knee conditions (Piercy et al. 2018).

Knoop et al. (2014) conducted an RCT to explore the complementary effects of a multimodal conservative treatment programme compared to standard care for patients with knee OA. The multimodal programme incorporated strengthening exercises, aerobic training, functional training, activity pacing and pain management education. After 12 weeks of intervention, participants in the multimodal group exhibited significant enhancements in physical functioning, pain relief, and self-efficacy compared to those receiving standard care. Notably, the study revealed that improvements in quadriceps strength and proprioceptive accuracy were independently linked to improved clinical outcomes (Knoop et al. 2014). This finding suggests that the different components of the programme contributed to patient improvements through different mechanisms.

The implementation of multimodal exercise programmes in clinical practice presents both opportunities and challenges (Collins et al. 2012). Adherence to exercise regimens is a crucial factor affecting long-term outcomes (Collado-Mateo et al. 2021). Studies conducted by Messier et al. (2013) and Skou et al. (2015) incorporated strategies designed to enhance adherence, including supervised sessions, comprehensive home exercise instructions, and consistent follow-up communications. In the IDEA trial, attendance at facility-based sessions averaged 70% over the 18-month intervention period, demonstrating that multimodal programmes can achieve reasonable adherence rates when they are well-structured and adequately supported (Messier et al. 2013).

An important factor to consider is customising multimodal programmes to meet individual needs and capabilities. Skou et al. (2015) used a semi-individualised approach in which the specific exercises within their neuromuscular programme were chosen based on individual assessments and adjusted according to participants' responses. This personalised aspect, within a standardised framework, provides a practical model for clinical implementation.

Current evidence supports multimodal exercise approaches for the management of CKP; however, several key questions remain regarding their optimal implementation (Fernandes et al. 2013; Juhl et al. 2014; Fransen et al. 2015; Minshull and Gleeson 2017; Arden et al. 2021). These questions include identifying the most effective combinations and proportions of various exercise types tailored to individual patient profiles, establishing clear progression criteria within multimodal programmes, and developing standardised assessment frameworks to inform personalised prescriptions. Additionally, research into the cost-effectiveness and long-term sustainability of benefits derived from multimodal programmes would offer valuable insights for healthcare systems and providers.

In summary, high-quality RCTs demonstrate that multimodal exercise approaches incorporating strengthening, aerobic, and neuromuscular components produce more favourable outcomes than single-modality interventions in managing CKP. By simultaneously addressing various aspects of physical function, including muscle strength, joint stability, cardiovascular fitness, and proprioceptive control, multimodal programmes provide a more holistic solution to the complexities of chronic knee conditions.

While the evidence supports multimodal exercise approaches as the current gold standard for managing CKP, effectively implementing these evidence-based principles in real-world settings remains a challenge. The potential benefits of combining strength, aerobic, and neuromuscular training can only be fully realised when exercises are executed properly, dosed appropriately, and performed consistently (Zeng et al. 2021). To understand the need for innovative solutions like biofeedback (a technique that provides patients with real-time physiological information about their movement patterns, muscle activity, or joint loading to help enhance exercise performance) (Giggins et al. 2013), it is essential to examine the specific challenges and limitations that hinder the effectiveness of traditional therapeutic exercise methods in clinical practice. These barriers obstruct optimal outcomes and highlight the critical gaps that must be addressed to improve treatment efficacy.

2.9 Challenges of Traditional Therapeutic Exercises

Therapeutic exercise is a fundamental intervention for managing CKP. Despite the strong evidence supporting its effectiveness, challenges in implementation and less-than-optimal outcomes continue to be issues in clinical practice. This section examines three interconnected aspects of therapeutic exercise for CKP: first, the limitations of traditional exercise approaches; second, the barriers to exercise adherence; and third, evidence-based strategies to improve adherence and outcomes. By critically analysing these factors, this section aims to identify gaps in current practices and explore opportunities for innovation in exercise prescription and delivery to enhance patient outcomes.

2.9.1 Limitations of Traditional Therapeutic Exercises

Traditional therapeutic exercises for CKP present significant challenges that can impede effective treatment and potentially worsen CKP conditions (Holden et al. 2012; Bennell et al. 2014). The primary concern lies in the mismatch between conventional exercise approaches and the specific needs of individuals with knee pain (Campbell et al. 2001).

High-impact activities and inappropriate exercise intensity can pose risks for those with knee pain (Beckwée et al. 2012). These exercises create movements that place excessive stress on the knee joint, potentially triggering increased pain and inflammation (Bennell et al. 2008). Similarly, conventional strength training exercises like deep squats and lunges can exert significant forces on compromised knee joints when not adequately adapted or executed (Escamilla et al. 2009). Repeatedly applying these forces without proper modification can aggravate existing conditions and hinder recovery (McAlindon 2014).

Load-bearing exercises present another challenge in traditional therapeutic approaches. Activities such as stair climbing, while typical in daily life, can place substantial stress on the knee joint (Hensor et al. 2014). For individuals with OA, these activities can lead to increased pain and inflammation, making everyday movements more challenging (Wallis et al. 2013). The risk of overexertion is exceptionally high in traditional exercise settings where individuals eager to progress may push beyond their safe limits without appropriate guidance (Palazzo et al. 2016).

The most fundamental limitation of traditional exercise programmes is their tendency toward a standardised approach (Collado-Mateo et al. 2021). Many programmes fail to adequately account for individual variations in pain levels, mobility restrictions, and underlying conditions (Hurley et al. 2018). This one-size-fits-all methodology overlooks the unique challenges and limitations faced by each person with CKP, potentially leading to suboptimal outcomes (Bennell et al. 2014). The lack of personalisation can result in inappropriate exercise selection, improper progression, and inadequate modification of movements to accommodate individual needs (Holden et al. 2012).

These limitations highlight the importance of developing clearer, more individualised approaches to knee pain management that consider the biomechanical stresses of various exercises and each person's specific needs (Dobson et al. 2016). A more targeted approach would help to ensure that therapeutic exercises support recovery rather than potentially compromise it (Fernandes et al. 2013).

2.9.2 Barriers to Exercise Adherence in CKP

Exercise adherence, defined as the degree to which an individual complies with their prescribed exercise regimen, poses a considerable challenge in managing CKP (Bennell et al. 2014). Studies have shown that adherence rates for long-term exercise programmes aimed at addressing knee OA can be as low as 30–50% (Aitken et al. 2010; Kolasinski et al. 2020). Such low adherence levels significantly diminish the potential benefits of therapeutic exercise (Aitken et al. 2010; Kolasinski et al. 2020).

2.9.2.1 Patient-Related Barriers

Several patient-related factors contribute to poor exercise adherence in individuals with CKP, including pain-related concerns, behavioural barriers, and practical limitations. Pain during exercise is a significant barrier to maintaining a consistent workout routine (Geneen et al. 2017). Uritani et al. (2020) found that fear of pain was associated with a 42% decline in exercise participation among individuals with knee OA (95% confidence interval (CI): 36-48%). This fear-avoidance behaviour creates a cycle where reduced activity leads to deconditioning, which subsequently exacerbates pain and disability (Uritani et al. 2020).

Motivational factors significantly influence adherence to exercise programmes. Research by Holden et al. (2023) found that patients with low self-efficacy for exercise are 3.1 times more likely to discontinue their programmes compared to those with high self-efficacy (odds ratio: 3.1, 95% CI: 2.1, 4.5, $p < 0.001$). Moreover, a disconnect between patients' expectations and realistic outcomes can lead to frustration, often resulting in the abandonment of the programme (Holden et al. 2023).

Socioeconomic barriers further hinder adherence to prescribed exercise programmes. Kolasinski et al. (2020) found that 63% of patients reported factors such as transportation difficulties, programme costs, and time constraints as primary reasons for not adhering to these programmes.

2.9.2.2 Healthcare System and Programme-Related Barriers

The design and implementation of exercise programmes are critical factors that impact adherence to these programmes (Collado-Mateo et al. 2021). De Santana et al. (2022) found that standardised programmes, which lacked personalisation, had adherence rates that were 27% lower compared to personalised programmes ($p < 0.01$). Additionally, inadequate supervision during the initial learning phase and insufficient follow-up contributed to elevated discontinuation rates (Hall et al. 2021).

The complexity of prescribed exercises can pose a barrier to adherence. Beckwée et al. (2012) demonstrated that programmes requiring specialised equipment or complex movement patterns experienced adherence rates that were 18% lower compared to more straightforward home-based programmes (95% CI: 12, 24%, $p < 0.05$). Furthermore, unclear instructions regarding exercise execution and progression often lead to patient uncertainty and diminished engagement (Beckwée et al. 2012).

2.9.3 Evidence-Based Adherence Strategies

Aitken et al. (2010) conducted a significant Cochrane review that laid the groundwork for understanding interventions aimed at improving exercise adherence. This systematic review evaluated 42 RCTs involving 8,243 participants suffering from chronic musculoskeletal pain, including those with knee OA (Aitken et al. 2010). The review found moderate evidence that adherence-focused interventions can effectively reduce pain in knee OA (SMD: -0.45, 95% CI: -0.65, -0.25, $p < 0.001$) and improve function (SMD: 0.41, 95% CI: 0.21, 0.61, $p < 0.001$) (Aitken et al. 2010). It highlighted that self-management programmes incorporating cognitive-behavioural strategies significantly improve adherence and clinical outcomes, demonstrating the importance of behavioural support in addition to physical therapy (Aitken et al. 2010).

The analysis revealed that supervised exercise sessions and individualised rehabilitation programmes were notably more effective in promoting adherence compared to unsupervised or group-based interventions (risk ratio [RR]: 1.65, 95% CI: 1.32, 2.07, $p < 0.001$) (Aitken et al. 2010). Furthermore, programmes that included adherence-specific components such as education, feedback, or goal setting showed enhanced outcomes (RR: 1.48, 95% CI: 1.14, 1.93, $p = 0.003$) (Aitken et al. 2010).

Building on this foundation, Ley and Putz (2024) conducted a recent systematic review that revealed moderate evidence supporting the effectiveness of booster sessions, professional supervision, and behaviourally graded activities for enhancing adherence. A notable finding from the review was that interventions using multiple behaviour change techniques, specifically eight or more, demonstrated significantly greater effectiveness compared to those employing fewer techniques (Odds Ratio: 2.16, 95% CI: 1.46, 3.18, $p < 0.001$) (Ley and Putz 2024).

Koh et al. (2017) introduced Action and Coping Planning (ACP) as a cost-effective behavioural intervention for managing knee pain. In their RCT involving 373 participants with early symptoms of knee OA, the intervention group received structured planning and barrier management strategies. The experimental group showed a significantly higher frequency of completed exercise sessions compared to the control group, with a mean difference of 2.9 sessions per week (95% CI: 2.0, 3.8, $p < 0.001$) (Koh et al. 2017). These findings highlight the effectiveness of ACP in translating intentions into actionable behaviours, thus improving adherence to home-based exercise programmes (Koh et al. 2017).

However, despite these promising results, the study revealed that participants in the experimental group still did not meet the recommended minimum exercise frequency for managing knee OA, achieving only 67% of the recommended sessions compared to 41% in the control group (Koh et al. 2017). This emphasises an important gap in the literature: even with evidence-based behavioural interventions, participants may still face challenges in adherence.

Jinnouchi et al. (2023) evaluated the effectiveness of a brief, therapist-led self-exercise education programme, known as brief-See, in comparison to material-based education alone. After 12 weeks, participants in the brief-See group experienced a 9.4% increase in total knee function, as measured by the knee injury and osteoarthritis outcome (mean difference: 9.4, 95% CI: 4.7, 14.1, $p < 0.001$) (Jinnouchi et al. 2023). In contrast, the control group showed no significant changes. Additionally, pain self-efficacy improved significantly in the brief-See group, with an increase of 5.4 points in the pain self-efficacy questionnaire score (95% CI: 2.3, 8.5, $p = 0.001$) (Jinnouchi et al. 2023).

Adherence rates were notably higher in the brief-See group, with 81% of participants reporting that they exercised four or more days per week after 12 weeks, compared to only 46% in the control group ($\chi^2 = 12.7$, $p < 0.001$) (Jinnouchi et al. 2023). This study demonstrates the potential of brief, therapist-led education to enhance both adherence and functional outcomes (Jinnouchi et al. 2023). However, the intervention had a limited impact on pain intensity and quality of life, suggesting that more comprehensive approaches may be necessary to address these issues.

A systematic review conducted by Collado-Mateo et al. (2021) examined fifty-five studies to identify fourteen key factors that affect exercise adherence in patients with chronic diseases and older adults. The findings highlighted that successful adherence strategies must simultaneously address multiple domains. The review found that individualised exercise prescriptions were associated with a 24% increase in adherence rates compared to standardised programmes (95% CI: 16, 32%, p <

0.001). Furthermore, professional supervision resulted in a 31% higher adherence rate than unsupervised programmes. Additionally, the integration of social support was linked to a 19% improvement in adherence (95% CI: 11, 27%, $p < 0.01$). Finally, digital monitoring and feedback systems enhanced adherence by 22% compared to traditional delivery methods (95% CI: 14, 30%, $p < 0.01$) (Collado-Mateo et al. 2021).

Despite the growing body of evidence on adherence strategies, several important gaps and contradictions remain in the literature. A fundamental challenge is the lack of standardised measures for assessing adherence across different studies. Aitken et al. (2015) identified seven methods for measuring adherence: session attendance, self-reported logs/diaries, questionnaires, phone or in-person interviews, technology-based monitoring, clinician observations, and physiological or biochemical measures. This diversity makes direct comparisons between interventions complex, undermining the ability to establish definitive best practices.

Additionally, some studies have revealed a contradiction: improved adherence does not consistently lead to better clinical outcomes. For instance, while Koh et al. (2017) showed that their action and coping planning intervention significantly increased exercise frequency, participants reported pain levels similar to those in the control group. This indicates that adherence alone may be insufficient if factors such as exercise quality, intensity, or specificity are not optimised.

Most studies have less than nine months of follow-up periods, with many limited to just 12 weeks (e.g., Jinnouchi et al. 2023). This short-term focus fails to address the chronic nature of knee conditions, leaving questions about long-term adherence unanswered. Hall et al. (2021) found that adherence typically declines by 50% within six months after supervised intervention periods end, highlighting the need for sustainable approaches.

The evidence reviewed in this section demonstrates several effective strategies that significantly improve exercise adherence among individuals with CKP. Personalisation appears to be a fundamental element, with individualised exercise prescriptions showing a 24% increase in adherence rates compared to standardised programmes (Collado-Mateo et al. 2021). This directly addresses the limitations of one-size-fits-all approaches highlighted earlier. Professional supervision emerges as another critical strategy, improving adherence by 31% compared to unsupervised programmes (Collado-Mateo et al. 2021). This supervision helps to overcome barriers related to exercise complexity and uncertainty about proper execution. The systematic review by Aitken et al. (2010) further confirmed that supervised sessions were significantly more effective than unsupervised interventions (risk ratio: 1.65, 95% CI: 1.32, 2.07, $p < 0.001$).

Behavioural interventions show promise, with Action and Coping Planning techniques increasing exercise frequency by 2.9 sessions per week (Koh et al. 2017). Similarly, brief therapist-led education programmes have demonstrated remarkable effectiveness, with Jinnouchi et al. (2023) reporting that 81% of participants in their brief group exercised on four or more days a week, compared to just 46% in the control groups.

The integration of multiple behaviour change techniques offers significant benefits, with Ley and Putz (2024) finding that interventions using eight or more techniques were substantially more effective than those employing fewer approaches. Additionally, the integration of social support improved adherence by 19% (Collado-Mateo et al. 2021), addressing important motivational barriers.

Digital monitoring and feedback systems enhanced adherence by 22% compared to traditional delivery methods (Collado-Mateo et al. 2021), although implementation challenges remained significant. Programmes incorporating specific adherence components, such as education, feedback, and goal setting, also showed enhanced outcomes (RR: 1.48, 95% CI: 1.14, 1.93, $p = 0.003$) (Aitken et al. 2010).

These evidence-based strategies demonstrate that effective adherence approaches must be multi-faceted, addressing both patient-related factors (such as motivation and pain-related fear) and healthcare system barriers (including programme design and supervision). However, despite these advances, significant gaps remain in the literature.

While digital technologies show promise in enhancing adherence, significant barriers to implementation remain. Collado-Mateo et al. (2021) noted that issues with usability, cost concerns, and limitations in digital literacy, especially among older adults, have restricted the real-world application of these approaches. Furthermore, many technology-based interventions lack validation against established clinical protocols.

Finally, despite widespread recognition that personalisation improves outcomes, few studies have developed systematic frameworks for tailoring exercise programmes. Holden et al. (2023) argue that current approaches to "personalisation" often rely on clinician intuition rather than validated algorithms or decision support tools, leading to inconsistent applications in practice. The extensive challenges identified in traditional therapeutic exercise approaches clearly necessitate innovative solutions to enhance knee pain management. Recent systematic reviews by Ley et al. (2024) and Collado-Mateo et al. (2021) highlight that even the most advanced behavioural strategies for improving adherence remain insufficient when patients lack objective guidance on exercise execution and progression.

These limitations have stimulated growing interest in technology-assisted rehabilitation as a potential solution to bridge the implementation gap between evidence-based exercise prescription and real-world practice. The integration of digital technologies offers promising opportunities to address these challenges through real-time feedback, objective monitoring, and personalised adaptation of exercise parameters. The next section explores the rapidly evolving landscape of technological interventions in exercise rehabilitation, examining how these innovations may overcome the limitations of traditional approaches while enhancing treatment precision, engagement, and outcomes for individuals with CKP.

2.10 Technology in Exercise Rehabilitation

In the last decade, technology has significantly advanced exercise rehabilitation by providing effective solutions to the challenges previously discussed, particularly those related to adherence, proper execution, and personalisation. This section explores the evolution of rehabilitative technology, tracing its development from basic feedback tools to sophisticated machine-learning systems. It also assesses how these innovations address the implementation gap between evidence-based exercise prescriptions and their practical application in real-world contexts.

Early technological interventions primarily focused on creating accessible motion-tracking systems to enable objective assessments of movement quality. Capecci et al.’s (2018) work on Kinect-based monitoring systems marked a significant advancement in affordable, markerless motion tracking for home-based rehabilitation. This system allows clinicians to remotely evaluate motor performance during rehabilitation for neurological and orthopaedic conditions, providing real-time kinematic feedback through detailed performance scores (Capecci et al. 2018). The study showed a strong correlation between the system's assessments and clinical judgments, demonstrating the feasibility of low-cost alternatives to traditional motion capture technologies (Capecci et al. 2018).

Building upon earlier foundational research, Richards et al. (2018) investigated gait retraining for individuals suffering from medial knee OA. Their comprehensive study illustrated the effectiveness of utilising real-time feedback to significantly reduce the first peak knee adduction moment, which is crucial for minimising stress on the knee joint, while also enhancing various functional outcomes, such as walking stability and overall mobility. However, the research also uncovered a notable limitation: the challenge of sustaining these beneficial effects over the long term. This finding underscores a critical consideration for technology-based interventions: the need to design systems that not only deliver immediate and actionable feedback but also foster enduring behavioural change within the complexities of real-world environments (Richards et al. 2018).

A significant shift has occurred as researchers have developed more sophisticated feedback mechanisms specifically tailored to meet rehabilitation needs. In their 2020 scoping review, Brennan et al. (2020) examined digital biofeedback systems for targeted exercise rehabilitation in home settings, identifying thirteen systems, five of which were designed explicitly for knee rehabilitation. These systems utilised various sensor technologies, including inertial measurement units (used to track movements and orientations in three-dimensional space, this technology plays a crucial role in providing real-time feedback for exercises, especially in rehabilitation settings), smartphones, and tablets, delivering feedback primarily through visual or auditory channels in real-time (Brennan et al. 2020).

The review highlighted that knee rehabilitation systems often use inertial measurement units to monitor knee ROM and provide immediate feedback to improve exercise performance and adherence (Brennan et al. 2020). While these innovations show promise, Brennan et al. (2020) identified significant gaps, particularly the need for more robust evaluation methods and evidence-based feedback design to maximise effectiveness. Their findings revealed a problematic pattern in rehabilitation technology development: developers typically establish technical feasibility first, with comprehensive clinical validation occurring much later. This sequence often creates a disconnect between technological capabilities and proven therapeutic benefits, potentially leading to sophisticated systems that function well technically but may not optimise clinical outcomes (Brennan et al. 2020).

Marshall et al. (2020) made significant strides in understanding movement dynamics by exploring the effectiveness of visual biofeedback for enhancing lower extremity kinematics in recreationally active females with medial knee displacement (a condition that can lead to pain and injury). Their innovative intervention used a Microsoft Kinect system, which projected real-time knee-abduction angles onto a vibrant, colour-coded monitor (Marshall et al. 2020). This setup empowered participants to adjust their movements immediately, fostering greater awareness of their biomechanics. The results showed that participants in the feedback group demonstrated an average reduction of 6.16° in knee abduction during landing compared to their counterparts in the control group. Significantly, 75% of individuals in the feedback group no longer exhibited medial knee displacement following the intervention, in stark contrast to only 33% of those in the control group (Marshall et al. 2020).

This study demonstrated the potential of accessible technology to produce measurable improvements in biomechanical performance (Marshall et al. 2020). Nevertheless, it also identified significant challenges within the field. While the technology demonstrated positive immediate effects, the research left unanswered important questions regarding the long-term retention of these improvements. Furthermore, the participant group consisted exclusively of young, recreationally active females with similar physical characteristics and baseline fitness levels. This lack of diversity raised concerns about whether similar results would be observed in older adults, individuals with different body compositions or varying fitness levels, or those with more severe knee conditions, highlighting the necessity for further investigation across varied demographic settings.

As technology has advanced, researchers have started to incorporate game elements and motivational features to tackle challenges related to adherence to exercise programmes (Lin et al. 2022) studied a computer-aided rowing exercise system designed for older adults with mild knee OA. This system combined low-impact exercises with technology-supported feedback presented through a game-based interface (Lin et al. 2022). Over a 12-week programme, the exercise intensity progressively increased from 50% of an individual's one-repetition maximum (Lin et al. 2022).

The results showed significant improvements in muscle strength, including strength in the hip abductors, adductors, flexors, extensors, and knee extensors, as well as measures of functional fitness, such as functional reach and balance (Lin et al. 2022). Participants reported that the system was motivating and user-friendly, suggesting that it might overcome common barriers to consistent exercise participation, although adherence rates were not directly compared to conventional approaches (Lin et al. 2022).

This study exemplifies how technology can address multiple barriers to exercise adherence, making rehabilitative activities more engaging while also providing immediate feedback on performance (Lin et al. 2022). Despite these promising findings, the intervention was conducted in a supervised, laboratory-based setting, which may not fully reflect adherence or outcomes in home environments. Furthermore, excluding individuals with severe OA or other comorbidities limits the applicability of the findings to more diverse patient populations (Lin et al. 2022).

Hribernik et al. (2022) conducted a systematic review that thoroughly analysed real-time biomechanical feedback systems used in sports and rehabilitation. Their research emphasised how these systems—comprising sensors, processing units, and actuators—can enhance motor learning, rehabilitation outcomes, and athletic performance (Hribernik et al. 2022). The review found that most biomechanical feedback systems focused on repetitive movements, such as gait retraining and physiotherapeutic exercises, while others targeted sports-related activities like running, cycling, and balance training. The feedback modalities used were mainly visual (60%), followed by auditory (25%) and haptic (15%). Visual displays were particularly effective in rehabilitation settings, whereas auditory and haptic feedback showed advantages in dynamic sports activities (Hribernik et al. 2022).

This review offered valuable insights into the effectiveness of different feedback modalities across various contexts, providing crucial guidance for future system development (Hribernik et al. 2022). However, it also highlighted significant limitations in existing research: most studies prioritised technical aspects over user experience or clinical outcomes, were conducted in controlled environments with small sample sizes, and rarely evaluated long-term functional improvements (Hribernik et al. 2022).

Recent advancements have incorporated machine learning to enhance system adaptability and personalisation. Hamilton et al. (2023) underscored the potential of advanced technologies to improve lifestyle interventions for knee OA, mainly through telerehabilitation and biofeedback systems. Nevertheless, they pointed out that many of these technologies are still in their early development phases, with only a few successfully transitioning into clinical practice (Hamilton et al. 2023).

Chen et al. (2024) assessed a machine-learning-based lower-limb exercise training system aimed at individuals aged fifty-five and older suffering from knee pain. This system provided video demonstrations, real-time feedback on movement quality, and comprehensive tracking of exercise performance and progress. User testing with ten participants (mean age 68.4 years) yielded an SUS score of 72.8, reflecting above-average usability. Participants notably valued the real-time feedback for enhancing their exercise performance and the ability to monitor their progress over time. However, technical challenges remained significant: the camera calibration was particularly upsetting, leading to a task success rate of just 10% and frequent requests for assistance (Chen et al. 2024). These findings illustrate the ongoing struggle between technological complexity and user accessibility, especially for older adults with limited digital literacy.

Considering the ongoing challenges faced by traditional rehabilitation methods, VR presents itself as a potentially game-changing solution for exercise rehabilitation (Lányi 2014). With its unique blend of immersion, engagement, and precise movement tracking capabilities, VR effectively addresses many obstacles to exercise adherence (Sherman and Craig 2003). By creating immersive and interactive environments, it enhances motivation and enjoyment, ultimately improving the rehabilitation experience (Sherman and Craig 2003).

Beyond its motivational advantages, VR confronts accessibility issues by facilitating home-based exercise, thus eliminating the transportation challenges and scheduling conflicts often encountered with facility-based programmes (Mallari et al. 2019). Moreover, VR environments can be tailored to instil a sense of safety and control, which is particularly advantageous for individuals with physical limitations or exercise-related anxiety (Adomavičienė et al. 2019). This customisation allows users to gradually adapt to physical activity in controlled, supportive settings, directly tackling barriers related to pain management and functional limitations (Adomavičienė et al. 2019; Mallari et al. 2019).

The next section will look closely at how VR technology is used in healthcare. It will highlight the key features of VR and discuss its potential to change exercise therapies for people with CKP and similar conditions.

2.11 VR in Healthcare Settings

2.11.1 Definition of VR

The concept of VR in medical applications began with innovative foundational work in the 1960s (Mandal 2013). Ivan Sutherland's 1965 introduction of the "Ultimate Display" concept represented the first vision of environments that could simulate reality with interactive and responsive elements (Mandal 2013). This foundational concept was further developed in the late 1980s when Jaron Lanier popularised the term "virtual reality," focusing on immersive experiences through head-mounted displays (Høeg et al. 2021). Mandal's (2013) work synthesised these early concepts, establishing the critical components of immersion and presence as fundamental to effective VR applications in healthcare settings.

Building on these principles, VR can be defined as a computer-generated interactive and immersive technology that enables users to engage with simulated environments, whether realistic or imaginary, through specialised input and output devices such as head-mounted displays, motion-tracking systems, and other sensory feedback tools. The defining characteristics of VR include the illusion of presence ("being there"), interactivity, and the replication of sensorimotor experiences that allow users to navigate and manipulate the virtual world as if it were real (Kardong-Edgren et al. 2019).

2.11.2 Potential Benefits of VR in Therapeutic Exercise

VR technology provides an immersive and interactive environment that can help engage patients in their rehabilitation process. The interactive nature of VR exercises can motivate patients to actively participate in their therapy sessions, leading to increased adherence and better outcomes (Alexandre and Postolache 2018). VR technology enables physiotherapists to customise exercises and interventions based on individual patient needs (Elaraby et al. 2023). This allows for tailoring of VR programmes to target specific areas of improvement, such as balance, strength, or range of motion, which enhances the effectiveness of treatment (Elaraby et al. 2023).

Recent research has shown that VR technology can significantly improve the motor function, balance, gait, and daily activities of patients suffering from medical conditions such as stroke, spinal cord injury, and Parkinson's disease. Several studies have been conducted to support this claim, including those by Ahmad et al. (2019), Domínguez-Téllez et al. (2020), and Miguel-Rubio et al. (2020).

Moreover, VR has been found to be an effective treatment method for reducing pain, anxiety, and stress in patients undergoing physiotherapy and rehabilitation. The immersive experience of VR can distract patients from pain sensations and create a more positive therapeutic environment. Studies conducted by Tuck et al. (2022) and Simons et al. (2022) support this. It has emerged as an effective way to evaluate treatment progress and outcomes objectively. With VR, physiotherapists can monitor patient performance in real-time, track progress, and make necessary adjustments to their interventions. This approach allows for more precise and data-driven rehabilitation strategies (Alexandre and Postolache 2018).

VR-based physiotherapy interventions can be delivered remotely, enabling patients to access therapy sessions from the comfort of their own homes. This increased accessibility can improve patient compliance with treatment plans and reduce barriers to care (Chau et al. 2021). Moreover, VR is also an effective training tool for physiotherapy students and healthcare professionals. Through realistic simulations of clinical scenarios and hands-on practice opportunities, VR can enhance learning outcomes and skill development (Lucena-Anton et al. 2022).

2.11.3 VR Applications for Knee Pain Management

The first significant practical application in rehabilitation came from Fitzgerald et al. (2007), who developed an innovative system combining a wearable motion capture suit with VR biofeedback to instruct athletes on improving performance through a series of prescribed rehabilitation exercises. Their study included two participants: one athlete with a grade two strain of the medial collateral ligament and one healthy athlete. The system provides real-time guidance and analysis for people in sports rehabilitation. The engaging game design gives players immediate feedback on their exercises, helping them improve their body alignment and movement. While this early system was effective in providing real-time feedback and customisation, it also faced challenges. These included complex calibration processes, limitations on offline analysis, and high implementation costs.

The transition to broader clinical applications began with Abdelazim et al.'s (2016) RCT, which compared the effectiveness of VR training, sensory motor training, and conventional exercise training in managing unilateral chronic knee OA. Sixty participants were randomly assigned to one of the three intervention groups and underwent eight weeks of therapy, with outcomes measured in terms of pain intensity, joint proprioception, functional disability, and quality of life (Abdelazim et al. 2016).

The findings demonstrated significant improvements across all groups, with VR training consistently outperforming sensory motor training and conventional exercise training. Pain intensity, measured using the VAS, decreased most significantly in the VR training group. Similarly, joint proprioception improved in all groups, with the VR training group showing the largest increase in position sense. Functional disability, assessed using the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), decreased most significantly in the VR training group. Quality of life scores also improved across all groups, with the VR training group achieving the highest increase (Abdelazim et al. 2016).

The VR training intervention included the use of the commercial "Light Race" game, which required stepping motions to enhance lower limb strength, balance, and flexibility. These gamified exercises not only provided effective physical therapy but also increased patient engagement and motivation. However, a notable limitation of the "Light Race" game is its lack of personalisation, as it does not provide tailored difficulty levels based on the individual’s strength or physical abilities. This could potentially limit the game's efficacy for patients with varying levels of knee OA severity or physical capacity. Sensory motor training focused on sensory-motor integration through static, dynamic, and functional exercises, while conventional exercise training involved walking and basic ROM activities (Abdelazim et al. 2016).

Despite the positive outcomes, the study had some additional limitations. The eight-week follow-up period was relatively short, leaving questions about the long-term sustainability of the interventions. Additionally, the participant group was relatively homogeneous in terms of age and OA severity, limiting the generalisability of the findings to more diverse or advanced OA populations. The supervised setting also raises concerns about adherence and effectiveness in unsupervised home environments (Abdelazim et al. 2016).

Overall, the study highlights the superior efficacy of VR training in managing pain, improving proprioception, reducing disability, and enhancing quality of life in individuals with knee OA. By combining gamified elements with exercise therapy, VR training offers a highly engaging and effective alternative to traditional rehabilitation methods (Abdelazim et al. 2016). Future research should explore long-term outcomes, assess the feasibility of unsupervised VR training at home, and investigate its applicability across diverse patient populations. Additionally, developing VR systems with personalised difficulty levels tailored to individual needs could further enhance their therapeutic potential.

Pruna et al. (2017) developed a specialised 3D virtual system designed for knee rehabilitation, using the Unity 3D platform. This computer-based environment simulates both real-world and imaginary scenarios in three dimensions, specifically aimed at assisting patients with knee OA in performing knee flexion, extension, and strengthening exercises. The system incorporates 3-Space Mocap Sensors, developed by YEI Technology, which track the orientation and movement of objects in three-dimensional space for motion capture. By integrating these sensors with the Unity 3D environment, the study created interactive virtual games to enhance the rehabilitation process. The primary goal was to provide a personalised and engaging rehabilitation experience while ensuring that exercises were performed correctly through real-time visual and auditory feedback.

The system demonstrated high usability and effectiveness. The average Suitability Evaluation Questionnaire score was 53 ± 0.56 (out of a maximum of 65), indicating strong user acceptance. Participants reported enjoying the experience and found the system immersive, with minimal discomfort such as dizziness or nausea. They expressed confidence in the system’s ability to aid rehabilitation and showed enthusiasm for using it as an alternative to traditional methods.

Real-time visual and auditory feedback ensured exercises were completed correctly, addressing a significant limitation of unsupervised rehabilitation. The interactive nature of the games motivated participants to engage with the system, and the adaptive difficulty levels allowed exercises to match their capabilities. However, even though the results from this study were significant, they cannot be generalised to all CKP populations, as the sample size was small and the included subjects were only knee OA patients.

Howard's (2017) comprehensive meta-analysis of VR rehabilitation programmes identified the efficacy of VR rehabilitation programmes in improving physical outcomes such as motor control, balance, gait, and strength. The findings reveal that VR rehabilitation programmes are generally more effective than traditional rehabilitation approaches. Significant improvements were observed in strength and gait, while motor control and balance showed less consistent outcomes. The study also identified three potential mechanisms behind the success of VR rehabilitation programmes. First, the increased excitement and engagement associated with the VR rehabilitation programme make it a more enjoyable experience, probably boosting patient motivation and adherence to the therapy. Second, the physical fidelity of VR environments, which closely mimic real-life activities, eliminates the need for patients to translate practised behaviours into real-world contexts. Finally, VR rehabilitation programmes often incorporate realistic cognitive challenges, enhancing patients' preparedness for multitasking and real-world scenarios (Howard 2017).

Despite its promising results, the study acknowledged several limitations. The proposed mechanisms of excitement, physical fidelity, and cognitive fidelity lacked robust empirical validation, leaving uncertainties about their direct contribution to the observed outcomes (Howard 2017). Additionally, the studies included in the meta-analysis used diverse methodologies and non-standardised outcome measures, complicating cross-study comparisons. Control groups in many studies were minimal or absent, raising questions about whether VR rehabilitation's benefits are due to the intervention or simply the added activity. Small sample sizes in several studies further limit the generalisability of the findings. Moreover, most studies focused on short-term outcomes, with little exploration of the long-term sustainability of VR rehabilitation benefits (Howard 2017).

The study concluded that VR rehabilitation programmes are a promising advancement in rehabilitation, offering potential benefits for physical and neurological impairments. However, further research is essential to confirm the underlying success mechanisms and optimise these programmes for long-term effectiveness and broader applicability (Howard 2017).

Gumaa and Rehan Youssef (2019) conducted a systematic review of VR rehabilitation in orthopaedic conditions, analysing nineteen controlled trials while concentrating on methodological quality using the PEDro scale. Their rigorous quality assessment approach and comprehensive analysis of various VR applications strengthened their findings. However, the review faced several limitations: the high heterogeneity in VR interventions and outcome measures complicated direct comparisons, and many of the included studies displayed only moderate methodological quality scores. Although they identified promising trends in balance and proprioception outcomes, the inability to perform a meta-analysis due to study heterogeneity constrained the strength of their conclusions. The review offered valuable insights into implementation factors such as patient acceptance and adherence.

Lin et al.'s (2020) RCT examined the effectiveness of active video games (AVG) compared to traditional therapeutic exercises for managing knee OA. The study included eighty participants aged 40–85 years who were randomly assigned to either an active video game or a therapeutic exercise group. Both groups completed three sessions per week for four weeks, with outcomes assessed at baseline, immediately after the intervention, and three months post-treatment. Primary outcomes included the WOMAC scores for pain, stiffness, and physical function, while secondary outcomes focused on mobility, balance, quality of life, and adherence (Lin et al. 2020).

Both groups experienced significant improvements in WOMAC pain, stiffness, and physical function scores, with no significant differences between groups. However, the AVG group showed superior performance in dynamic balance, 10-metre walking time, and stair ascent time compared to the therapeutic exercise group, indicating that AVGs may offer additional benefits for improving functional mobility and agility. Quality of life, as measured by the physical health domain of the World Health Organisation Quality of Life-Brief Version, also improved significantly more in the AVG group, suggesting that the interactive nature of AVGs contributes positively to overall physical well-being (Lin et al. 2020).

The AVG intervention used a commercially available system, the Hot Plus system, featuring two games, "Whack-a-Mole" and "Archery." These games required participants to perform lower limb movements on a step-sensing pad, with increasing difficulty levels designed to enhance strength, coordination, and ROM. Participants in the AVG group demonstrated higher adherence rates (100%) compared to the therapeutic exercise group (93%), highlighting the engaging and enjoyable nature of AVG as a factor in improved compliance.

Despite these promising findings, the study had some limitations. The follow-up period was limited to three months, leaving the long-term sustainability of improvements unclear. Additionally, both interventions were conducted in supervised settings, which may not accurately reflect adherence or effectiveness in unsupervised home environments (Lin et al. 2020). The use of commercially available games, rather than therapeutic games specifically designed for knee OA, limited the ability to tailor exercises to individual needs or varying levels of OA severity. Future research should investigate long-term outcomes, unsupervised application, and the development of personalised therapeutic games to maximise their clinical utility.

Moreover, Byra and Czernicki (2020) conducted a narrative review focusing on VR rehabilitation for knee and hip conditions, analysing 10 RCTs. The strength of the review lies in its detailed examination of various VR applications and its comprehensive assessment of multiple outcomes. However, as a narrative review, it lacked the statistical rigour of a meta-analysis, and the relatively small number of included studies (10) limits the generalisability of the findings. The authors provided valuable critical analysis of methodological issues in existing research and identified specific areas where VR showed promise, such as pain management and ROM. Their conclusion regarding the insufficient evidence for VR's superiority over conventional therapy is well-supported by their analysis, although it is limited by the quality and quantity of available research. The review contributes significantly by highlighting the need for standardisation in VR interventions and outcome measures in future research.

In recent years, there has been a growing emphasis on advanced applications that focus on detailed outcome measures. Ebrahimi et al. (2021) conducted a randomised clinical trial to evaluate the effects of VR training on clinical outcomes and brain activity in women with patellofemoral pain syndrome. The study assessed improvements in balance, pain, quality of life, and function, alongside changes in brain activity using quantitative electroencephalogram analysis. Participants were divided into a VR training group and a control group, with the intervention consisting of 24 VR training sessions over eight weeks using Kinect-based commercial games (Ebrahimi et al. 2021).

The findings demonstrated significant improvements in the VR training group compared to the control group. Balance, measured using the Modified Star Excursion Balance Test, increased significantly in all directions (anterior, medial, and lateral) following the intervention. Pain intensity, evaluated using the VAS, decreased by more than 2 cm in the VR training group, reaching the minimal detectable change threshold, and indicating a clinically meaningful reduction. Additionally, quality of life scores, measured using the SF-36 questionnaire, improved significantly in the VR training group. Functional outcomes, assessed via the Kujala questionnaire, improved by over sixteen points, exceeding the minimally important change threshold (Ebrahimi et al. 2021).

The VR training intervention also led to significant changes in brain activity, with increased alpha and theta wave power in the frontal, parietal, and occipital regions post-intervention. These findings suggest enhanced neuroplasticity, sensorimotor processing, and cognitive function associated with VR training. The interactive and engaging nature of the Kinect-based games facilitated adherence and motivation, potentially reducing perceived effort compared to traditional therapy (Ebrahimi et al. 2021).

However, the study had several limitations. The use of commercial Kinect-based games, rather than purpose-built therapeutic software, restricted the personalisation of difficulty levels or exercise intensity to match individual capabilities. This lack of customisation may have limited the intervention's effectiveness for participants with varying degrees of patellofemoral pain severity or fitness levels. Additionally, the study exclusively focused on women with patellofemoral pain, limiting the generalisability of findings to men or individuals with other musculoskeletal conditions. The short-term follow-up period of one month precluded the assessment of the long-term sustainability of clinical and neuroplastic improvements (Ebrahimi et al. 2021).

Ebrahimi et al.'s (2021) study highlights the potential of VR training as a comprehensive rehabilitation approach for patellofemoral pain, addressing both physical and neurocognitive aspects of recovery. While the results are promising, future research should focus on developing personalised therapeutic VR programmes, extending follow-up periods, and including diverse populations to optimise the clinical applicability of VR training for musculoskeletal rehabilitation.

Chen et al. (2021) conducted a systematic review and meta-analysis examining technology-supported exercise programmes for knee OA and CKP. They systematically searched multiple major databases and adhered to the PRISMA guidelines, strengthening methodological quality. The review included 12 RCTs with a detailed analysis of heterogeneity and risk of bias. However, limitations included substantial heterogeneity across studies ($I^2 > 50\%$) in key outcomes, alongside most included studies having small sample sizes. While the meta-analysis suggested benefits for pain and quality of life, the absence of improvement in physical function raises questions about the clinical significance of technology-supported interventions. The authors' subgroup analyses of different technology types and programme features provided valuable insights for future implementation. However, the quality of evidence was rated as moderate due to methodological limitations in the primary studies.

Jachak and Phansopkar (2022) provided valuable insights through a study that aimed to investigate the effectiveness of Oculus-guided VR therapy as an adjunct to conventional therapy for patients with knee OA. The goal was to determine whether combining VR-based exercises with traditional rehabilitation methods could enhance outcomes such as pain reduction, improved ROM, and increased muscle strength. The patients, initially presenting with an 8/10 on the numerical pain rating scale and a WOMAC score of 54, completed a four-week VR rehabilitation programme using Oculus-guided exercises. Despite high initial pain levels, the patients showed significant improvements in both pain reduction and ROM.

A total of seventy patients aged 50–65 years with unilateral or bilateral KOA (grades 1 and 2) participated in the study. Participants were divided into two groups: a control group receiving conventional therapy only and an experimental group receiving 20 minutes of Oculus-guided VR therapy in addition to 20 minutes of conventional therapy, five days a week for six weeks. Conventional therapy included strengthening exercises such as straight leg raises and mini squats, flexibility exercises like hamstring stretches, Maitland mobilisation, and ultrasound therapy. In the VR sessions, participants engaged in a cycling game on a static bike, which encouraged knee flexion and extension in an immersive, gamified environment.

The results showed significant improvements in the experimental group across all measured outcomes. Pain levels, assessed using the Numerical Pain Rating Scale (0-10), were 2.68, compared to 1.65 in the control group. Functional ability, measured using the WOMAC, also improved significantly, with the experimental group achieving a mean improvement of 26.28 compared to 13.62 in the control group.

In terms of joint mobility, the experimental group demonstrated a greater increase in ROM, with a mean improvement of 26.37 degrees versus 17.80 degrees in the control group. Muscle strength (knee flexor and extensor muscles), assessed through Manual Muscle Testing, also improved more in the experimental group, with a mean increase of 1.20 compared to 0.68 in the control group.

The study demonstrated that Oculus-guided VR therapy is an effective adjunct to conventional therapy for patients with knee OA. By providing an engaging and interactive platform, VR therapy boosted patient motivation and adherence to rehabilitation, leading to better outcomes in pain management, mobility, and strength. However, the immersive nature of VR therapy may not be entirely safe for all patients, particularly those prone to dizziness, disorientation, or balance issues, which could increase the risk of falls or other adverse events.

Additionally, the study used only one type of VR game, limiting the variety of exercises and potentially restricting the generalisability of the results. Current physiotherapy guidelines, such as OARSI's latest discussion group, recommend combining rehabilitation with multiple types of exercises, including strengthening, flexibility, balance, and functional training, to address the diverse needs of knee OA patients comprehensively (Howard et al. 2023). Future research should consider incorporating a broader range of VR activities and multi-modal exercise programmes to align with these guidelines and further validate the role of VR in holistic rehabilitation strategies.

Another study was conducted to evaluate the feasibility of a novel video-game-based electromyography biofeedback system for the rehabilitation of patients with knee OA (Krepkovich et al. 2022). The system was designed to provide patients with real-time feedback on their muscle activity, while also making the rehabilitation process more engaging and enjoyable. The study included nineteen participants with knee OA. Patients were randomised to one of two groups: the experimental group, which used a video-game-based electromyography biofeedback system, or the control group, which used a traditional electromyography biofeedback system (Krepkovich et al. 2022). Over six weeks, patients in both groups undertook a variety of rehabilitation exercises.

The study found that patients who used the video-game-based electromyography biofeedback system produced significantly greater knee extension torque than patients who used the conventional electromyography biofeedback system. They also reported they enjoyed using the system and that it helped them to stay motivated during their rehabilitation exercises. They also exercised for longer periods of time and reported being more engaged with the video game. These findings suggest that the video-game-based electromyography biofeedback system may be a more effective way to improve knee function in patients with OA than conventional electromyography biofeedback (Krepkovich et al. 2022).

However, the study also has some weaknesses. First, it was conducted over a relatively short period of time (six weeks). It is possible that the benefits of the video-game-based electromyography biofeedback system would be even greater if used for a longer period. Second, the study was conducted in a laboratory setting. It is unclear whether the results would be the same if the system were used in a home setting.

A mixed-methods feasibility study explored the use of exergaming through the Nintendo Wii Fit™ to improve balance and reduce the risk of falls in individuals with knee OA. Participants engaged in an eight-week programme involving Wii Fit™ balance games, with assessments focused on feasibility, acceptability, safety, and clinical outcomes, such as balance, muscle strength, and fear of falling (Manlapaz et al. 2022).

The programme demonstrated high feasibility, with an 83% retention rate and a 78% compliance rate. Participants found the programme's frequency (three sessions per week) and duration (45–60 minutes per session) acceptable. Importantly, no adverse events were reported, confirming the intervention's safety. Clinically, significant improvements were observed in dynamic balance (mean score increased from 72.67 to 73.92, $p = 0.035$) and physical function, as measured by the Timed-Up and Go Test (TUG: mean score improved from 7.93 seconds to 7.18 seconds, $p = 0.028$). Fear of falling decreased significantly, with scores on the short form Falls Efficacy Scale dropping from a mean of 11.75 to 10.25 ($p = 0.018$). Quality of life and recreational activity levels, assessed through the KOOS-QoL and KOOS-Sports/Recreation scores, also improved significantly (Manlapaz et al. 2022).

Qualitative findings provided additional insights into the programme's acceptability. Participants described the gamified nature of the Wii Fit™ as enjoyable, engaging, and motivating. Many appreciated the interactive elements, including competitive gameplay and opportunities for family involvement. However, challenges were noted, such as the repetitive nature of game screens and occasional difficulties with the technology's accuracy and interface. Despite these challenges, participants expressed a strong preference for exergaming over traditional exercise methods (Manlapaz et al. 2022).

The intervention used a mix of supervised and home-based sessions, with participants completing five balance games per session. Safety precautions, such as chair support during gameplay, were implemented to ensure participant well-being. However, the study exclusively relied on Nintendo Wii Fit™, a commercial gaming system that lacks customisation for individual therapeutic needs. Additionally, the absence of a control group and the small sample size (12 participants) limit the generalisability of the findings (Manlapaz et al. 2022).

This study demonstrates the feasibility and potential effectiveness of exergaming in improving balance and reducing falls for individuals with knee OA (Manlapaz et al. 2022). While the results are promising, future research should address the limitations by incorporating custom-made exergaming tools, larger sample sizes, and control groups to strengthen the evidence base. Exergaming's engaging and gamified approach presents a valuable opportunity to enhance adherence and motivation in rehabilitation programmes for knee OA.

Mete and Sari (2022) conducted a clinical RCT to evaluate the effectiveness of exergaming as an adjunct to conventional physiotherapy for patients with knee OA. The aim was to determine whether exergaming could enhance outcomes such as muscle strength, range of motion, pain relief, kinesiophobia (fear of movement), proprioceptive insight, postural stability, and functional status when combined with traditional rehabilitation. A total of 60 patients with knee OA (47 female, 13 male) aged 40–65 (mean age: 57.36 ± 7.26) participated in this RCT. Participants were divided into two groups: the study group, which received conventional physiotherapy and exercise, and the control group, which received only conventional physiotherapy. Both groups underwent treatment on five days a week for six weeks (Mete and Sari 2022).

The MarVAJED system was used for exergaming. This system provided interactive exercises through visual and auditory feedback. It included two games: "Crazy Wings" and "Blasting Ball." In "Crazy Wings," participants controlled a bird figure representing their knee joint. The bird moved upward with knee flexion and downward with extension, requiring patients to navigate through virtual obstacles by performing the corresponding movements. In "Blasting Ball," participants inflated a virtual ball by flexing their knee and then exploded it upon reaching a target flexion angle. These games were designed to encourage precise knee movements, improve muscle activation, and enhance postural control. The sensors were placed above and below the knee, tracked movement, and calibrated the ROM for personalised gameplay (Mete and Sari 2022).

The results showed significant benefits in the study group compared to the control group. Pain, measured using the VAS, decreased significantly more in the study group. Similarly, knee flexion and extension ROM improved in both groups, but the study group experienced greater gains. Postural stability, assessed using the PEDALO Sensamove Balance System, showed significant improvement only in the study group. Reductions in kinesiophobia scores, assessed with the TAMPA scale, and improvements in functional status (WOMAC index) were also more noticeable in the study group (Mete and Sari 2022).

While muscle strength improved in both groups, there was no significant difference, possibly because the exergames focused more on movement accuracy and control than resistance exercises. Participants in the study group also reported higher satisfaction and engagement with rehabilitation, with 60% expressing high satisfaction with the exergaming experience (Mete and Sari 2022).

In conclusion, combining exergaming with conventional physiotherapy improved outcomes in pain relief, ROM, postural stability, kinesiophobia, and functional status in knee OA patients. Exergaming's interactive and engaging nature enhanced motivation and adherence to rehabilitation programmes. Further studies are needed to assess long-term effects and optimise the inclusion of resistance-based exercises to address muscle strength improvements comprehensively.

A recent meta-analysis by Lo et al. (2024) evaluated the effectiveness of immersive and non-immersive VR assisted active training compared to conventional physiotherapy in managing chronic musculoskeletal pain. It included 28 RCTs with 1,144 participants and analysed outcomes related to pain intensity, functional disability, and kinesiophobia across different pain regions, including the back, neck, and knees (Lo et al. 2024).

For knee pain, non-immersive VR was not found to improve pain intensity or functional disability significantly. Similarly, evidence for VR interventions in other regions, such as shoulder, hip, and mixed musculoskeletal pain, was inconclusive due to the limited number of studies. These findings suggest that the application of VR in regions beyond the back and neck requires a more robust investigation to establish its effectiveness (Lo et al. 2024).

The included studies revealed methodological challenges, with most exhibiting a high risk of bias or concerns related to randomisation and blinding. Variability in intervention designs, VR hardware and software, and participant demographics contributed to high heterogeneity, which limited the generalisability of the results (Lo et al. 2024). The review highlights the lack of significant findings for knee pain and other regions, indicating that more research is needed to explore VR's broader applicability (Lo et al. 2024). Future studies should focus on long-term effects, adherence, and cost-effectiveness to optimise the integration of VR into chronic pain management practices.

Guo et al. (2024) evaluated the effectiveness of digital healthcare systems, including VR and augmented reality (AR), in managing knee joint pain. The study focused on the impact of these systems on pain levels, balance, range of motion, and walking velocity in patients with knee OA or post-total knee replacement (TKR). By comparing digital healthcare systems with standard rehabilitation approaches, the study aimed to determine the potential benefits of integrating advanced technologies into knee rehabilitation (Guo et al. 2024).

While the findings highlight some advantages, such as significant pain reduction in OA patients and improved balance across patient groups, they also reveal critical limitations in the application and effectiveness of these technologies (Guo et al. 2024). One of the key issues was the variability in protocols and technologies: the studies employed inconsistent training approaches, with differences in duration, frequency, and types of exercises, making it challenging to compare outcomes or generalise findings (Guo et al. 2024).

The VR systems varied widely, with some studies using commercial platforms and others employing custom-designed systems (Guo et al. 2024). Commercial VR systems were not always tailored for clinical use, reducing their effectiveness for targeted rehabilitation (Guo et al. 2024). Additionally, many interventions lacked personalisation, which is crucial for addressing the specific needs of patients with conditions like OA or TKR (Guo et al. 2024).

Another notable limitation was the reduced effectiveness of VR interventions in specific populations (Guo et al. 2024). For example, while VR demonstrated benefits for OA patients in reducing pain and improving balance, its efficacy for TKR patients was limited (Guo et al. 2024). Furthermore, VR interventions showed no significant improvement in critical functional outcomes such as ROM and walking velocity, limiting their utility for certain rehabilitation goals (Guo et al. 2024). Most studies focused on the short-term effects of VR interventions, leaving the long-term sustainability of benefits, such as pain reduction and functional improvement, largely unexplored. This short-term focus raises questions about the broader applicability of VR systems for ongoing rehabilitation (Guo et al. 2024).

Technological and usability issues also posed challenges: some VR systems were complex or costly, limiting accessibility for widespread use, particularly in home-based settings (Guo et al. 2024). Patients, especially older adults, often faced difficulties navigating these systems without additional support or training (Guo et al. 2024). Immersive VR systems also had the potential to cause cybersickness, including symptoms like dizziness or nausea, which could hinder patient adherence (Guo et al. 2024).

Integration challenges further complicated the use of VR systems. Most interventions relied on VR as an adjunct to traditional rehabilitation rather than a standalone treatment. This dependency on traditional rehabilitation makes it difficult to isolate the specific benefits of VR (Guo et al. 2024). Moreover, not all VR systems effectively provide real-time feedback or adequately monitor and correct improper movements, reducing their utility for precise rehabilitation (Guo et al. 2024).

Finally, the studies often had small sample sizes, limiting findings' generalisability to broader populations (Guo et al. 2024). Additionally, some studies exhibited potential biases, such as inadequate blinding or selection biases, affecting the reliability of their outcomes (Guo et al. 2024). In summary, while VR shows promise in managing knee joint pain, its current limitations—such as variability in design, population-specific efficacy, technological constraints, and integration challenges—underscore the need for more standardised, personalised, and validated VR interventions to maximise its therapeutic potential (Guo et al. 2024).

2.11.4 Overall Summary of VR Applications for CKP Management

The application of VR in knee pain management has evolved significantly, highlighting notable progress while underscoring the need for further development and standardisation. Research consistently demonstrates VR's effectiveness in reducing pain, particularly in managing CKP in conditions such as OA. Studies suggest that mechanisms like distraction, enhanced neuroplasticity, and increased engagement contribute to these benefits (Ebrahimi et al. 2021). Additionally, VR has been demonstrated to improve patient engagement and adherence to rehabilitation programmes, with adherence rates often surpassing traditional therapy, driven by VR systems gamified and interactive nature (Lin et al. 2020).

Technological advancements in VR rehabilitation have moved from basic motion capture systems (Fitzgerald et al. 2007) to sophisticated platforms integrating multiple therapeutic elements (Krepkovich et al. 2022). However, many studies still rely on commercial gaming systems rather than specialised tools, highlighting a gap in tailored solutions. Methodological limitations, such as small sample sizes, short study durations, and lack of long-term follow-up data, persist across research efforts, often focusing narrowly on specific populations like knee OA patients.

Challenges to clinical implementation include cost, the need for technical support, limited availability of customised systems, and integration with existing healthcare infrastructures. Future research should prioritise standardised protocols, developing cost-effective home-based applications, longer-term studies with diverse populations, and improved integration with traditional therapy approaches to overcome these barriers.

The collective evidence indicates that VR offers significant benefits for managing knee pain. These advantages include improved patient engagement, customisable exercise programmes, real-time feedback, and support for remote rehabilitation.

However, rigorous research and technological advancements are still necessary to establish VR as a standard therapeutic tool.

To achieve success, it is crucial to incorporate several key factors, such as integrating feedback mechanisms, allowing for customisable difficulty levels, ensuring professional supervision, and systematically progressing exercises. Overall, the development of VR demonstrates a promising path toward more effective and accessible interventions for managing CKP.

2.12 Literature Review Summary

This literature review examined the complex setting of CKP management, with a particular focus on the potential role of VR in therapeutic exercise delivery. The analysis identified key themes that establish the foundation for investigating VR-based solutions in home-based therapeutic exercise.

The epidemiological data demonstrate significant variability in the prevalence of CKP, ranging from 10% to 20% globally, with higher rates among older adults (Sammito et al. 2021). This prevalence has been rising, with knee OA increasing by 25-30% over the past decade (Pal et al. 2016). This substantial prevalence, coupled with the difficulties accessing usual physiotherapy services, highlights the need for innovative, home-based solutions to enhance treatment accessibility and improve patient engagement.

Usual physiotherapy approaches emphasise exercise therapy as fundamental to managing CKP, with strong evidence supporting multimodal interventions incorporating strengthening, aerobic, and neuromuscular exercises (Holden et al. 2023). However, the literature reveals significant challenges in exercise delivery and adherence, particularly in home-based settings (Aitken et al. 2015; Kolasinski et al. 2020). These challenges include maintaining proper exercise form, limited motivation, and the lack of real-time feedback: areas were technological solutions, such as VR, could provide significant advantages.

The emergence of VR in rehabilitation represents a promising solution to these limitations. Studies suggest that VR-based interventions can improve pain management, functional mobility, and exercise adherence compared to conventional approaches (Lin et al. 2020; Jachak and Phansopkar 2022). However, recent systematic reviews highlight several critical gaps in the current research (Lo et al. 2024; Guo et al. 2024). These gaps include limited investigation into home-based VR applications for therapeutic exercise, insufficient evidence on the appropriate level of challenge and exercise fidelity in VR-based rehabilitation, a need for a better understanding of usability and acceptability factors, and the lack of standardised protocols for implementing VR in home-based rehabilitation.

While commercial gaming systems show promise for rehabilitation, their limited customisation capabilities and lack of therapeutic specificity remain significant constraints (Manlapaz et al. 2022). The literature suggests a clear need for purpose-built VR solutions that specifically address the requirements of therapeutic exercise while maintaining patient engagement and ensuring proper exercise execution (Chen et al. 2024).

In conclusion, despite significant progress in understanding both CKP management and VR applications in rehabilitation (Hamilton et al. 2023), considerable work remains to optimise these interventions for home-based therapeutic exercise. The development and evaluation of specialised VR toolkits are crucial steps in addressing current limitations and enhancing the accessibility and effectiveness of therapeutic exercise for individuals with CKP.

2.13 Objectives

The gaps and challenges identified in the literature directly inform the focus of this thesis, which **aims to:**

- Evaluate an early-stage prototype of a VR-based physiotherapy toolkit designed for people with CKP to use at home.

The following objectives support this aim:

1- Systematically identifying, summarising, and evaluating the quality of literature investigated the potential of VR in knee therapeutic exercises (Chapter 3).

2- Exploring whether the VR games are ‘fit-for-purpose' by providing an appropriate level of challenge and accurately mirroring exercises, assessed through joint ROM and muscle activities, to ensure that they meet the physical therapy needs (Chapter 5).

3- Assessing the usability and acceptability of a VR prototype toolkit among participants with CKP (Chapter 5).

CHAPTER 3: An Umbrella Review

Virtual Reality in Knee Therapeutic Exercises

3.1 Introduction

In Chapter 2, a thorough literature search was conducted to identify studies on VR technology. These studies explored a variety of VR gaming technologies, each with its own unique features and applications. However, the diversity of these technologies means that their effectiveness may vary among various populations and interventions. Importantly, while VR has been studied in several contexts, the existing literature lacks a focused examination of its use specifically for managing CKP. Most studies were systematic reviews that have primarily addressed acute knee conditions or post-surgical rehabilitation, with insufficient attention given to CKP. This gap is notable, as many acute knee conditions can progress to a chronic state, highlighting the need for targeted research in this area.

Additionally, a thorough evaluation of the outcomes measured in these reviews, such as functional performance, pain severity, and quality of life, remains crucial for developing evidence-based recommendations for clinical practice. The lack of systematic reviews specifically focusing on VR for CKP highlights the need for a broader analysis of VR applications across various knee conditions.

To address these gaps, an umbrella review was chosen instead of a systematic or scoping review for several reasons. First, the umbrella approach allows for the synthesis of existing systematic reviews, providing a comprehensive overview of the evidence related to both acute and chronic knee conditions. Second, given the limited research focused specifically on CKP, this approach helps to identify transferable principles from acute and post-surgical virtual rehabilitation interventions that could be applicable to chronic pain management. Finally, an umbrella review has the methodological advantage of assessing the quality of evidence across multiple systematic reviews, which strengthens the foundation for their specific virtual rehabilitation-based physiotherapy prototype aimed at CKP.

This umbrella review synthesises data from systematic reviews to examine the effectiveness of VR in managing knee pain for individuals with OA and post-surgical patients. Although these two groups have different backgrounds, they face similar challenges, such as pain and functional limitations, making them relevant for a comprehensive assessment of VR's therapeutic potential. Furthermore, understanding the entire progression of knee conditions from acute injury to chronic pain offers valuable insights for developing interventions that can be effective at various stages of this progression.

The review analysed outcome measures, including pain relief, functional improvement, and quality of life. It also explored how variations in VR technologies and exercises impact effectiveness in both chronic and postoperative contexts. This often-overlooked distinction between surgical and non-surgical approaches is essential for customising VR strategies to meet specific clinical needs. Additionally, it helped to identify which elements can be most effectively adapted for managing CKP.

The findings from this study will enhance current practices and optimise VR interventions for knee pain, addressing both acute and chronic conditions. This chapter will detail the methods used, including the search strategy employed to identify all relevant systematic reviews and the eligibility criteria applied. It will also outline the screening and selection methods for systematic reviews, data extraction procedures, methodological quality assessment, primary study overlaps, and data analysis. Finally, the chapter will present the characteristics of the included reviews, a synthesis of the findings, a discussion of the results, future recommendations, and practical implications. It will conclude with a summary of the key points.

3.2 Methods

A protocol was developed by following the Joanna Briggs Institute (JBI) manual for evidence synthesis (Aromataris and Munn 2020) and registered in the International Prospective Register of Systematic Reviews (PROSPERO, number: CRD42022323746). In this umbrella review, the JBI methodology was followed to conduct a narrative synthesis, as it is a valuable approach when meta-analysis (pooling of quantitative data) is not feasible due to the heterogeneity of the included studies. Also, the JBI Data Extraction Form for Review for Systematic Reviews and Research Syntheses was used, and the AMSTAR 2 toolkit was applied to assess the methodological quality of the included studies.

3.3 Search Strategy

A search was conducted in the following databases: AMED, CINAHL, EMBASE, MEDLINE, IEEE Explore, PubMed, PEDro, Scopus, and Web of Science. The search strategy combined the following keywords {*Knee* AND *Virtual reality* AND *Rehabilitation* AND *therapeutic Exercise*}. Following the same strategy, the grey literature was also searched (e.g., Google Scholar).

Population.	Intervention AND		Comparator	Outcome
Knee OR Anterior Knee Pain Syndrome OR Pain Syndrome OR Patellofemoral OR Patellofemoral Pain OR Patellofemoral Pains OR Patellofemoral Syndrome OR Osteoarthritis of the Knee OR Knee Osteoarthritis OR OA OR Chronic knee pain OR patella pain OR kneecap pain OR total knee replacement OR TKR	Virtual Realities OR Virtual Reality OR Exergame	Rehabilitation OR Exercise OR therapy OR game OR Physiotherapy OR Physical therapy OR Physical OR Movement	Conservative treatment OR Usual treatment	Pain OR Pain level OR Pain perception OR Pain experience OR Quality of life OR Muscle strength OR Balance OR Muscle power OR physical function OR Kinematics OR Range of Motion OR ROM

3.3.1 Eligibility Criteria

Inclusion Criteria

- Reviews that included adults (18 years and older) diagnosed with CKP, knee OA, or
- Reviews that included patients who have undergone any knee surgeries.
- Reviews that focused exclusively on the knee. If reviews included general or regional specific populations, only the knee-related data was extracted and analysed if possible.
- Reviews that evaluated the effectiveness of interventions such as:

    - Custom-made or clinically developed VR-based rehabilitation tools, exergames, or gamified exercises specifically designed for rehabilitation purposes.
    - Any forms of computer-assisted techniques that were used in conjunction with sensor-based rehabilitation technologies to create a VR environment.
- Reviews must report on at least one of the following outcome measures:
    - Pain measurement.
    - Physical function.
    - Quality of life.

Exclusion Criteria

- Off-the-shelf commercial games (e.g., Wii Fit, Xbox Kinect) not specifically designed or adapted for rehabilitation purposes.
- Reviews involving patients with neurological disorders.
- Reviews that focused on paediatric populations (under 18 years old).
- Reviews not reporting on any relevant clinical outcomes (e.g., pain, function, quality of life) related to rehabilitation.
- Reviews not written in English language.

3.3.2 Screening and selection of SRs

One reviewer (AAM) screened all citations for their abstracts and titles and excluded those which did not meet the eligibility criteria. All relevant studies were exported to the Rayyan website to remove duplicates and full-text screening that was assessed independently by two reviewers (AAM and AP) (Ouzzani et al. 2016).

3.4 Data Extraction

Data were extracted independently by the two reviewers, AAM and AP, by using a predefined extraction form (JBI data extraction form), and a third reviewer (DS) joined the team for the last two systematic reviews (Khabsa et al. 2015).

The data extraction tool included the following criteria: the objectives of the included review, information regarding the citation details (e.g., author list, journal, year of publication), the number of databases sourced and searched, the date range of included studies that informed each outcome of interest, the setting and context, the participants, the types/number of country/studies of the original primary research studies in the included research synthesis, the outcomes reported by the included reviews that were related to the umbrella review question, the instrument used to appraise the primary studies in the research synthesis and the rating of their quality, and the type of review and the method of synthesis/analysis employed to synthesise the evidence, as well as any comments or notes the umbrella review authors might have regarding any included study. All extracted data are in Appendix 1.

3.4.1 Assessment of Methodological Quality

The methodological quality of systematic reviews and meta-analyses was assessed by the three reviewers (AAM, AP and DS) using the AMSTAR-2 tool, which is valuable for promoting critical appraisal and ensuring that evidence synthesis is conducted with high methodological rigour (Shea et al. 2017), thereby increasing the credibility and usefulness of systematic reviews as a source of evidence-based information. In the application of the AMSTAR-2 tool, each review was evaluated based on sixteen domains, as set out in Appendix 2. For each domain, "Yes," "Partial Yes," or "No" were used to indicate full, partial, or non-compliance with the criteria.

Based on this, the overall methodological quality of each review was categorised as follows: High-Quality: Reviews that met all critical domain criteria ("Yes") and had no more than one "No" in the non-critical domains. Moderate Quality: Reviews that had one "No" in the critical domains and no more than one "No" in the non-critical domains. Low Quality: Reviews with two "No" responses in the critical domains. Critically Low Quality: Reviews with more than two "No" responses in the critical domains.

3.4.2 Degree of Primary Study Overlap

Pieper et al. (2014) introduced the CCA index to quantify publication overlap in umbrella reviews. This method involves constructing a citation matrix with primary publications in rows and various systematic reviews in columns to determine how frequently a study is cited in systematic reviews. The CCA methodology has been integrated into several automated tools for overlap analysis. In 2022, Bracchiglione et al. developed an Excel-based tool called GROOVE (Graphical Representation of Overlap for Overviews) for calculating overlaps using the CCA methodology, which has been used in this umbrella review.

3.5 Data Analysis

The umbrella review used the descriptive Narrative Synthesis approach, which involves summarising and explaining findings from systematic reviews using text and tables to describe the included reviews (Popay et al. 2006).

3.6 Results

A total of 2,056 records were identified through comprehensive searches across nine databases. Rayyan software was used to manage the records and remove duplicates (Ouzzani et al. 2016). After this process, 1,534 duplicates were removed, leaving 521 records for the title and abstract screening. Of these, 513 records were excluded based on predefined exclusion criteria:

- Did not involve any forms of VR that were previously mentioned in the eligibility criteria = 51 records.
- Not a systematic review = 70 records.
- Did not include pain, function, or quality of life as a primary outcome = 202 records.
- Did not include knee conditions in their studies = 190 records.

Following the abstract screening, eight full-text reviews were assessed for eligibility. No additional studies were excluded at this stage. These eight studies were included in the final analysis for this umbrella review.

This selection process is summarised in the PRISMA flow diagram below (Figure 3), which outlines the progression from initial identification to the final inclusion of relevant studies. The process ensured that only studies focusing on VR interventions for knee conditions were included in the final review.

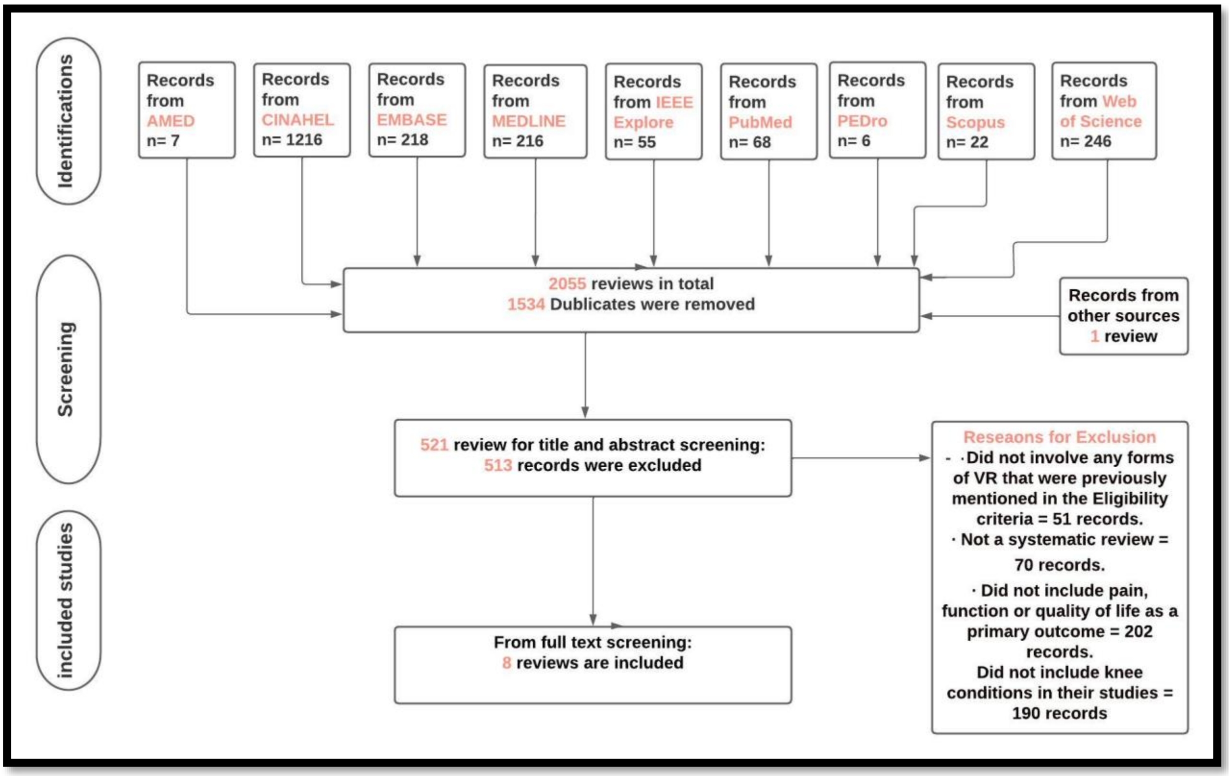


Figure 3: Search Results Reported according to PRISMA Guidelines.

For the methodological quality of the included reviews, Table 3 presents detailed responses for the AMSTAR -2 tool domains. This table provides a view of the methodological strengths and weaknesses of each review. The methodological quality of two reviews was considered as critically low (Byra and Czernicki 2020; Gazendam et al. 2022), while the other six reviews were considered as low quality (Gumaa and Rehan Youssef 2019; Wang et al. 2019; Blasco et al. 2021; Chen et al. 2021; Fernandes et al. 2022; Peng et al. 2022) based on the AMSTAR-2 checklist.

Table 3: Results of the AMSTAR-2 Checklist.

Article	Overall	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16
Gumaa and Rehan Youssef (2019)	**Low quality**	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No	Yes
Wang et al. (2019)	**Low quality**	Yes	Yes	No	PY	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes
Byra and Czernicki (2020)	**Critically low quality**	Yes	No	Yes	PY	No	Yes	PY	PY	Yes	No	No MAC	No	Yes	No	No	Yes
Blasco et al. (2021)	**Low quality**	Yes	Yes	Yes	PY	Yes	Yes	Yes	PY	Yes	No	No MAC*	No MAC	Yes	Yes	No MAC	Yes
Chen et al. (2021)	**Low quality**	Yes	Yes	No	PY*	Yes	Yes	Yes	PY	Yes	Yes	Yes	No	No	Yes	No	Yes
Fernandes et al. (2022)	**Low quality**	Yes	No	No	Yes	Yes	No	Yes	Yes	Yes	No	Yes	No	Yes	Yes	No	Yes
Gazendam et al. (2022)	**Critically low quality**	Yes	No	No	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes	No	No	No	Yes
Peng et al. (2022)	**Low quality**	Yes	Yes	No	PY	Yes	Yes	PY	PY	Yes	Yes	No	Yes	Yes	Yes	No	Yes

*PY: partial yes, No MAC: no meta-analysis conducted. Q2, 4, 7, 9, 11, 13, 15 = critical domain.

The CCA Index

Figure 4 presents the overlap between individual studies included across eight systematic reviews. This visual overview helps to illustrate how much overlap exists between the different systematic reviews in terms of shared studies. Each cell in the matrix compares two reviews, with percentages indicating how much of their content overlaps in terms of shared primary studies.

The color-coded system represents different levels of overlap:

Green (Moderate overlap, 5% to 10%): Most pairs of reviews showed minimal overlap, indicating that the primary studies included in these reviews were largely distinct.

Yellow (high overlap, 10-15%): Three pairs of reviews exhibited moderate overlap, meaning that a small but notable portion of their included primary studies were the same.

Orange (very high overlap, ≥15%): Six pairs of reviews show significant overlap. The highest overlap was between Gazendam et al. (2022) and Peng et al. (2022), with 44.4% overlap, suggesting that nearly half of their included primary studies were the same.

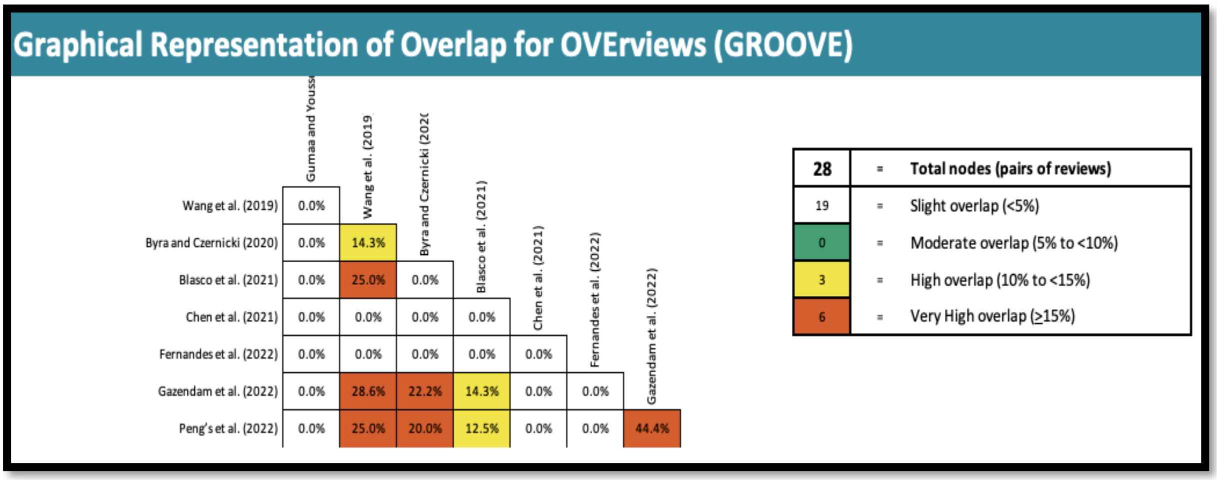


Figure 4: GROOVE Tool Analysis of the Overlapping Individual Studies

Figure 5 provides a summary of the overall overlap between the systematic reviews. The numbers on the right side quantify the overlap:

- **28 total nodes (pairs of reviews)** were analysed.
- **19 pairs** showed **slight overlap**, indicating that most of the reviews contained mostly distinct studies.
- No pairs had **moderate overlap** (5–10%), which is typically an indicator of some but not overwhelming redundancy.
- **3 pairs** had **high overlap** (10–15%), meaning they shared a moderate proportion of primary studies.
- **6 pairs** exhibited **very high overlap** (≥ 15%), with the highest overlap being between **Gazendam et al. (2022)** and **Peng et al. (2022)** at 44.4%.

The total **covered area** was **18.42%**, meaning that nearly one-fifth of the studies were repeated across the reviews. After adjusting for structural zeros (where overlap is impossible, such as when reviews were published at different times), the corrected covered area was **6.77%**, which is categorised as **moderate overlap**.

However, some reviews, particularly Gazendam et al. (2022) and Peng et al. (2022), showed very high overlap (44.4%), meaning that these reviews shared a substantial proportion of their included studies. This overlap should be carefully considered when synthesising the results, as it may lead to redundancy in the findings if not addressed. Overall, while the overlap across reviews was moderate (6.77%), the reviews still provided a diverse set of primary studies, reducing the risk of over-representing the same data and ensuring a broader evidence base for the umbrella review.

Overall results

Number of columns (number of reviews)	c	8
Number of rows (number of index publications)	r	19
Number of included primary studies (including double counting)	N	28
Covered area	N/(rc)	18.42%
Corrected covered area	(N-r)/(rc-r)	6.77%
Interpretation of overlap	Moderate overlap	
Structural Zeros	X	0
Corrected covered area (adjusting by structural zeros)	(N-r)/(rc-r-X)	6.77%
N° of non-overlapped primary studies	In 1 SR	15
Number of overlapped primary studies	In 2 SRs	1
	In 3 SRs	1
	In 4 SRs	2
	In 5 SRs	0
	In 6 SRs	0
	In 7 SRs	0
	In 8 SRs	0
	In 9 SRs	0
	In 10 SRs	0
	In 11 SRs	0
	In 12 SRs	0
	In 13 SRs	0
	In 14 SRs	0
	In 15 or more SRs	0

Figure 5: Overall results of the Overlapping Individual Studies

3.6.1 Characteristics of the Included Reviews

The characteristics of the eight included systematic reviews are summarised in Table 4. The primary studies were published from 2003 to 2021 and were made up of 70 RCTs and one case-control study. The total number of participants across the eight systematic reviews was 5,264, ranging from 128 to 835 in each systematic review.

Gumaa and Rehan Youssef (2019) conducted a systematic review to evaluate the effectiveness of VR interventions for musculoskeletal disorders affecting different parts of the body. Although the review included diverse interventions such as simulators and commercial games like Wii Fit, only two trials related to OA and TKR focused on custom-made VR systems, such as a VR-enabled rowing exercise programme and a custom-built device with tailored computer games.

Gumaa and Rehan Youssef's (2019) review included 14 studies that showed comparable outcomes between VR and traditional exercise programmes, particularly in terms of pain reduction and functional improvement. This led the authors to conclude that VR could be a viable alternative to traditional exercise-based rehabilitation for knee OA. To reach this conclusion, the authors assessed the quality of the included studies using the Evaluation Guidelines for Rating the Quality of an Intervention Study, finding that most were of moderate quality. The evidence demonstrated that both VR and traditional exercise interventions led to similar improvements in managing knee OA, particularly in reducing pain and improving joint function.

Additionally, the review highlighted some potential advantages of VR, such as personalising rehabilitation programmes and enhancing patient motivation and engagement, especially in home-based settings. VR was noted to improve adherence to rehabilitation exercises by making them more interactive and enjoyable. However, the authors pointed out that evidence on the effectiveness of VR for other knee conditions, such as after TKR, was limited or inconclusive, and called for more high-quality research in these areas.

According to the AMSTAR 2 criteria, the systematic review by Gumaa and Rehan Youssef (2019) received a low-quality score. Notably, the review authors did not account for the risk of bias in individual studies when interpreting or discussing the results. This raises concerns about the robustness of the conclusions since inadequate consideration of risk of bias may impact the overall reliability of the review findings. Additionally, the review authors did not perform an adequate investigation of publication bias when conducting quantitative synthesis. The absence of such an investigation and discussion of its likely impact on the results of the review suggests a potential limitation in the review's ability to provide a comprehensive and unbiased overview of the available evidence.

Wang et al. (2019) conducted a systematic review focussing on the safety and efficacy of technology-assisted rehabilitation for patients who had undergone total hip or knee replacement surgery. The review analysed 17 RCTs for TKR and four

RCTs for total hip replacement, assessing a variety of technology-based rehabilitation interventions.

Among the studies on knee musculoskeletal disorders, three relevant RCTs evaluated the effectiveness of VR in rehabilitation. One study used an interactive virtual toolkit that contained wireless sensors, a 3D avatar, and a web portal that allowed therapists to track patient progress. Patients performed exercises using the avatar as feedback while the wireless sensors monitored their movement in real-time, helping therapists provide timely adjustments. Another study combined robot-assisted knee movement training with a virtual environment. For example, a robotic leg guided patients through movements while they interacted with a virtual setting, simulating activities like walking or stretching. Another study used a VR-enabled rowing system, where patients simulated rowing movements to improve knee function post-surgery.

The outcome measurements ranged from subjective assessments (e.g., VAS pain, knee kinaesthesia grade) to functional evaluations (e.g., 6-minute walking test, Hospital for Special Surgery Knee Score, Functional Ambulation Categories, Timed Up and Go Test, Berg Balance Score, and 10-m sitting–standing time). Although the review found moderate-quality evidence showing statistically significant improvements in pain and low-quality evidence for functional mobility post-TKR, the clinical significance of these effects was limited. This means that while the improvements were measurable and statistically meaningful, the changes were often too small to have a meaningful impact on the patient's day-to-day life.

Lastly, the review received a low-quality score on the AMSTAR 2 criteria, primarily due to insufficient investigation of publication bias during the quantitative synthesis. This highlights potential concerns about the comprehensiveness and robustness of the evidence, suggesting a need for more high-quality, rigorously conducted RCTs.

In 2020, Byra and Czernicki conducted a systematic review aimed at evaluating the effectiveness of VR in rehabilitating hip and knee OA and TKR. The analysis included 10 RCTs, with a primary focus on TKR rehabilitation (seven trials) and OA (two trials). Of these trials, four met the inclusion criteria for VR-based interventions, while the remaining studies used off-the-shelf games like Nintendo Wii Fit.

The VR setups varied, including the VR Rehabilitation System, the Hot Plus system featuring active video games, an immersive virtual environment simulating rowing, and rehabilitation software activated on a laptop.

The Virtual Reality Rehabilitation System from Khymeia, Italy, is specifically designed for clinical rehabilitation. This system features interactive games with visual and auditory biofeedback. Patients engaged in exercises aimed at enhancing balance and lower limb function, receiving real-time feedback from the system to ensure accurate task performance. Additionally, the Hot Plus system from Supreme Investment Co., Taipei, Taiwan, focuses on muscle strength, coordination, and range of motion of the lower limbs through interactive video games. This system incorporates sensory pillows that allow patients to control the virtual environment by transferring their body weight.

Another study used a custom VR rowing exercise system in which participants performed rowing movements to aid with knee flexion and extension following TKR. Finally, the rehabilitation software is a specialised programme for home-based rehabilitation that includes custom-developed software tailored for therapeutic exercises, accessible on a laptop. This enables patients to engage in prescribed exercises while receiving visual feedback. The programme incorporates a knee joint exercise system utilising motion sensors and real-time visual biofeedback (Rehabilitation Visualisation System) to focus on muscle strengthening and improving ROM.

Evaluation measures involved a combination of objective and subjective assessments. Joint mobility was objectively measured with a goniometer, patient-reported outcomes were assessed using the Oxford Knee Score, and health-related quality of life was comprehensively measured with the Short Form Health Survey (SF-12). Subjective experiences related to motivation were assessed using the Intrinsic Motivation Inventory, while user satisfaction and usability of systems were evaluated with the SUS.

Although the overall effectiveness of VR-based rehabilitation remained uncertain, the review suggested that VR interventions showed promise in managing pain, providing postural training, and enhancing proprioception. Studies included in the review evaluated the usability of the Rehabilitation Visualisation System both in hospital settings and at home, indicating the significance of user-friendly interfaces and accessibility of VR technologies for patients undergoing rehabilitation after TKR.

Patient satisfaction and motivation were key aspects evaluated in the studies, emphasising the acceptability of VR-based rehabilitation programmes. Participants reported high satisfaction levels, motivation to engage in exercises, and positive feedback on the usability of VR systems, indicating a favourable reception of VR interventions in the postoperative rehabilitation of orthopaedic conditions like OA and TKR.

The assessment of Byra and Czernicki's (2020) review using the AMSTAR tool revealed significant issues, resulting in a critically low-quality rating. The review lacked clear methods, consistency in protocol, and appropriate statistical techniques, raising concerns about its reliability. Consequently, it may have overestimated the effectiveness of VR interventions by not accounting for study quality or differences.

Additionally, the review did not address publication bias, potentially skewing the findings in favour of positive results. It also failed to consistently consider the risk of bias in the included studies, further weakening the evidence. These limitations diminish the review's credibility and utility, making its findings less reliable for clinical practice, particularly regarding the effectiveness of VR-based rehabilitation for conditions like OA and TKR.

Blasco et al. (2021) conducted a systematic review to investigate the effect of training with VR tools for rehabilitation after TKR. The review included six trials, of which only three incorporated VR rehabilitation methods in their protocols. The first trial was an RCT that used the Interactive Virtual Telerehabilitation System, which allows for remote rehabilitation supervised by a 3D avatar, with a physical therapist monitoring biometric data from a distance. This system was used to compare the effectiveness of virtual rehabilitation against conventional physiotherapy. The second trial was a case-control study that used a customised 3D game-based rehabilitation setup combined with Microsoft Kinect technology to engage patients in exercises aimed at improving knee function, particularly focusing on the ROM after TKR. In the third trial, a platform was used to enhance balance abilities. This platform provided real-time feedback during exercises, similar to the Wii Balance Board but designed specifically for rehabilitation, with simpler software and additional assessment features. The remaining three trials in the review used off-the-shelf games (such as Nintendo Wii Fit).

The review measured a diverse set of outcomes. Patient-reported outcomes were captured using the WOMAC, assessing both functional and patient-reported aspects, including knee ROM. Strength was assessed as an objective outcome. Functional mobility was assessed through the Timed Up and Go test. The subjective experience of pain was quantified using the VAS, while knee bending represents a subjective measure related to joint movement. Patient satisfaction was analysed qualitatively and quantitatively, but no impact of VR training rehabilitation on outcomes such as falls, anxiety, or quality of life was assessed in the included studies. The studies concluded that therapy with and without VR training was similarly effective in improving functional outcomes and reducing pain. However, according to the AMSTAR 2 criteria, Blasco et al.'s (2021) systematic review received a low-quality score due to the absence of a meta-analysis, which raises concerns about the comprehensiveness of the evidence synthesis, suggesting a reliance on narrative or qualitative approaches that may limit the overall conclusiveness of the findings. Additionally, the review's failure to adequately investigate publication bias raises questions about the potential impact of bias on the comprehensiveness of the evidence considered.

Chen et al. (2021) investigated the impact of technology-supported exercise programmes on knee pain, physical function, and quality of life in individuals with knee OA and/or CKP. These outcomes were assessed through self-reported measures, such as pain scales and questionnaires, without specifying types of measures. Within this review, one RCT employed VR technology to provide interactive feedback on their exercise programme within a 3D environment. The VR technology included a sensor-based motion and physical activity tracker to facilitate and encourage exercise performance in women with OA.

Overall, using VR technology-supported exercises seems to be an effective approach for short-term improvement in knee pain and quality of life. However, it was challenging to identify significant changes in outcomes and assess the effects of VR technology. One of the main reasons for this challenge was the short intervention duration in the RCT, which was less than three months. This limited period might not have been sufficient to observe significant or long-lasting improvements, as chronic conditions like knee OA often require extended rehabilitation to achieve substantial changes. Additionally, rehabilitation progress is usually gradual, and short-term studies may fail to capture the full impact of VR-supported exercises on joint function and pain relief.

According to the AMSTAR-2 criteria, the systematic review by Chen et al. (2021) received a low-quality score as the review authors did not account for the risk of bias in individual studies when interpreting or discussing the results. Additionally, the review authors did not perform an adequate investigation of publication bias when conducting the quantitative synthesis. The absence of such an investigation and discussion of its likely impact on the results of the review suggests a potential limitation in the review's ability to provide a comprehensive and unbiased overview of the available evidence.

The study by Chen et al. (2021) did not explicitly mention conducting specific usability testing of VR technology for delivering exercise programmes to individuals with knee OA (Chen et al. 2021). While the study highlighted the use of VR as one of the technologies employed in the exercise programmes, it focused more on the effects of these programmes on knee pain, physical function, and quality of life, rather than on the usability aspects of the VR technology itself.

Fernandes et al.'s (2022) systematic review aimed to assess the effectiveness of exergames in comparison to usual rehabilitation after anterior cruciate ligament reconstruction (ACLR). Only two studies included VR-based games. One of the studies used the GenuSport Knee Trainer, which is an app-based exergame system designed for active muscle training through interactive games, developed by Weber-Spickschen, and constructed by the Department of Medical Device Construction, Hanover Medical School, Germany. Another study employed an immersive VR environment, where patients performed exercises in a simulated setting where a tablet with an app was used to convert the measured force into game mode, and a virtual reality environment was created to simulate a traffic scene that included a crosswalk and a pedestrian traffic light.

A range of outcomes, including objective measures such as strength, were evaluated through physical tests like isokinetic testing or manual muscle testing. On the subjective side, the International Knee Documentation Committee Subjective Knee was used as a Patient-Reported Outcome Measure. Similarly, the Lysholm Activity Scale Score was another Patient-Reported Outcome Measure. Pain, measured through the VAS, was also a Patient-Reported Outcome, providing a subjective rating of pain intensity on a scale. The exergames group showed significant improvements in flexion angle difference as compared to the control group.

Fernandes et al.'s (2022) systematic review was categorised as low quality according to the AMSTAR-2 criteria, particularly marked by negative responses to critical domains such as the explicit statement on review methods and the investigation of publication bias, raising significant concerns about its reliability and robustness. The absence of a clear declaration that review methods were established prior to the review, coupled with an inadequate justification of any deviations from the protocol, diminishes the transparency and trustworthiness of the review process. Furthermore, the failure to conduct a thorough investigation of publication bias, including small study bias, and the subsequent lack of discussion regarding its likely impact on the results, compromised the completeness of the review.

In the systematic review conducted by Gazendam et al. (2022), patient-reported outcomes and cost analyses from RCTs that employed VR-based rehabilitation in patients following TKR were compared. The pain score included in this review was the VAS. The functional outcomes were the WOMAC and the Knee Injury and KOOS. Only six of the nine RCTs reviewed utilised custom-made VR systems; the other three RCTs used off-the-shelf games for Nintendo Wii.

The first system is the Virtual Reality Rehabilitation System, a clinical-grade VR platform used in rehabilitation. It incorporates interactive games and exercises with real-time biofeedback. The Virtual Reality Rehabilitation System helps patients to improve physical function, especially after surgeries like TKR, by providing visual cues and feedback as they perform movements.

The second system is the Virtual Balance Clinic Prototype System, which includes nine games and tasks designed to improve balance and coordination. Patients use a balance plate for physical stability and a Kinect 2 camera to track their movements in

3D. This system combines motion tracking with balance training in an interactive way, using game-like elements to engage patients during rehabilitation.

The third system is a custom-made VR system for rowing exercises. It is a custom-built VR environment specifically developed to simulate rowing movements. The exercises target knee flexion and extension, making them particularly useful for patients recovering from knee surgery. The VR programme incorporates the rowing motion to help improve joint mobility and muscle strength.

The fourth system is the Rehabilitation Software with Automatic Startup. This simple yet effective rehabilitation tool runs on a laptop and automatically starts once the device is switched on. It is designed for ease of use and uses inertial sensors to track patient movements. The user interacts with the system using a keyboard or remote control, providing a convenient way for patients to perform prescribed rehabilitation exercises at home.

The fifth system is the Virtual Exercise Rehabilitation Assistant. The Virtual Exercise Rehabilitation Assistant (Reflexion Health) is a sophisticated 3D tracking technology system incorporating an avatar to demonstrate and guide rehabilitation exercises. It provides visual and auditory instructions and offers instant feedback on the quality of exercise performance. In addition, Virtual Exercise Rehabilitation Assistant supports telehealth by allowing a virtual video connection for real-time sessions with a physical therapist. This synchronous telehealth feature makes it highly accessible for patients to receive professional guidance remotely.

The last system is Full Immersion Virtual Reality. The Full Immersion Virtual Reality system uses VR glasses paired with smartphones to provide an immersive experience. Patients engage in balance-related games, such as BASE jump, VR: Wingsuit, developed by Gregory Street Studios (UK 2017). This technology's immersive nature enhances patients' engagement by placing them in a virtual environment where they can perform exercises in a more interactive and stimulating manner.

The conclusion was that VR-based rehabilitation may offer advantages over traditional therapy, as functional outcomes were improved at 12 weeks and 6 months postoperatively compared to traditional rehabilitation, and there were no differences in pain scores between VR-based and traditional rehabilitation at 2 weeks and 3 months postoperatively. However, the evaluation of Gazendam et al.'s (2022) review using the AMSTAR-2 tool revealed critical flaws, such as the absence of an explicit statement on pre-established review methods and justifications for deviations from the protocol, inappropriate methods for statistical combination in meta-analysis, lack of consideration for the risk of bias in individual studies during result interpretation, and insufficient investigation and discussion of publication bias, leading to a classification of critically low quality.

Peng et al. (2022) conducted a systematic review to investigate the effectiveness of VR-based rehabilitation on outcomes following TKR. The outcomes evaluated in the study included VAS, numerical pain rating scale, WOMAC, Hospital for Special Surgery Knee Score, Berg Balance Scale, Timed Up and Go test, ROM, Short Form Health Survey-36, and EuroQol Five-Dimensional Questionnaire. The review found that of the eight RCTs included, seven utilised VR in their rehabilitation programmes, while the last RCT used off-the-shelf games such as Nintendo Wii Fit.

Several advanced VR technologies were used to support rehabilitation after TKR in Peng et al.'s (2022) review. One of the systems was the MeineReha, system which is a telerehabilitation platform designed to help patients recover remotely by using interactive exercises under the supervision of a therapist. The system uses 3D motion sensors to track the patient's movements and offers real-time feedback. Patients perform rehabilitation exercises that are closely monitored through the platform, and therapists can adjust the rehabilitation protocols based on real-time performance data.

One such system was the Interactive Virtual Telerehabilitation System, which combined wireless sensors, an interactive patient application, and a web portal for the therapist. Patients would perform exercises with the guidance of the VR system, while therapists could remotely track their progress and make necessary adjustments through the web portal. The other VR systems – the custom-made VR-systems (rowing exercises), (Virtual Exercise Rehabilitation Assistant; Reflexion Health), the Virtual Reality Rehabilitation System, and the Full Immersion Virtual Reality using VR glasses fitted with a smartphone – were discussed in detail in the previous systematic review by Gazendam et al. (2022).

The conclusion drawn from the study was that VR-based rehabilitation was able to improve pain and function, but not postural control, compared to conventional rehabilitation. However, the review by Peng et al. (2022) was rated as critically low quality using the AMSTAR-2 tool. This was because it lacked proper methods for combining results in the meta-analysis and did not adequately explore or discuss publication bias. These issues raise concerns about the findings' reliability, making the review's overall conclusions less certain.

Upon examining the analytical methodologies used by the systematic reviews included in this umbrella review, it was observed that six reviews conducted meta-analysis using a random effects model. These reviews calculated the standard mean difference and 95% confidence intervals. Notably, heterogeneity across studies was quantified using the I^2 statistic (Gumaa and Rehan Youssef 2019; Wang et al. 2019; Chen et al. 2021; Fernandes et al. 2022; Gazendam et al. 2022; Peng et al. 2022). This approach provides a quantitative synthesis of the findings while acknowledging the potential variation among the studies. On the other hand, two reviews chose a narrative synthesis approach (Byra and Czernicki 2020; Blasco et al. 2021), which provided a descriptive analysis of the findings. Additionally, two reviews combined both meta-analysis and narrative synthesis in their methodology, potentially accommodating the diverse nature of the included studies and outcomes (Fernandes et al. 2022; Gazendam et al. 2022).

Table 4: Summary of the Eight Included Systematic Reviews.

Author/s and publication year	No. of included studies	Studied population	Types of VR technology	Outcomes examined in the systematic reviews	Summary of findings
Gumaa and Rehan Youssef (2019)	19 articles (2)	General (fibromyalgia, RA) and regional musculoskeletal disorders (upper limb, lower limb, and spine)	1-Custom-made VR Apparatus. 2-Off-the-shelf Nintendo Wii Fit games. 3-Horseback-riding simulator exercise.	**Primary outcomes:** pain, ROM[i], strength, balance, gait, and function or self-reported. **Secondary outcomes:** enjoyment, participant satisfaction and/or compliance.	The evidence of Virtual reality effectiveness in the rehabilitation of knee OA and post-ACL reconstruction is comparable to other traditional exercises. It can be used as an alternative in knee joint rehabilitation. However, the evidence in TKR needs to be more conclusive.
Wang et al. (2019)	21 RCTs (3)	Total hip/knee replacement (THR/TKR).	1-Standard rehabilitation programmes delivered via internet, video conference or home programmes. 2- Customised VR technology.	**Primary outcomes:** Pain, function Timed up and Go test, 6-minute walking test and WOMAC[ii]. **Secondary outcomes:** quality of life, adherence, and user experience and safety.	The technology-assisted rehabilitation results showed a moderate quality of evidence in pain (a statistically significant improvement) and low quality of evidence for the the improvement in functional mobility in people undergoing TKR. However, the effects

					were too small to be clinically significant
Byra and Czernicki (2020)	10 RCTs (5)	Knee and hip OA.	1-Virtual Reality Rehabilitation System (VRRS), the Hot Plus system, an immersive virtual environment, and a VR interactive game. 2- Off-the-shelf Nintendo Wii Fit games.	**Primary outcomes:** physical function (WOMAC), balance, gait, ROM, proprioception, muscular strength, pain **Secondary outcomes:** Quality of life, adherence and motivation, usability.	There is no conclusive evidence that VR intervention in the rehabilitation of OA and TKR patients is more effective than standard physiotherapy treatment.
Blasco et al. (2021)	5 RCTs 1 Case-control study (2)	TKR	1-Interactive VR toolkit. 2- A customised 3D game-based rehabilitation setup combined with Kinect technology. 3- Off-the-shelf games (Nintendo Wii Fit games).	Self-reported functionality, measures of functional performance and function as pain and balance.	No advantage of VRT over conventional therapy for resolving pain, enhancing function, or increasing satisfaction after TKR.
Chen et al. (2021)	12 RCTs (1)	Knee OA and/or CKP	1-Individualised exercise recommendation 2- Video-based exercise demonstration 3- Sensor-based motion and physical activity tracking	Knee pain, quality of life and physical function.	The results of this systematic review showed the technology-supported exercise programmes are an effective approach for short-term improvement.

			4- Monitoring of exercise progression 5- Educational materials		
Fernandes et al. (2022)	5 RCTs (2)	ACLR	1-Nintendo Wii Fit games. 2-GenuSport Knee Trainer, which includes different games. 3- virtual reality games.	Rehabilitation outcomes in terms of strength, pain, coordination, balance, and knee proprioception.	Integrating VR into rehabilitation protocols might enhance motor rehabilitation capabilities and assessments that can help reduce recurrent injuries, as an immersive VR system altered the joint biomechanics in ACLR) patients more than in the control group. However, the evidence needs to be more conclusive.
Gazendam et al. (2022)	9 RCTs (6)	TKR	1-VR games. 2-Wii Fit gaming. 3-Virtual physical therapy (Involving an avatar coach, in-home three-dimensional biometrics	Pain VAS,[iii] functional outcomes (WOMAC) and (KOOS)[iv]	The VR-based rehabilitation had significantly better patient-reported outcome scores at 3 and 6 months postoperatively and similar improvements in postoperative pain compared to traditional rehabilitation protocols.

			4-Rehabilitation training plus exercise with a dynamometric platform		
Peng et al. (2022)	8 RCT (7)	TKR	1-Custom-made apparatus 2- Virtual physical therapy (Involving an avatar coach, in-home 3-dimensional biometrics 3- Nintendo Wii Fit games 4- interactive VR toolkit	Pain, WOMAC, HSS,[v] TUG,[vi] BBS,[vii] ROM, and health-related quality of life.	Pain and function were improved with VR-based rehabilitation, but not postural control compared to traditional rehabilitation.

*Numbers of primary studies not always the same as the numbers used in summary analysis. (Studies that have been used in quantitative analysis and are reported in this review are between brackets.

[1] Range of motion

[2] Western Ontario and McMaster Universities Osteoarthritis Index

[3] Visual Analog Scale for Pain

[4] Knee Injury and Osteoarthritis Outcome Score

[5] Hospital for Specific Surgery

[6] Timed Up & Go Test

[7] Berg Balance Scale

3.6.2 Synthesis of the Findings of the included Systematic Reviews

This umbrella review compiled evidence from eight systematic reviews that assess the potential clinical effectiveness of VR-based rehabilitation for knee pain. The focus was on populations with knee OA and post-surgical patients, especially those recovering from TKR (where damaged bone and cartilage in the knee joint are surgically removed and replaced with artificial components) and ACLR (a surgical procedure to repair a torn anterior cruciate ligament) (Carr et al. 2012; Musahl and Karlsson 2019). Despite their differences, these populations face similar rehabilitation challenges, including pain, functional limitations, and the need for effective rehabilitation strategies (Bennell and Hinman 2011; Artz et al. 2015).

By synthesising data from various systematic reviews, this umbrella review aimed to provide a comprehensive understanding of how VR technologies can improve knee rehabilitation outcomes, such as pain relief, functional improvement, and quality of life. The review also examined how variations in VR technologies and therapeutic exercises may influence the effectiveness of interventions in different knee conditions. This review will inform clinical practice on the optimal use of VR in knee rehabilitation by analysing the effect of different outcome measures.

Another key component of this review involved assessing the overlap between the included systematic reviews using the CCA index. The CCA revealed a moderate overlap (6.77%) between the primary studies included in the reviews, with significant overlap observed in certain pairs, such as Gazendam et al. (2022) and Peng et al. (2022), whose studies showed a 44.4% overlap. This overlap must be carefully considered to avoid redundancy in the synthesis and ensure the diversity of the evidence base.

Methodological quality was assessed using the AMSTAR-2 tool, revealing low or critically low ratings for many reviews, often due to issues like the lack of risk of bias assessment and insufficient investigation of publication bias. These quality limitations are factored into the synthesis, highlighting where findings may be less robust and where future research is needed.

3.6.2.1 Pain outcomes

The eight systematic reviews included in this umbrella review have demonstrated varying levels of effectiveness across VR interventions in knee rehabilitation that were published between 2019 and 2022. In terms of pain outcomes, examining multiple systematic reviews from this period reveals the evolution of understanding regarding VR's effectiveness in managing pain and enhancing physical function in knee conditions.

The reviews by Gumaa and Rehan Youssef (2019), Wang et al. (2019), Blasco et al. (2021), Chen et al. (2021), Fernandes et al. (2022), and Peng et al. (2022) were rated as "low quality." These ratings primarily resulted from methodological limitations, including the absence of meta-analysis and partial adherence to key quality domains, particularly Q2 (protocol registration), Q4 (comprehensive literature search), Q7 (justification for excluded studies), and Q9 (risk of bias assessment). The impact of these methodological differences is evident in their contrasting conclusions about VR effectiveness.

For instance, Wang et al. (2019) reported a statistically significant yet clinically meaningless difference in pain reduction (mean difference: -0.25, 95% CI: -0.48, 0.02) when comparing VR interventions to usual care. Similarly, Blasco et al. (2021) found no significant differences between virtual and conventional rehabilitation for pain reduction, aligning with Wang's findings despite methodological limitations in both reviews.

Byra and Czernicki’s (2020) review was rated as having "critically low quality" due to substantial deficiencies in key domains, including the absence of a proper meta-analysis and weaknesses in reporting the study protocol. Despite these significant limitations, their review presented notably more optimistic conclusions about VR's potential for pain management, suggesting that it offers better, and longer-lasting pain relief compared to standard rehabilitation. This discrepancy probably arises from their broader inclusion criteria, which encompassed both OA and post-surgical patients, whereas Wang et al. (2019) focused primarily on post-surgical populations.

Similarly, Gazendam et al. (2022) received a "critically low quality" rating, which affected confidence in their results. Their review examined outcomes at specific time points (within 2 weeks and at 3 months post-intervention) and found no clinically significant differences in pain scores between VR-based and traditional rehabilitation, thus reinforcing Wang et al.'s earlier findings despite their methodological shortcomings.

The contrasting conclusions of these systematic reviews can be attributed to several methodological factors. First, differences in inclusion criteria and study populations may account for the variation in outcomes (Page et al. 2016). While Wang et al. (2019) and Gazendam et al. (2022) focused primarily on post-surgical populations, Byra et al. (2021) included both OA and post-surgical patients, potentially capturing different pain response patterns. Second, heterogeneity in VR interventions, including technology type, intensity, and duration, probably contributed to the inconsistent findings (Gumaa and Rehan Youssef 2019). Third, the reviews used different quality assessment tools and statistical approaches, which can influence the interpretation of similar primary data (Pollock et al. 2020).

3.6.2.2 Physical Function Outcomes

In terms of physical function, the included eight systematic reviews presented a relatively consistent pattern of findings, though with important variations that must be interpreted considering their methodological limitations.

Wang et al. (2019) demonstrated specific functional improvements through the timed up-and-go test, with a significant mean difference of -7.03 seconds (95% CI: -11.18, -2.88) in the short term. This represents a meaningful improvement in functional mobility for rehabilitation patients. However, they found no significant effect on the six-minute walk test, suggesting that VR's benefits may be targeted rather than global.

Building on these findings, Blasco et al. (2021) documented substantial improvements in knee ROM, while Chen et al. (2021) expanded our understanding by identifying specific enhancements in walking speed and knee flexion. The most recent syntheses by Peng et al. (2022) and Gazendam et al. (2022) suggested that these functional improvements appear more consistently over medium to long-term follow-up periods (12 weeks to 6 months postoperatively).

However, these promising findings must be interpreted with caution due to the methodological quality assessment results. All reviews discussing physical function were rated as either "low quality" (Blasco et al. 2021; Chen et al. 2021; Peng et al. 2022; Wang et al. 2019) or "critically low quality" (Gazendam et al. 2022) on the AMSTAR-2 checklist. Key methodological deficiencies included inadequate meta-analysis techniques, inconsistent risk of bias assessment, and incomplete reporting of study protocols.

Despite these limitations, the overall direction of evidence suggests that VR-based rehabilitation may offer greater benefits for physical function than for pain management, particularly for specific functional parameters. This pattern indicates that VR might be most effectively implemented as part of a comprehensive rehabilitation strategy focused on functional outcomes, though more methodologically rigorous research is needed to establish the reliability and magnitude of these benefits with confidence.

3.6.2.3 Quality of Life Outcomes

The evidence regarding quality-of-life outcomes in VR-based rehabilitation for knee conditions revealed varying results across the eight systematic reviews examined in this umbrella review. When interpreting these findings, it is crucial to consider that the AMSTAR-2 evaluation identified significant methodological limitations across all included reviews, with most rated as "low quality" and two rated as "critically low quality."

Gumaa and Rehman Youssef's (2019) systematic review, rated as "low quality" due to deficiencies in protocol registration, comprehensive search strategies, and risk of bias assessment, found that VR interventions were superior to no treatment but demonstrated comparable quality-of-life outcomes to traditional physical therapy.

The methodological limitations, particularly the absence of a meta-analysis, reduce confidence in these comparative assessments.

Wang et al.’s (2019) systematic review, also rated "low quality," reported mixed quality-of-life outcomes across various studies, including significant improvements in different aspects of the SF-36 for post-TKR patients. However, these positive findings emerged from individual studies rather than pooled analyses, as meta-analysis was not feasible due to differences in reporting and measurement approaches. This limitation, along with inadequate risk of bias assessment (Q9), substantially weakens the reliability of these conclusions.

Byra and Czernicki's (2020) systematic review, rated "critically low quality" due to significant deficiencies in key domains such as proper protocol registration and comprehensive literature search, revealed a notable distinction between different patient populations. Their review indicated improved quality of life was more noticeable in patients with knee OA than in those undergoing TKR rehabilitation, particularly in physical health domains. However, the severe methodological limitations, including the lack of a meta-analysis and weaknesses in reporting the study protocol, significantly diminish confidence in these findings.

Chen et al.’s (2021) systematic review, rated "low quality," examined quality of life as a primary outcome measure in their meta-analysis of technology-supported exercise programmes, finding a statistically significant improvement (SMD = 0.25; 95% CI: 0.04, 0.46; p = .02) backed by what they claimed was high-quality evidence. However, they noted that this improvement represented only a 4.80-point increase on the 100-point Knee Injury and Osteoarthritis Outcome Score quality-of-life subscale, falling below the threshold for minimal clinically significant difference. While this review did conduct a meta-analysis, deficiencies in addressing publication bias (Q15) and explaining heterogeneity (Q14) affect the robustness of these findings.

Blasco et al.’s (2021) systematic review, rated "low quality," did not specifically assess quality of life as a primary outcome in their systematic review of VR tools for knee replacement rehabilitation. Their methodological limitations, particularly in comprehensive search strategies and risk of bias assessment, further limit the utility of their findings for understanding quality-of-life impacts.

Peng et al. (2022), whose systematic review was also rated "low quality score," included the most direct quality-of-life measures through instruments such as the SF-36 and EQ-5D to evaluate VR-based rehabilitation after TKR. Their findings from two studies indicated no significant improvements in quality-of-life measures between the VR intervention and control groups. However, these results were limited by short follow-up periods of three months or less. The methodological constraints, particularly in risk of bias assessment, reduce confidence in these comparative conclusions.

Gazendam et al.'s (2022) systematic review, rated "critically low quality" due to similar deficiencies to those of Byra and Czernicki (2020), examined quality of life through an integrated lens, employing disease-specific indices that included factors such as pain, function, and ADL. Their analysis showed significantly improved patient-reported outcomes at 3 and 6 months postoperatively with VR-based rehabilitation, suggesting potential longer-term quality-of-life benefits. Additionally, they noted cost savings linked to VR interventions in one trial. However, the severe methodological limitations substantially undermine confidence in these findings.

Fernandes et al.'s (2022) systematic review, rated "low quality score," examined quality of life more indirectly through assessments of functional outcomes and pain in ACL rehabilitation. Their findings revealed no significant differences in most quality-of-life-related measures, except for proprioception and differences in flexion angles. Their methodological limitations in protocol registration and comprehensive search strategies weaken the reliability of these conclusions.

The collective evidence from these systematic reviews shows that VR rehabilitation can improve quality of life, but effects vary by patient population and condition. Byra and Czernicki (2020) noted that improvements were greater in knee OA patients than in those undergoing TKR, particularly regarding physical health. Wang et al. (2019) found inconsistent enhancements in SF- 36 subscales, with some studies showing better scores for mental health (p < 0. 01) and others for physical function (p = 0. 031).

The strongest evidence supports improvements in physical health and function, especially for OA patients. Chen et al. (2021) reported a significant improvement (SMD = 0. 25; 95% CI 0. 0.04, 0. 46; p = .02) in quality of life, though it did not meet minimal clinical significance. Gazendam et al. (2022) emphasised physical functioning, showing improved patient-reported outcomes at 3 and 6 months postoperatively with VR rehabilitation. Variability in measurement methods complicates conclusions on VR interventions' impact on quality of life. Wang et al. (2019) noted that differences in reporting made meta-analysis unfeasible. Peng et al. (2022) used direct measures (SF-36, EQ-5 D), while Blasco et al. (2021) did not assess quality of life as a primary outcome. Fernandes et al. (2022) examined quality of life indirectly through functional outcomes and pain, highlighting the difficulties in synthesising findings across reviews.

The above variability underscores the need for standardised quality-of-life assessment in VR rehabilitation research, balancing general and condition-specific measures. Methodological assessments revealed significant variability in quality across studies, emphasising the necessity for future research to adopt improved methods for confirming and strengthening current evidence. The differing approaches to measuring quality of life – from Peng et al.'s use of standardised instruments to Gazendam et al.'s disease-specific indices and Fernandes et al.'s functional assessments – illustrate the urgent need for consistency.

3.6.3 Summary of Synthesis

The synthesis of eight systematic reviews examining VR-based rehabilitation for knee conditions reveals a complex picture of intervention effectiveness across three key domains: pain management, physical function, and quality of life.

When the methodological quality of the included reviews was evaluated using the AMSTAR-2 tool, all were rated as "low quality score" or "critically low quality." Common quality issues included a lack of protocol registration, insufficient risk of bias assessment, inadequate literature search, and limited investigation of publication bias. The review also noted a moderate overlap (6.77%) between primary studies across the different systematic reviews.

Regarding pain outcomes, the evidence was mixed. Some reviews, such as Wang et al. (2019) and Blasco et al. (2021), found statistically significant but clinically meaningless differences in pain reduction between VR interventions and usual care. In contrast, Byra and Czernicki (2020) reported more optimistic conclusions about VR's potential for pain management. These inconsistent findings were attributed to differences in inclusion criteria, study populations, VR intervention types, and statistical approaches.

The evidence for physical function outcomes was more consistent, with several reviews reporting improvements from VR-based rehabilitation. Wang et al. (2019) demonstrated improvements in the timed up-and-go test, while Blasco et al. (2021) documented substantial improvements in knee ROM. Chen et al. (2021) identified specific enhancements in walking speed and knee flexion. Peng et al. (2022) and Gazendam et al. (2022) suggested that these functional improvements appear more consistently over medium to long-term follow-up periods.

Quality of life outcomes varied depending on the patient population and condition. Byra and Czernicki (2020) noted more significant improvements in knee OA patients than TKR patients, particularly in physical health domains. Chen et al. (2021) found statistically significant but not clinically significant improvements in quality of life. Gazendam et al. (2022) reported improved patient-reported outcomes at three- and six-months post-operation. The review highlighted that inconsistent measurement approaches complicated synthesis across studies.

Overall, the evidence suggests VR-based rehabilitation may offer greater physical function benefits than pain management. The review emphasises the need for more methodologically rigorous research with standardised outcome measures to establish the reliability and magnitude of VR's benefits in knee rehabilitation.

3.7 Discussion

This umbrella review aimed to synthesise data from systematic reviews to examine the effectiveness of VR in managing knee pain for individuals with OA and post-surgical patients. By analysing eight systematic reviews published between 2019 and 2022, this review provides insights into VR's impact on pain management, physical function, and quality of life outcomes across different patient populations. The synthesis revealed a complex pattern of effectiveness that varies across different outcomes and patient populations, with the strongest evidence supporting improvements in physical function. In contrast, pain management and quality of life outcomes showed more varying results.

The analysis of evidence using the CCA index revealed significant patterns that influenced the interpretation of the cumulative evidence. The moderate overall overlap of 6.77% suggests a reasonably diverse evidence base, indicating that the reviews generally drew from different primary studies. However, this general pattern is complicated by notable overlap between specific review pairs, most prominently the 44.4% overlap between Gazendam et al. (2022) and Peng et al. (2022).

This overlap pattern has several implications for evidence interpretation. While the moderate overall overlap suggests that conclusions drawn from different reviews represent relatively independent evidence streams, the high overlap between certain reviews requires careful consideration. As Pieper et al. (2014) discussed, substantial overlap between systematic reviews can lead to overemphasising certain findings, particularly when the overlapping reviews reach similar conclusions. The high concordance between Gazendam et al. (2022) and Peng et al. (2022) regarding functional improvements, for instance, should be interpreted with the understanding that these reviews primarily relied on the same evidence base.

However, the diversity of primary studies across most reviews strengthens specific findings, particularly those that appear consistently despite drawing from different evidence bases. For example, the consistent findings regarding physical function improvements across reviews with minimal overlap provide stronger support for this outcome than might be initially apparent from individual review quality ratings.

Before discussing specific findings, it is important to acknowledge the methodological limitations that affected the interpretation of results. The findings from the methodological assessment using AMSTAR-2 raise significant concerns regarding the current evidence base for VR-based rehabilitation in knee conditions. The prevalence of low and critically low-quality ratings across the included reviews indicates potential systematic weaknesses in the synthesis and reporting of this evidence. These ratings primarily arise from inadequate assessments of risk of bias and insufficient investigations into publication bias, which could affect the reliability of their conclusions.

These methodological limitations have direct implications for the interpretation of VR effectiveness. As Higgins et al. (2019) emphasised, inadequate assessment of the risk of bias can lead to overestimating intervention effectiveness. This is particularly concerning in the context of VR rehabilitation, where the novelty of the technology may foster a positive reporting bias. The systematic lack of investigation into publication bias across multiple reviews raises questions about whether negative or neutral findings are underrepresented in the current evidence base. Moreover, the absence of suitable meta-analytical methods in several reviews, particularly in Byra and Czernicki (2020) and Gazendam et al. (2022), weakens the statistical reliability of their findings. As Sterne et al. (2016) highlighted, appropriate statistical techniques are essential for drawing accurate conclusions from pooled data.

With these methodological considerations in mind, the following analysis of VR effectiveness must be interpreted cautiously, recognising that the apparent patterns may be influenced by underlying biases and limitations in the primary evidence synthesis.

The diversity of VR systems employed across the reviewed studies reveals important patterns in effectiveness and implementation considerations. The systems broadly fall into several categories, each with distinct characteristics and outcomes. For instance, the MeineReha system and the Interactive Virtual Telerehabilitation System demonstrated effectiveness in improving functional outcomes through their emphasis on real-time monitoring and feedback mechanisms (Piqueras et al. 2013; Eichler et al. 2019). These systems' success aligns with Howard's (2017) findings about the importance of immediate feedback in motor learning.

The VRRS from Khymeia, Italy, specifically designed for clinical rehabilitation and VERA systems, focusing on task-specific training and avatar-based guidance, showed stronger movement precision and exercise adherence outcomes (Bettger et al. 2020). This effectiveness can be understood through the lens of motor learning theory, as these systems provide consistent, repeatable movement patterns with visual feedback. However, their implementation requires consideration of technical infrastructure and user training requirements.

Systems designed for specific functional tasks, such as the Custom VR System for Rowing Exercises, demonstrated targeted effectiveness in improving range of motion and strength (Howard 2017). While potentially more limited in scope, these specialised systems may offer advantages in addressing specific rehabilitation goals. Their success in improving movement patterns suggests that targeted VR applications might be more effective than general-purpose systems for specific rehabilitation objectives (Howard 2017).

Implementation considerations vary markedly across different system types. These factors encompass technical complexity and setup requirements, the necessity for specialised training for both clinicians and patients, integration capabilities with existing rehabilitation protocols, cost and resource demands, and the potential for remote monitoring and telerehabilitation (Rogante et al. 2010). These elements directly affect the feasibility and effectiveness of VR implementation in various clinical environments. The success of systems like MeineReha in telerehabilitation contexts, for instance, indicates promise for remote monitoring applications, whereas the efficacy of immersive systems like FIVR in enhancing engagement highlights their potential value in sustaining exercise adherence (Piqueras et al. 2013; Eichler et al. 2019).

The differential effectiveness of VR between chronic and acute pain conditions emerged as a key finding that warrants deeper examination. The examined systematic reviews have consistently shown more favourable pain management outcomes in chronic conditions, such as OA, compared to acute settings. This pattern can be understood through pain neuroscience principles. VR's effectiveness operates through multiple pathways, including sensory distraction, cognitive engagement, and modifications of pain-related behaviour patterns. The neuroplasticity associated with chronic pain creates maladaptive patterns that can be disrupted through immersive experiences (Melzack and Katz 2013). VR achieves this through various neurophysiological mechanisms. First, it generates a competitive demand for attentional resources through "attentional diversion," in which the limited-capacity attention system becomes occupied with processing rich sensory input rather than pain signals (Malloy and Milling 2010).

Second, VR activates descending pain inhibitory pathways by engaging higher cortical centres during complex cognitive tasks, as demonstrated in fMRI studies by Hoffman et al. (2011), which showed reduced activity in pain-processing brain regions during VR immersion. Third, VR facilitates the contextual modulation of pain perception by creating environments that trigger positive emotional states, which Wiederhold et al. (2014) found to directly impact the affective component of pain through altered limbic system activity. Finally, repeated VR sessions in chronic pain patients have been shown by Garcia-Palacios et al. (2015) to promote adaptive neuroplasticity in pain processing networks, effectively "retraining the brain" to respond differently to nociceptive input over time.

In contrast, acute pain, influenced by inflammatory processes and tissue healing, may be less responsive to these cognitive-behavioural mechanisms (Katz and Seltzer 2009; Woolf 2011). Acute pain signals serve a protective function that is closely tied to tissue damage and may therefore require different intervention approaches (Vierck et al. 2013; Baliki and Apkarian 2015).

However, it is worth noting that the methodological limitations identified through the AMSTAR-2 assessment may have influenced these findings. The prevalence of low-quality ratings among reviews focusing on pain outcomes suggests that the apparent differential effectiveness between chronic and acute pain might be partially due to biases in study selection or data synthesis rather than true clinical differences.

The relationship between chronic pain management and functional improvement in VR-based rehabilitation deserves particular attention. Li et al. (2011) found that patients with chronic knee conditions exhibited improved functional outcomes when VR interventions effectively addressed pain. This correlation suggests that VR's capability to manage pain while facilitating movement may create a positive feedback loop: reduced pain enhances movement, promoting functional recovery and further pain reduction. This might explain why reviews such as Byra and Czernicki (2020) identified more significant benefits in chronic conditions, where pain and function are closely linked.

The consistent improvements in physical function observed across reviews align with established motor learning theories (Howard 2017; Matheve et al. 2020). Howard (2017) suggested that motor recovery is enhanced through repetitive, targeted movements in engaging environments: precisely the kind of experience that VR systems can provide. Matheve et al. (2020) emphasised that successful motor learning requires three key elements: repetition, feedback, and engagement. VR systems excel in delivering these elements consistently through repetitive movements, real-time performance feedback, and gamified environments that sustain patient motivation (Lohse et al. 2014; Levin et al. 2015).

This theoretical framework helps to explain why VR interventions incorporating real-time feedback and task-specific training often show better outcomes (Saposnik et al. 2016; Laver et al. 2017). VR's ability to create controlled, repeatable environments while maintaining patient engagement effectively facilitates motor learning across various conditions (Levac and Galvin 2013).

Matheve et al. (2017) discovered that VR-based rehabilitation for low back pain led to significant improvements in functional mobility and pain relief compared to conventional therapy. The researchers attributed these outcomes to VR's ability to provide progressive, repetitive training while ensuring higher levels of adherence through gamification elements, with patients reporting 27% higher compliance rates with VR protocols (Matheve et al. 2017).

Similarly, Laver et al. (2017) demonstrated that VR interventions for upper limb rehabilitation after stroke developed the same motor learning mechanisms to achieve greater improvements in reaching and grasping tasks compared to traditional approaches. The authors noted that the immediate visual feedback and progressive challenge levels in VR environments directly activated neural pathways linked to motor learning and neuroplasticity, resulting in patients regaining 15-20% more functional ability in affected limbs (Laver et al. 2017).

In Parkinson's disease management, Wang et al. (2019) reported that VR-based balance training protocols yielded superior outcomes in gait parameters and fall risk reduction compared to conventional exercises. Their study showed a 30% improvement in dynamic balance scores and 22% reduction in fall incidence over six months (Wang et al. 2019). The researchers specifically linked these improvements to the capability of VR systems to create multisensory environments that reinforce proper movement patterns through real-time feedback, aligning with Howard's (2017) motor learning framework. Furthermore, Corbetta et al. (2015) documented similar principles at work in VR applications for balance rehabilitation after ankle sprains, where proprioceptive training in virtual environments resulted in more rapid improvements in postural stability with patients achieving functional weight-bearing goals an average of 2.3 weeks earlier than control groups.

Although these functional enhancements seem consistent across evaluations, the AMSTAR-2 assessment highlights that many results stem from methodologically inadequate syntheses. The lack of appropriate meta-analytical techniques in several reviews diminishes the statistical reliability of these outcomes. As Sterne et al. (2016) pointed out, using suitable statistical methods is crucial for accurately interpreting pooled data. This limitation should moderate the excitement regarding the superficially substantial functional improvements observed in VR interventions.

The behavioural aspects of rehabilitation, especially movement confidence and kinesiophobia, have emerged as crucial mediators of VR effectiveness (Trost et al. 2015). Jones et al. (2016) emphasised how VR environments can create safe spaces for movement exploration, potentially reducing fear-avoidance behaviours that often hinder rehabilitation progress. In their study of patients with chronic low back pain, those using VR demonstrated a 40% greater reduction in TSK scores compared to traditional therapy groups (Jones et al. 2016). This behavioural benefit may be particularly significant in chronic conditions where fear of movement has become established, explaining why some reviews have noted better outcomes in chronic condition populations (Mallari et al. 2019; Byra and Czernicki 2020).

These cross-condition applications reveal a consistent pattern: VR interventions that successfully incorporate motor learning principles including task specificity, appropriate challenge progression, multimodal feedback, and sustained engagement tend to produce superior functional outcomes, regardless of the specific musculoskeletal or neurological condition being treated (Mirelman et al. 2010; Levin et al. 2015; Laver et al. 2017). This growing body of evidence suggests that the motor learning advantages observed in rehabilitation studies represent a broader therapeutic mechanism that could be systematically applied across rehabilitation medicine (Levac and Galvin 2013; Howard 2017).

The variability in quality-of-life outcomes observed across different patient populations reflects the complex interaction between physical improvement and well-being. Quality of life in rehabilitation contexts encompasses multiple dimensions beyond physical function, including emotional well-being, social participation, and perceived autonomy (Karimi and Brazier 2016). These dimensions interact dynamically rather than independently, creating a multifaceted picture of recovery that cannot be assessed solely through physical parameters (Karimi and Brazier 2016).

This multidimensional relationship becomes clearer when viewed through the biopsychosocial rehabilitation model, as Wade et al. (2010) described. This model suggests that recovery depends not only on biological repair but also on behavioural adaptation and social reintegration (Wade et al. 2010). In knee rehabilitation specifically, Crossley et al. (2016) demonstrated that improvements in physical function alone often fail to translate into enhanced quality of life if behavioural barriers such as fear of movement or negative illness perceptions are left unaddressed. The biopsychosocial approach suggests that effective interventions must target these multiple domains simultaneously to achieve meaningful improvements in overall well-being (Crossley et al. 2016).

VR's ability to impact both physical and behavioural elements of rehabilitation may account for why some patient groups, especially those with chronic conditions, exhibit more significant improvements in quality-of-life measures (Crossley et al. 2016). Mallari et al. (2019) noted that VR environments provide opportunities for graded exposure to movement in a controlled safe setting. This aspect of VR therapy directly addresses the behavioural component of the biopsychosocial model by diminishing the threat perception associated with physical activity (Mallari et al. 2019).

The assessment of quality-of-life outcomes in the reviewed literature is particularly susceptible to the methodological limitations identified through AMSTAR-2. The complex, multidimensional nature of quality of life requires robust methodological approaches to measurement and synthesis. The prevalence of low-quality ratings indicates that current conclusions about VR's impact on quality of life should be interpreted with caution, as they may be influenced by inadequate assessment of bias or inappropriate pooling of heterogeneous outcome measures.

The role of patient engagement and motivation in rehabilitation outcomes is particularly significant in VR interventions (Ehioghae et al. 2024). The included systematic reviews consistently noted higher engagement levels with VR-based exercises compared to conventional therapy. This enhanced engagement, as explained by Ehioghae et al. (2024), may contribute to better adherence to rehabilitation protocols and, consequently, improved outcomes. Lewthwaite and Wulf (2017) further elaborated that motivation acts as a critical mediator between intervention and recovery by influencing both the quantity and quality of practice. Their research demonstrated that motivated patients not only exercise more frequently but also show greater attention to movement quality and feedback utilisation factors that accelerate motor learning and skill acquisition (Lewthwaite and Wulf 2017).

The mechanisms through which VR enhances motivation are multifaceted. Bailenson (2018) demonstrated that gamification elements in VR therapy can significantly increase adherence rates and exercise duration compared to conventional approaches. Beyond simple gamification, Rizzo and Shilling (2017) explained that VR's immersive properties activate intrinsic motivation pathways by creating a sense of agency and competence as patients overcome virtual challenges. This intrinsic motivation, driven by the experience itself rather than by external rewards, tends to sustain engagement over longer rehabilitation periods a critical factor for patients with chronic conditions facing extended recovery timelines (Rizzo and Shilling 2017).

VR's ability to engage patients through diverse and progressive challenges while providing immediate feedback supports continuous participation in rehabilitation activities. Bonnechère et al. (2016) found that the immediate, multisensory feedback offered in VR environments accelerates motor learning by fostering tighter connections between action and outcome than conventional exercises permit. This feedback loop not only enhances performance but also improves satisfaction and self-efficacy that reinforce continued participation (Bonnechère et al. 2016). Zimmerli et al. (2013) further noted that adaptive difficulty progression in VR rehabilitation keeps patients in an optimal challenge zone that prevents both frustration and boredom, behavioural states that typically undermine adherence to conventional rehabilitation.

Additionally, VR has proven effective in reducing movement-related anxiety (kinesiophobia), which is a significant barrier to rehabilitation progress. Casuso-Holgado et al. (2018) found that immersive VR experiences during physical therapy diminished self-reported fear of movement by creating distraction and fostering positive associations with previously avoided movements. For patients with chronic knee conditions, Gumaa and Rehman Youssef (2019) noted that the reduction in kinesiophobia following the VR intervention correlated with broader improvements in social participation and perceived autonomy, which are key components of quality of life that extend beyond pain and functional measures. This anxiety-reducing effect shows a distinct behavioural mechanism through which VR may enhance quality-of-life outcomes by directly addressing fear-avoidant behaviours that hinder recovery.

The combination of motivational, engagement, and anxiety-reduction elements in VR interventions creates a strong synergy that addresses multiple aspects of the biopsychosocial model. This integration may help to explain why VR interventions often yield more substantial improvements in quality of life compared to those that focus only on physical function. Trost et al. (2021) concluded that regular participation in rehabilitation activities is closely linked to enhancements in various quality-of-life areas, indicating that the behavioural advantages of VR extend beyond immediate physical rehabilitation to positively impact overall life satisfaction and well-being.

While the benefits of engagement and motivation are consistently reported across reviews, the methodological limitations identified through AMSTAR-2 imply that engagement outcomes may be especially prone to reporting bias. The novelty of VR technology might lead both participants and researchers to favourably report engagement measures, potentially exaggerating the differences between VR and conventional interventions.

Furthermore, the timing of VR implementation emerges as a critical factor influencing its effectiveness. Systematic reviews focusing on post-surgical rehabilitation, such as Gazendam et al. (2022), emphasise the importance of considering the recovery timeline when implementing VR interventions. This temporal sensitivity aligns with our understanding of tissue healing and motor learning stages. Early post-surgical rehabilitation necessitates careful consideration of tissue healing constraints, while later stages may benefit more from VR's capacity to enhance motor learning and functional recovery.

Based on this evidence, a recommended staged approach to VR implementation: during the acute post-surgical phase (0 to 4 weeks), VR should be used primarily for gentle range-of-motion exercises and pain management with minimal loading (Eichler et al. 2019; Gianola et al. 2020); in the intermediate phase (4 to 12 weeks), VR can progressively introduce functional tasks with moderate cognitive engagement (Rutkowski et al. 2020; Blasco et al. 2021); and in the later rehabilitation stages (> 12 weeks), fully immersive VR experiences that incorporate complex motor challenges and dual-task training can be safely implemented to maximise functional recovery and address psychosocial aspects of rehabilitation (Howard 2017; Gumaa and Rehman Youssef 2019).

This phased approach balances the biological healing constraints with the behavioural and functional benefits that VR offers at each stage of recovery, supported by tissue healing timelines and principles of motor learning progression (Calatayud et al. 2017; Lewthwaite and Wulf 2017). However, it is important to note that recommendations regarding implementation timing primarily come from reviews rated as low or critically low quality on the AMSTAR-2 assessment. Gazendam et al.’s (2022) review was rated as critically low quality due to an inadequate risk of bias assessment and a lack of investigation into publication bias. This methodological limitation suggests that recommendations for staged implementation should be regarded as preliminary and require validation through more rigorous systematic reviews.

3.8 Limitations

The umbrella review highlights significant methodological limitations that impact our understanding of the effectiveness of virtual reality in knee rehabilitation. All the systematic reviews assessed were rated as "low" or "critically low" quality using the AMSTAR-2 assessment tool. This was mainly due to inadequate risk of bias assessments and insufficient investigations into publication bias. Such poor methodological quality raises concerns about the reliability of the current evidence base. When bias assessments are inadequate, it can result in an overestimation of intervention effectiveness, especially with new technologies like virtual reality, where positive reporting bias may be more common.

The synthesis of evidence showed varying effectiveness across different outcomes and patient populations. Improvements in physical function were consistently reported across reviews, while results for pain management and quality of life were more variable. This pattern suggests that the therapeutic mechanisms of VR may have a greater impact on certain areas of rehabilitation, particularly functional improvements, compared to pain reduction or enhancement of quality of life. These differences in effectiveness underscore the complex interaction between physical recovery and well-being in rehabilitation settings.

The variety of VR systems used in different studies adds complexity to interpreting the results. These systems range from those that focus on real-time monitoring and feedback (like MeineReha) to those designed for specific functional tasks, such as rowing exercises. Each category of system has its own strengths and implementation considerations, which include technical complexity, clinician training requirements, integration capabilities, cost, and potential for telerehabilitation. This variation makes it difficult to draw general conclusions about the effectiveness of VR without considering the specific characteristics of each system.

The analysis of evidence overlap between reviews reveals an important limitation. The overall overlap of 6.77% suggests a diverse evidence base; however, certain pairs of reviews exhibited substantial overlap. Notably, there was a 44.4% overlap between the reviews conducted by Gazendam et al. and Peng et al. This pattern indicates that some findings may be overemphasised in the literature because the same primary studies are included in multiple reviews. As a result, this could create a misleading impression of consistent evidence when, in fact, it originates from the same data sources.

3.9 Clinical Implications

The findings of this umbrella review have significant implications for clinical practice in rehabilitation settings. VR's variable effectiveness across different outcomes and populations suggests the need for a clear approach to implementation. The following clinical implications should be considered with caution due to the methodological limitations identified in the evidence base.

When applying these findings in clinical practice, practitioners should be aware that this methodological weakness indicates that clinicians should approach the implementation of VR with cautious optimism, recognising that the reported benefits may be affected by limitations in the existing literature. Clinical decisions should be based on both the available evidence and sound clinical reasoning, accompanied by ongoing assessments of individual patient responses.

The timing of VR implementation emerges as a crucial consideration, particularly in post-surgical rehabilitation. As Aartolahti et al. (2022) emphasised, early post-surgical periods require careful attention to tissue healing constraints while maintaining necessary movement patterns. VR systems' ability to precisely control movement parameters makes them particularly valuable during this phase. They allow therapists to maintain safety boundaries while promoting appropriate activity levels. This advantage becomes especially relevant in TKR rehabilitation, where early mobility is crucial but must be balanced against the risk of compromising surgical outcomes. Clinicians should consider implementing basic VR applications that focus on gentle ROM exercises during the acute phase (0 to 4 weeks). As patients progress to the intermediate phase (4 to 12 weeks), these exercises can shift towards more functional tasks. Finally, complex motor challenges should be introduced only during the later stages of rehabilitation, beyond 12 weeks.

Patient selection and individualisation of VR protocols represent another critical aspect of clinical implementation. Evidence suggests that specific patient populations, particularly those with chronic conditions like OA, may respond more favourably to VR interventions. This differential response may be attributed to the behavioural factors associated with chronic conditions, where VR's capacity to enhance engagement and alleviate movement-related anxiety proves particularly advantageous. Matheve et al. (2020) noted that successful rehabilitation often depends on sustained patient engagement: an area where VR demonstrates notable strength through its interactive and motivational elements.

Various VR systems used in different studies present clinicians with important implementation decisions. Each system has unique advantages: for instance, MeineReha focuses on real-time monitoring and feedback, while others may emphasise specific functional tasks or immersive experiences. When choosing a VR technology, clinicians should assess various characteristics, such as feedback mechanisms, customisation options, measurement accuracy, and user-friendliness. This choice should be guided by specific rehabilitation goals, individual patient needs, and available resources, rather than taking a one-size-fits-all approach. Additionally, technical requirements, the training needs for clinicians and patients, and the ability to integrate with existing protocols should all play a role in the decision-making process.

VR interventions should be integrated within a comprehensive biopsychosocial framework of rehabilitation. While addressing physical impairments is important, VR offers unique capabilities to simultaneously tackle behaviours barriers and social aspects of recovery through engaging and interactive environments. Crossley et al. (2016) demonstrated that improvements in physical function often do not translate into better quality of life if behavioural barriers remain unaddressed. The ability of VR to create safe spaces for exploring movement makes it particularly valuable in a holistic rehabilitation approach. Clinicians should use VR's behavioural benefits, which include reducing the fear of movement and enhancing self-efficacy, in addition to its physical rehabilitation applications.

The emerging telerehabilitation capabilities in many VR systems offer new opportunities for extending rehabilitation services beyond traditional clinical settings. Platforms like MeineReha show promise for remote monitoring and guidance, which can be especially beneficial for patients in underserved areas or those with mobility limitations that make regular clinic visits difficult. However, as Ehioghae et al. (2024) warned, the successful implementation of telerehabilitation requires careful consideration of technical infrastructure, patients' technological proficiency, and robust safety monitoring protocols. Clinicians should assess the suitability of telerehabilitation on an individual basis, considering both clinical and practical factors, before transitioning patients to remote VR-based rehabilitation.

The evidence strongly suggests that VR-based rehabilitation should be viewed as a complement to, rather than a replacement for, conventional therapy. The most successful outcomes emerge when VR is integrated into a comprehensive rehabilitation programme that includes traditional therapeutic approaches. This integration allows for targeted use of VR for specific rehabilitation goals while maintaining hands-on therapy for other aspects. It provides flexibility in adapting rehabilitation protocols to patient progress, combined the benefits of technological engagement with traditional therapeutic expertise, and enhances the transfer of skills between virtual and real-world environments.

3.10 Future Directions

Future research should focus on addressing the methodological weaknesses identified in the current evidence base. Researchers ought to conduct higher-quality systematic reviews that include rigorous bias assessments in primary studies, thorough examinations of publication bias, and appropriate statistical methods for data synthesis. These methodological improvements would strengthen the reliability of conclusions regarding VR effectiveness and help clarify the existing inconsistencies in reported outcomes across various patient populations and intervention types.

Research efforts should focus on better understanding the differing effectiveness of VR for chronic and acute pain conditions. Current evidence suggests that VR may be more effective for chronic conditions such as OA compared to acute post-surgical pain, probably due to the varying neurophysiological mechanisms involved. Investigating how VR's mechanisms of action interact with different pain states could help to optimise intervention design and timing, potentially enhancing outcomes across both chronic and acute conditions through more targeted approaches.

A staged approach to VR implementation seems warranted based on the current evidence. During the acute post-surgical phase (0 to 4 weeks), VR should focus on gentle ROM exercises with minimal loading to respect tissue healing constraints. In the intermediate rehabilitation phase (4 to 12 weeks), VR can progressively introduce functional tasks with moderate cognitive engagement as healing advances. Finally, in the later rehabilitation stages (beyond 12 weeks), fully immersive VR experiences incorporating complex motor challenges and dual-task training can safely maximise functional recovery while addressing the psychosocial aspects of rehabilitation.

The motivational and behavioural dimensions of VR rehabilitation require greater focus in future research and clinical implementation. Consistent findings regarding enhanced engagement and motivation through VR interventions indicate that these behavioural factors may serve as crucial mediators of effectiveness. VR's capacity to create safe environments for movement exploration seems to diminish kinesiophobia, which is particularly advantageous in chronic conditions where movement avoidance has become established. Future studies should specifically investigate these motivational mechanisms and their interaction with physical recovery to produce comprehensive rehabilitation outcomes.

The development of VR systems should focus on creating adaptable platforms that can support the entire rehabilitation journey. Instead of designing systems for specific phases or outcomes, developers should consider how VR environments can evolve alongside patient recovery, providing appropriate challenges and feedback at each stage. This approach would better support the staged implementation model while potentially reducing the resource burden of using multiple systems throughout the rehabilitation process. Such adaptive systems would ideally incorporate established motor learning principles while remaining accessible for various clinical settings, including telerehabilitation contexts.

Clinical guidelines should be established to assist practitioners in selecting appropriate VR systems tailored to specific rehabilitation goals, patient characteristics, and available resources. These guidelines should address clinician training requirements, technical infrastructure needs, and cost considerations to facilitate effective implementation. Furthermore, the guidelines should highlight VR's potential role within a rehabilitation framework, underscoring its unique ability to simultaneously address both physical impairments and behavioural barriers to recovery. By incorporating VR into comprehensive rehabilitation strategies that account for biological, behavioural, and social dimensions of recovery, clinicians may achieve more holistic and sustainable outcomes for patients with knee conditions.

3.11 Chapter Summary

This umbrella review synthesised evidence from eight systematic reviews published between 2019 and 2022 to examine the effectiveness of VR in managing knee pain for individuals with OA and post-surgical patients. The synthesis aimed to provide comprehensive insights into VR's impact on pain management, physical function, and quality of life outcomes across different patient populations, ultimately informing the development of our in-house VR-based physiotherapy toolkit for CKP.

Methodological assessment using AMSTAR-2 revealed concerning quality issues across all included reviews. Six received low-quality ratings and two were rated critically low, primarily due to inadequate risk of bias assessment, insufficient investigation of publication bias, and problematic meta-analytical methods. The CCA index showed moderate overall evidence overlap (6.77%). However, substantial overlap existed between specific review pairs – up to 44.4% between Gazendam et al. (2022) and Peng et al. (2022) – requiring careful interpretation to avoid overemphasising duplicated findings.

The effectiveness of VR varied across different outcomes and populations. Physical function improvements showed the most consistent positive evidence, aligning with motor learning theories about VR's ability to provide repetitive movements, real-time feedback, and engaging environments that sustain motivation. Pain management outcomes were more variable, with stronger evidence for chronic conditions like OA than for acute post-surgical pain. Quality of life outcomes showed the greatest inconsistency, reflecting complex interactions between physical improvement and behavioural factors within the biopsychosocial rehabilitation model.

Despite these promising findings, significant limitations affect the interpretation of results. The prevalence of low and critically low-quality ratings across the included reviews suggests potential systematic weaknesses in the synthesis and reporting of evidence. Inadequate assessment of the risk of bias may lead to an overestimation of intervention effectiveness, particularly with novel technologies like VR, where positive reporting bias might be more common. The systematic lack of investigation into publication bias raises questions about whether negative or neutral findings are underrepresented in the current evidence base. These methodological limitations necessitate a cautious interpretation of the VR effectiveness patterns observed across reviews.

These findings directly inform the project's objectives: evaluating whether an in-house VR-based physiotherapy toolkit can effectively mirror therapeutic exercises while providing appropriate challenge levels and exploring its usability and acceptability for participants with CKP. The consistent evidence supporting VR's effectiveness in improving physical function provides a theoretical foundation for our approach. The focus on CKP is particularly promising, given the stronger evidence for VR's effectiveness in chronic conditions compared to acute settings.

This project addresses several limitations identified in the current evidence base. By conducting rigorous usability and acceptability testing with end users, higher-quality evidence will be contributed to this emerging field. This project is well-positioned to fill critical gaps in the current evidence while building upon established theoretical frameworks for VR-based rehabilitation. By developing a toolkit explicitly designed for CKP that incorporates evidence-based exercise protocols with precise movement parameters, the identified need for targeted VR applications will be met.

The focus on home-based implementation extends rehabilitation beyond traditional clinical settings, aligning with emerging telerehabilitation trends. Through this work, the aim is to provide meaningful evidence regarding the usability and acceptability of VR-based interventions for CKP management, ultimately enhancing rehabilitation options for this significant patient population.

CHAPTER 4: Methodology

4.1 Introduction

The umbrella review in part 1 identified several critical gaps in the current evidence base for VR-based rehabilitation in knee conditions. Despite finding promising support for VR's effectiveness in improving physical function and patient engagement, the review highlighted three key limitations requiring further investigation. First, the considerable diversity of VR systems across studies, with minimal standardisation, makes it difficult to determine which specific features contribute most to therapeutic outcomes. Second, while VR shows potential for improving physical function, there is limited research on whether movements executed within VR environments accurately replicate the biomechanical patterns and quality required for effective rehabilitation, particularly regarding joint loading, muscle activation patterns, and movement compensations that may occur when patients interact with virtual interfaces. Third, there is limited investigation into user experience factors that may influence the successful implementation of home-based VR rehabilitation, particularly for populations with CKP.

These identified gaps directly inform the objectives of part 2 and part 3: first, to evaluate whether an in-house VR-based physiotherapy toolkit can accurately replicate therapeutic movements and provide appropriate challenges across different difficulty levels; and second, to explore the usability and acceptability of the in-house VR-based physiotherapy toolkit for participants with CKP.

To address these objectives, part 2 employs detailed kinematic analysis using motion capture technology and EMG measurements to assess five different VR scenarios: marching, high stepping, weight-shifting, step forward, and sit-to-stand. Part 3 collects participant feedback during VR engagement using the think-aloud approach and the SUS, addressing the umbrella review's findings on the importance of behavioural factors and engagement in rehabilitation outcomes, especially for individuals with CKP.

Together, these parts will provide critical insights into both the biomechanical challenges and user acceptance of the VR toolkit, directly addressing the evidence gaps identified in the umbrella review and guiding potential improvements for home-based applications in managing CKP. This chapter outlines the methodological approach used to conduct the biomechanical evaluation and usability testing, including participant recruitment, data collection procedures, and analysis methods.

4.2 Research Design and Methodological Framework

4.2.1 Quantitative Research Approach

In this thesis, the primary research methodology employed was the quantitative approach. According to Creswell (2009), the quantitative approach is a well-established method that is particularly effective in answering research questions with precision. This approach emphasises the collection and analysis of numerical data to identify patterns, relationships, and trends, ensuring that findings are grounded in measurable evidence (Creswell 2009).

A key feature of quantitative research is its commitment to objectivity. Sarantakos (2017) highlighted that objectivity is fundamental in this methodology, as it aims to represent social reality accurately and without the influence of researcher bias. Researchers adopting this approach must maintain neutrality throughout the research process, from interacting with participants to gathering data and conducting analysis. By doing so, the quantitative method ensures that the results remain credible, reliable, and valid, offering an unbiased insight into the phenomena under investigation.

4.2.2 MRC Framework Implementation

As previously mentioned in Chapter 1, this thesis was guided by the MRC framework for complex interventions, with the TAM serving as a complementary framework within the MRC's development phase (Davis 2014; Skivington et al. 2021). The MRC framework provided the main structure for developing and evaluating complex interventions through four key phases: development, feasibility, evaluation, and implementation. This chapter discusses the stakeholders' engagements in the development phase.

4.2.3 Integration of TAM

The TAM was integrated into this research to address specific elements of the development phase, particularly in understanding and evaluating user acceptance of

VR technology (Taherdoost 2018). Originally proposed by Fred Davis in 1987, the TAM examines two key factors influencing user behaviour: perceived usefulness (the degree to which a person believes that using the technology will enhance their performance) and perceived ease of use (the extent to which a person believes that using the technology will be easy) (Davis 1987). These factors shape users' attitudes towards and intention to use the system (Taherdoost 2018).

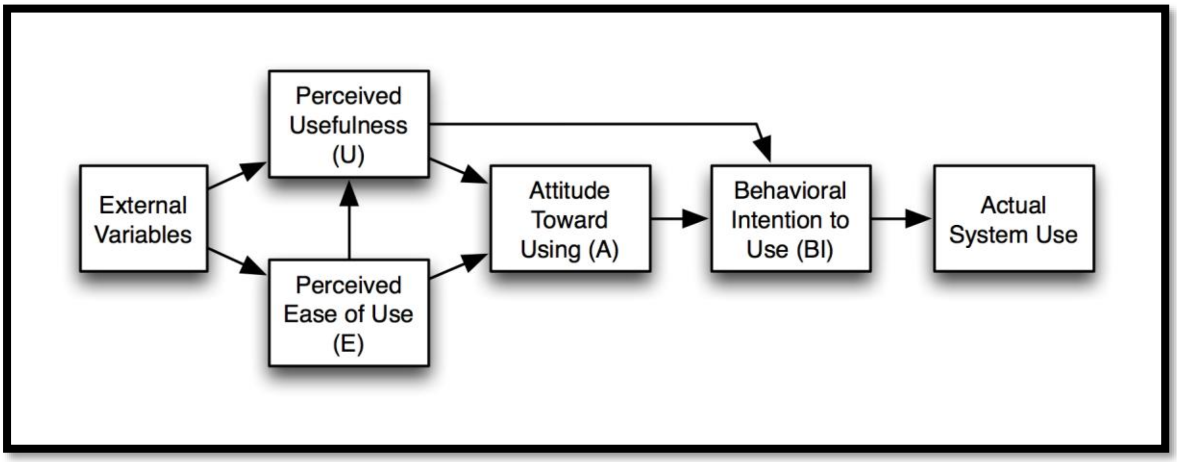


Figure 6 The Technology Acceptance Model, developed by Fred Davis (1987)

While several iterations of the TAM exist, including TAM 2, TAM 3, and the Unified Theory of Acceptance and Use of Technology (UTAUT: Venkatesh and Davis 2000), the original TAM was selected for this study due to its proven robustness and reliability across various contexts (King and He 2006). King and He's (2006) meta-analysis provides strong evidence for its selection as a theoretical foundation. The TAM's robustness is reflected in its consistent ability to explain a significant portion of the variance in user intentions and behaviour across diverse technologies and user groups. King and He's (2006) analysis of 88 published studies demonstrated that the TAM typically explained 30–40% of the variance in technology acceptance, notably high for behavioural research models. This statistical reliability gives researchers confidence that TAM measurements will yield consistent results across different contexts (King and He 2006).

Another reason for selecting the TAM was its cheapness. Unlike more complex models, the TAM achieves significant explanatory power with only a few key variables (Davis 1987). This simplicity makes it methodologically appealing, requiring fewer measurement items and smaller sample sizes while producing reliable results

(Davis 1987). King and He's (2006) analysis confirmed that even with its simplicity, the TAM offers comparable or superior predictive power to more complex models.

While the TAM offers a strong framework that focuses on perceived usefulness and ease of use, it overlooks several key aspects of acceptability that are more thoroughly explored in alternative models. One such model is the Theoretical Framework of Acceptability (TFA) developed by Sekhon et al. (2017). The TFA encompasses additional dimensions, including: affective attitude (how users feel about the intervention), burden (perceived effort required), ethicality (alignment with users' value systems), intervention coherence (users' understanding of how the intervention works), opportunity costs (what must be given up to engage), perceived effectiveness (whether it achieves its purpose), and self-efficacy (users' confidence in performing intervention behaviours).

Similarly, the UTAUT expands upon the TAM by introducing concepts such as social influence, facilitating conditions, performance expectancy, and effort expectancy. This model also considers moderating factors like age, gender, experience, and the voluntariness of use (Venkatesh et al. 2003).

The concept of acceptability is complex and includes not only whether users can and will use a technology, but also whether they should use it, want to use it, and find it compatible with their values and the context in which they operate. The TAM mainly focuses on the "can and will" aspects through its constructs of usefulness and ease of use.

In this exploratory study of a VR healthcare toolkit that is still in early development, the focused approach of the TAM was strategically appropriate for several reasons. First, at this stage of development, establishing basic usability and perceived value is essential before exploring more aspects of acceptability. Second, the scope of the study requires prioritising the key factors that are most likely to influence initial adoption decisions.

It is important to recognise that the study’s analysis framework, which focused specifically on the TAM constructs, may not encompass all dimensions of acceptability found in alternative models. The think-aloud data was primarily analysed through the lenses of perceived usefulness and ease of use. This focus potentially limited our ability to identify and measure other significant constructs, such as affective attitude, ethical considerations, or social influence, which are explicitly addressed in models like the Technology Fit Assessment (TFA) and the UTAUT.

This focused approach was intentionally chosen for several reasons aligned with the research objectives. First, during this early stage of evaluating the VR toolkit, it is vital to establish fundamental utility and usability, which are core constructs of the TAM. This foundational knowledge is essential before exploring more aspects of acceptability. Understanding whether users perceive the toolkit as potentially effective and manageable is a crucial first step in the development process. As development moves toward implementation, future research phases should expand beyond the TAM to include additional elements from more comprehensive frameworks of acceptability. This staged approach to understanding acceptability fits well with iterative design principles, where each phase of development tackles progressively more complex aspects of the user experience.

The TAM's simplicity and emphasis on essential elements (perceived usefulness and ease of use) greatly support the exploratory focus of this research, especially in evaluating healthcare technology (Holden and Karsh 2010). These core constructs are strong indicators of actual technology adoption, making them appropriate for assessing early-stage developments (Turner et al. 2010). Furthermore, while other acceptability models, such as the Theoretical Framework of Acceptability and the UTAUT, offer broader constructs, the TAM's specific focus on technology interaction makes it particularly suitable for evaluating a new virtual reality-based toolkit during its development stage (Sekhon et al. 2017).

4.3 Patient and Public Involvement

Patient and Public Involvement (PPI) represents a fundamental shift in healthcare research methodology, moving from conducting research 'on' or 'about' people to conducting research 'with' or 'by' them (Stallard and Rees 2014; Brett et al. 2017). This approach acknowledges that those with lived experience of health conditions provide valuable insights that complement professional and academic expertise. In the development of healthcare technology, PPI has become increasingly vital, as it helps to ensure that innovations address real user needs and preferences rather than just technical possibilities (Price et al. 2022).

The evaluation of the VR-based physiotherapy toolkit in this study was strengthened through meaningful engagement with key stakeholders, including members of the public and subject matter experts. This collaborative approach ensured that the final toolkit design met user needs and professional standards. The integration of PPI aligns with the MRC's emphasis on stakeholder engagement in toolkit development (Skivington et al. 2021). It reflects the growing evidence that public involvement improves research quality, relevance, and implementation (Brett et al. 2014).

The value of PPI in this research context is especially significant due to the interactive nature of VR-based toolkit (Ocloo et al. 2021). While technical experts can ensure system functionality and physiotherapists can verify therapeutic appropriateness, only potential end-users can provide real feedback on their lived experiences using the system. This three-way collaboration among public users, healthcare professionals, and technical experts creates a comprehensive development approach that addresses practical usability, clinical effectiveness, and technical feasibility (Greenhalgh et al. 2019).

Moreover, early engagement with patients and the public helps to identify and tackle potential barriers to adopting the toolkit before full-scale implementation, which could save resources and enhance the chances of successful execution (Wilson et al. 2015). This method is significant in developing digital health toolkit, where user acceptance and ability to engage with the technology are vital determinants of success (Ocloo et al. 2021).

4.3.1 Patient and Public Involvement Recruitment Strategy

The PPI members were recruited from the university's academic community. This approach was chosen for several reasons. First, academic institutions represent diverse communities that include individuals of various ages, backgrounds, and experiences with CKP, providing access to potential end-users of the VR toolkit. Secondly, recruiting through the academic community enabled the efficient identification of participants with different levels of technology familiarity, which was crucial for developing a toolkit that would be accessible to users with varying technical abilities. Additionally, the university setting facilitated access to subject-matter experts whose specialised knowledge was essential for refining the toolkit.

The recruitment process focused on identifying individuals who could provide informed feedback based on their personal experiences with knee pain or professional expertise. Although this convenience sampling method within the academic community may have limitations regarding population representation, it provided valuable initial insights for the toolkit's developmental phase. The academic setting also ensured that PPI members had a basic understanding of research processes, enabling them to provide structured feedback within the development framework.

4.3.2 Patient and Public Involvement Participants' Characteristics

Six people participated in reviewing the toolkit, all of whom were experiencing CKP, but they came from different backgrounds. The group included a physiotherapist, a healthcare management professional, a technologist, a health practitioner, and a member of the public. This combination created a balanced group that offered diverse yet complementary perspectives during the toolkit refinement process. Their shared experience with CKP, along with their varied professional and personal backgrounds, enabled them to provide unique insights that improved the toolkit.

4.3.3 Impact on Toolkit Development

The PPI participants reviewed and refined the VR scenarios, focusing specifically on the user interface elements and exercise instructions. Their feedback highlighted two critical aspects of the toolkit: First, the clarity of exercise instructions was assessed to ensure that users could easily understand and follow the required therapeutic movements. The physiotherapists' expertise was particularly valuable in ensuring that the instructions aligned with clinical best practices while remaining accessible to users. Secondly, the visual design elements were assessed, specifically the text size and colour choices within the virtual environment. This technical review ensured that on-screen information would be visible and readable during exercise execution.

Based on the collective feedback from the PPI participants, various improvements were implemented to enhance the toolkit's usability and effectiveness. These enhancements concentrated on optimising the visual presentation of information and ensuring clear communication of exercise instructions, resulting in a more user-friendly and therapeutically sound toolkit.

4.4 VR Toolkit

The umbrella review conducted by the author identified a critical need for VR-based home interventions in knee physiotherapy. Consequently, the author engaged with an established research programme, led by the lead supervisor, which is focused on developing a portable VR-based physiotherapy system. This system is designed to facilitate the transfer of rehabilitation from laboratory and clinical environments to patients' homes, incorporating both tailored interventions and biomechanical considerations. The author's involvement began during the initial testing phases as a PPI representative, providing user-centred feedback regarding the system's relevance and accessibility to patients. This contribution emphasises the extent to which the VR toolkit addresses the unmet needs identified in the umbrella review. Subsequently, the author conducted a formal evaluation of the system as part of their doctoral research, assessing its usability and suitability for clinical physiotherapy.

4.4.1 Overview of the VR-Based Physiotherapy Toolkit

The VR-based physiotherapy toolkit included an Alienware laptop (Dell) equipped with in-house developed VR software, an Azure Kinect DK sensor (Bennell et al. 2008b), and a large monitor connected via HDMI to display the game's scenarios in higher resolution for knee therapeutic exercises (Figure 7). Alienware laptops are known for their high-performance specifications, featuring powerful processors (Intel Core i9 or AMD Ryzen) and high-end graphics cards (NVIDIA GeForce models), making them ideal for resource-intensive applications like VR (Dell Technologies 2024). The Azure Kinect DK sensor integrated with the system through the Nuitrack plugin (3DiVi Inc).

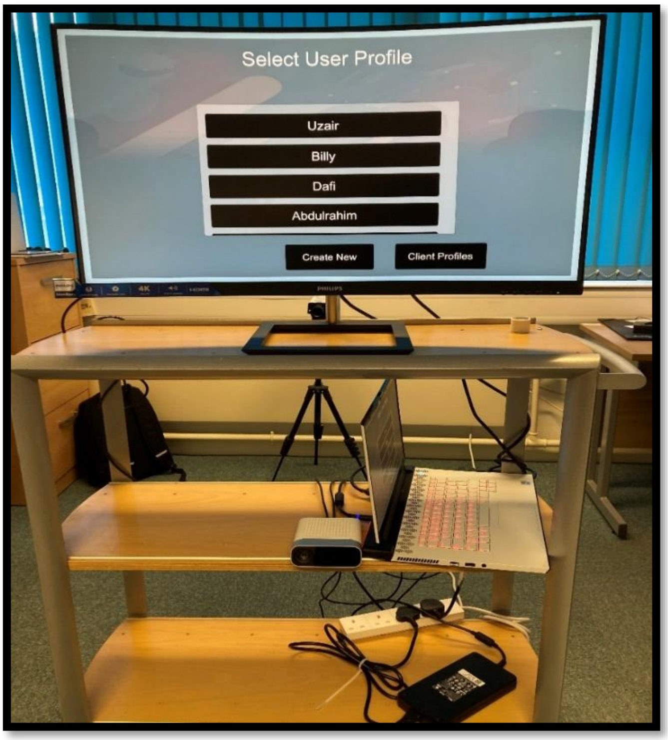


Figure 7: In-House VR Toolkit

The specific exercises included in the VR system were chosen based on findings from both the umbrella review and the literature review. These exercises target the primary issues that patients with CKP encounter. Balance deficits are common among these patients, who often exhibit impaired joint position sense and reduced dynamic stability (Ageberg and Roos 2015). Neuromuscular training has been shown to improve single-leg balance control by an average of 1.8 cm (Knoop et al. 2013).

Functional mobility is also compromised, as patients adopt altered movement patterns to avoid pain (Heiden et al. 2009). This leads to significant reductions in knee range of motion during daily activities (Verlaan et al. 2018). Moreover, the decline in cardiovascular fitness is associated with faster disease progression, while maintaining aerobic fitness can slow deterioration and decrease the need for surgery (Quicke et al. 2015).

The VR toolkit comprised five tailored VR scenarios that were designed in accordance with the needs of people with CKP, as recommended by NICE (2020). Clinical trials and systematic reviews showed that therapeutic exercises help to maintain or improve physical functioning and reduce and manage symptoms over the long term (Pedersen and Saltin 2015; Sherrington et al. 2019; Holden et al.

2023). They recommended that the exercises be tailored to the individual's needs, such as joint-specific-site exercises, which might increase exercise adherence and form regular exercise habits. Moreover, the systematic review by Holden et al. (2023) concluded that therapeutic exercise resulted in statistically significant improvements in pain and physical function in the short, medium, and long term compared to non-exercise controls.

Building on this foundation, specific exercises were selected based on their established physiological benefits. General aerobic fitness exercises, such as marching and high stepping, were chosen for the VR scenarios, as they enhance cardiovascular endurance through continuous movement. Pedersen and Saltin (2015) established in their comprehensive review that regular aerobic exercise improved cardiorespiratory fitness across 26 different chronic conditions, demonstrating significant enhancements in exercise capacity and reduced fatigue. Sherrington et al. (2019) further confirmed in their Cochrane review that these exercise programmes reduced fall rates among community-dwelling older adults.

Based on findings from Pua et al. (2017), weight-shifting exercises were included. These exercises showed that postural balance ability, particularly in mediolateral weight-shifting, was significantly linked to fall risk and could be enhanced through targeted training interventions.

Step-forward exercises were incorporated following evidence from a systematic review and meta-analysis by Okubo et al. (2017), which concluded that step training significantly improved reaction time, gait parameters, and balance while reducing falls among older adults. Their analysis of high-quality RCTs found a 50% reduction in fall incidence following step training interventions.

Sit-to-stand exercises were chosen due to their established significance in functional mobility. Bohannon (2019) noted that enhancements in the ability to rise from sitting are clinically significant predictors of increased functional capacity, while Pickford et al. (2019) confirmed that sit-to-stand training yields measurable improvements in lower limb strength and functional performance among diverse populations with mobility limitations.

The integration of these exercises into a VR environment is supported by Skjæret et al. (2016), whose integrative review of exergaming technologies showed that VR-delivered exercise can safely and effectively enhance physical function in older adults, particularly benefiting adherence and engagement. Similarly, Molina et al. (2014) reported in their systematic review that VR-based exercise programmes yielded significant improvements in physical functioning parameters, including balance and functional mobility. Figure 8 displays the main screen of the virtual reality scenarios from the toolkit.

Figure 8 VR Scenarios

4.4.2 Therapeutic Exercise Scenarios

4.4.2.1 Marching/Stepping in Place

Marching is a low-impact therapeutic exercise designed to enhance dynamic balance and can be adjusted to increase difficulty (Garber et al. 2011). For individuals experiencing CKP, this exercise offers several key therapeutic benefits: First, it strengthens the muscles of the lower limbs, particularly the quadriceps and hamstrings, which are crucial for maintaining knee joint stability and ensuring proper force distribution across articular surfaces (Bennell et al. 2013). Second, it enhances the knee joint's ROM and mobility by allowing for flexion and extension of the knee with each step in a controlled, low-load environment that facilitates movement without exacerbating pain (Sherrington and Tiedemann 2015). Third, it aids in retraining proper walking mechanics by promoting symmetrical weight-bearing and the timing of muscle activation, which is often disrupted in individuals with CKP, leading to compensatory movements and additional joint stress (Hurley et al. 2018).

Moreover, the controlled rhythm of marching helps to recondition the neuromuscular system, allowing for even force distribution through the lower body and reducing excessive stress on the knees. This process also promotes proprioceptive awareness, which is often diminished in chronic pain conditions (Vincent et al. 2012). The game features fifteen levels, beginning with a 6-minute stepping-in-place test as the assessment level and progressing to 2 minutes of stepping in place for the subsequent fourteen levels. A tutorial video was available for viewing before gameplay, providing instructions on how to play the game (Figure 9).

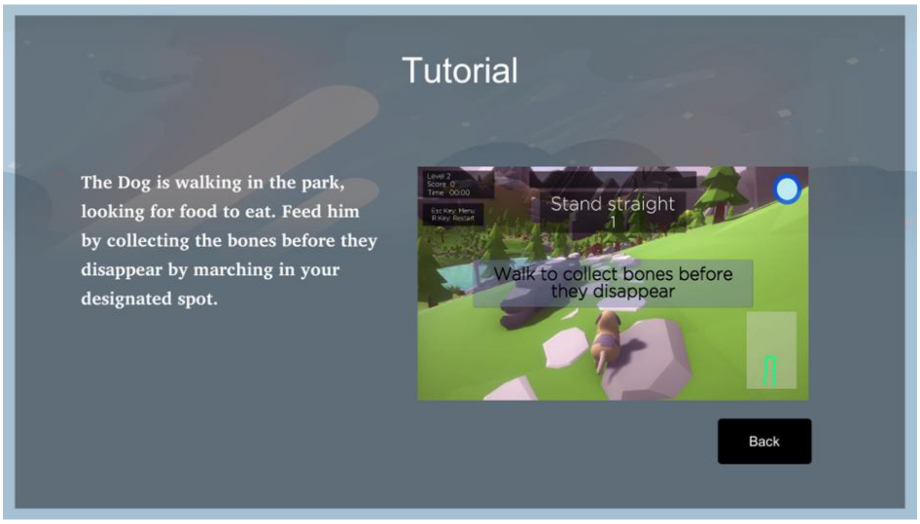


Figure 9 Marching Scenario

4.4.2.2 High Stepping

High stepping is a dynamic balance movement that involves raising the knees high while standing in place and maintaining controlled balance (Hatfield et al. 2016). It targets the hip flexor muscles, quadriceps, and core muscles, requiring both coordination and strength in the lower extremities. For individuals with CKP, high stepping offers significant benefits through multiple mechanisms: First, it strengthens the quadriceps muscles without creating high compressive forces across the patellofemoral joint, as the exercise focuses on concentric hip flexion rather than loaded knee extension (Pirayeh et al. 2022). Second, it enhances neuromuscular control and proprioception around the knee joint, which are often impaired in CKP conditions, aiding in the restoration of more optimal movement patterns (Bennell et al. 2013).

Third, the controlled, non-impact nature of high stepping enhances cardiovascular fitness while minimising joint stress compared to activities like running or jumping (Jorge et al. 2015). Additionally, by improving hip muscle strength and activation, high stepping aids in correcting biomechanical abnormalities that often contribute to CKP, such as decreased hip abductor strength and poor frontal plane control (Pirayeh et al. 2022). The game begins with a 2-minute assessment level and progresses through fourteen levels, each lasting 2 minutes. A tutorial video is available to watch before playing the game, providing instructions on how to play (Figure 10).

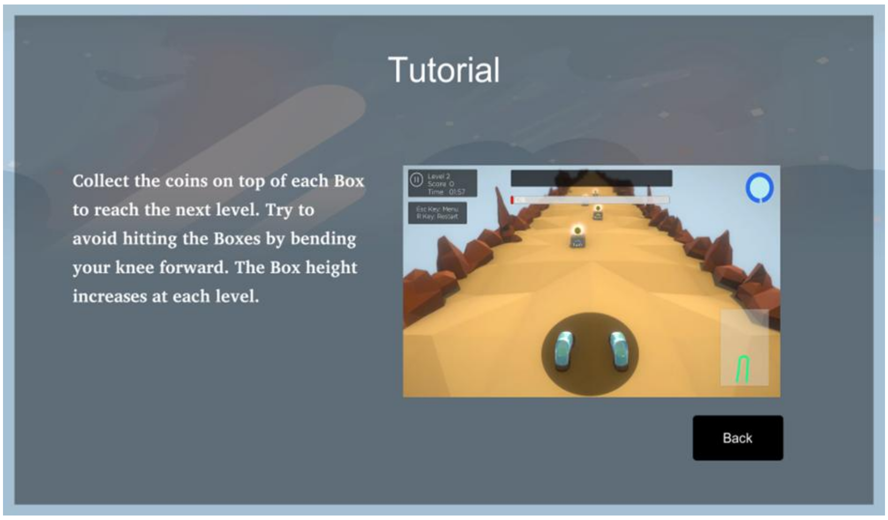


Figure 10 High Stepping Scenario

4.6.2.3 Weight Shifting

Weight shifting is a dynamic balance exercise that involves moving the trunk in all directions while remaining in the same spot (An et al. 2020). For individuals with CKP, weight-shifting exercises offer several therapeutic benefits: First, they redistribute joint loading patterns across the knee's articular surfaces, helping to decrease focal stress on damaged cartilage regions that typically endure excessive forces during static standing (Bennell et al. 2016). Second, they activate and strengthen the hip abductor and adductor muscles, which are often weak in people with knee pain, leading to improved frontal plane control during walking and other functional activities (Pua et al. 2017).

Third, shifting weight improves proprioceptive sensitivity and postural control strategies that often suffer in chronic knee issues, leading to better joint position awareness and increased balance confidence (Knoop et al. 2014). Moreover, controlled weight-shifting aids in retraining the neuromuscular system to more effectively anticipate and react to disturbances in daily activities, minimising the chance of aggravating movement-related pain (Hurley et al. 2018). The game consists of fifteen levels, beginning with an easy level and advancing to more challenging levels (Figure 11).

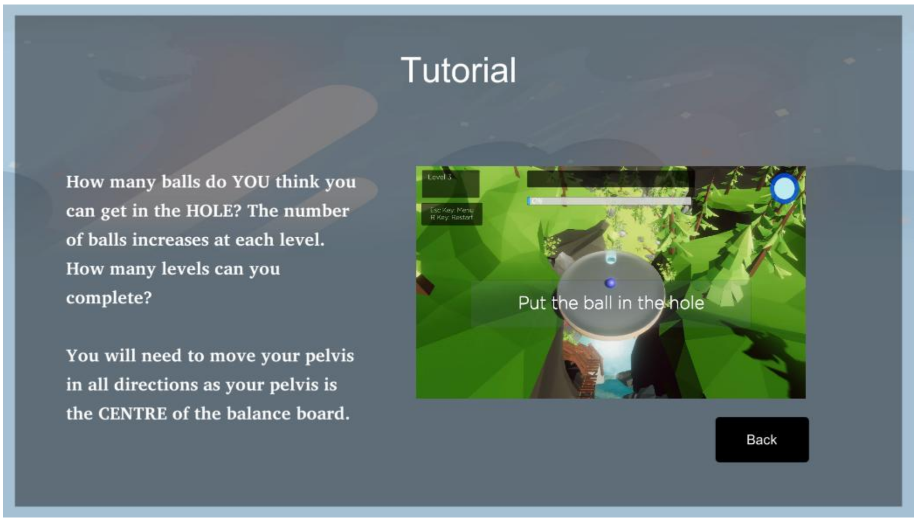


Figure 11 Weight-Shifting Scenario.

4.6.2.4 Step Forward

The step forward exergame is designed around the forward lunge: a functional lower-body exercise that effectively improves leg strength, stability, and overall lower-body performance. This exercise engages multiple muscle groups at once, including the quadriceps, hamstrings, Gluteus Maximus, and Gastrocnemius (Krause et al. 2018). Research has shown that forward lunges apply controlled stress to the knee, hip, and ankle joints, promoting joint stability and proprioception (Escamilla et al. 2009).

Clinical evidence supports the inclusion of lunge-based exercises in rehabilitation protocols. A comprehensive systematic review and meta-analysis by Goh et al. (2019) analysed the efficacy of exercise therapy for knee OA, concluding that structured exercise programmes significantly reduced pain scores and improved functional outcomes in patients with mild to moderate knee OA. These benefits were observed across various types of exercise that included functional movements like lunges.

In the step forward game, participants stand with their feet shoulder-width apart and take alternating steps forward with their right or left leg as directed by the game. The virtual environment represents the participant's legs as two birds on a nest, where players collect food that appears on tree branches by performing a forward lunge motion. Longitudinal studies have demonstrated that regular lunge training enhances performance in daily activities requiring single-leg stability and force production, such as stair climbing and rising from seated positions (Myer et al. 2014).

The game starts with an assessment level that evaluates the participant's current movement capabilities (Figure 12). This personalised assessment then establishes the parameters for the subsequent fourteen progressive levels, ensuring an appropriate challenge based on individual abilities. This tailored approach aligns with established exercise science principles of progressive overload and specificity (Paillard 2017), optimising both therapeutic effectiveness and participant safety through customised progression.

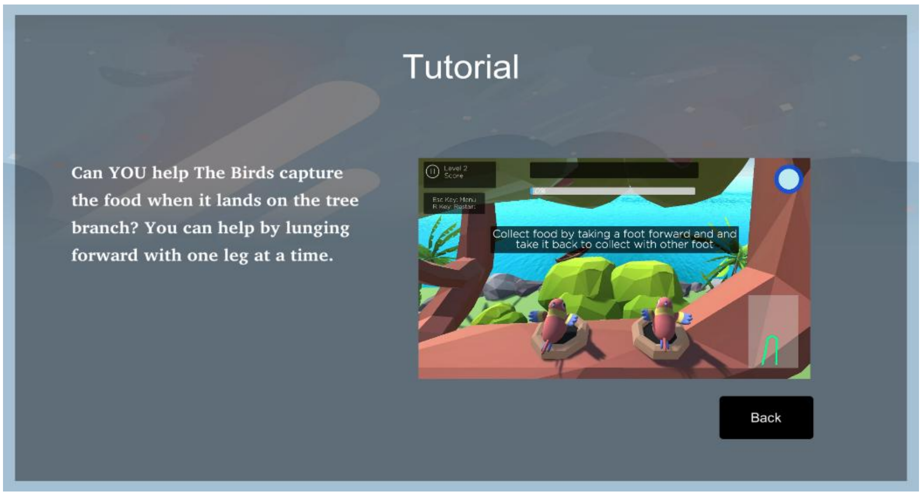


Figure 12 Step Forward Scenario.

4.4.2.5 Sit-to-Stand

The sit-to-stand movement is a fundamental functional task that is frequently performed in daily life. Biomechanically, it is defined as the transfer of the body's COM from a sitting position to a standing position while maintaining balance (Martinez-Hernandez and Dehghani-Sanij 2019). This movement has been extensively validated as a reliable assessment tool for lower extremity muscle strength and functional mobility across diverse populations (Staartjes and Schröder 2018; McAllister and Palombaro 2020).

Research has demonstrated that the sit-to-stand movement requires the coordinated activation of multiple muscle groups, particularly the quadriceps, hamstrings, and gluteal muscles, which makes it an excellent composite measure of lower limb strength and power (Jones et al. 2021). In this exergame implementation, players start with an assessment level that measures their performance on the 30-second sit-to-stand test. The game quantifies the player's movement speed and repetition count, then algorithmically adjusts the difficulty parameters across fourteen progressive levels based on this initial assessment (Figure 13). This strategy ensures a personalised challenge and follows established principles of exercise progression and adaptation (Fragala et al. 2019), maximising both engagement and therapeutic benefits throughout the toolkit levels.

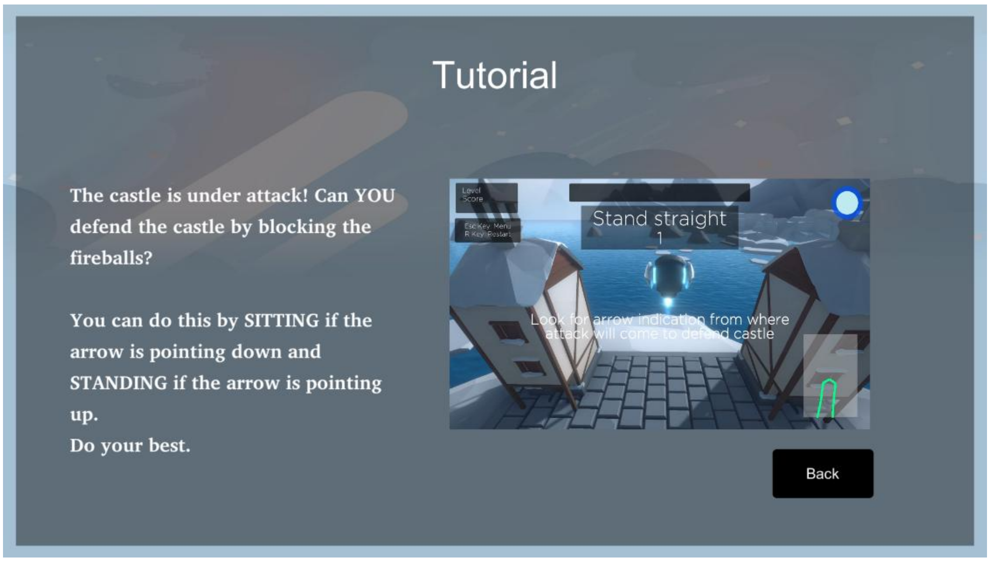


Figure 13 Sit-to-Stand Scenario.

4.4.3 Technical Equipment

4.4.3.1 Depth Camera

A new device released by Microsoft called Kinect for Azure (Microsoft Corporation, Redmond, WA, USA) has enabled developers to gather depth data from human body joints (Figure 14) (Microsoft.com 2022). It integrates multiple hardware components, including a 4K RGB video camera and an infrared depth sensor that measures the distance between the device and physical points. It supports both wide and narrow fields of view and connects to a laptop via a dedicated USB-C port. For this project, the Kinect was positioned at a height approximately 1.2 metres from the floor and at a distance of two metres from the monitor. This standardised positioning was critical, as the Kinect V2's skeletal tracking capabilities become less reliable beyond two metres, potentially affecting tracking accuracy and data quality (Wang et al. 2015).

The camera setup was maintained consistently across all participants to ensure a uniform field of view (FOV), depth accuracy, and skeletal tracking reliability. The Kinect V2 features a 1920 x 1080-pixel RGB camera and a 512 x 424-pixel depth sensor operating at 30 frames per second, with an infrared (IR) emitter for depth sensing (Wasenmüller and Stricker 2017). At the start of each VR scenario, a black screen displayed written instructions for the calibration: “Begin by standing two metres away from the camera and holding the N pose for 3 seconds. Then, take one step forward with both legs and hold that position for three seconds. Finally, take one step back and maintain that position for 3 seconds.”

Figure 14 Microsoft Kinect Camera

4.4.3.2 Motion Analysis Capture (MVN)

This study employed 3D kinematic analysis to quantify joint angles and movement patterns during the VR exercise levels. For accurate motion capture, the MVN Awinda system (BIOMECH Awinda; Xsens Technologies, Enschede, The Netherlands) which is a validated IMU based system that enables wireless, full-body motion tracking, was used. This technology has been validated in several studies for its accuracy in capturing human movement, with high reliability demonstrated for joint angle measurements across various movement tasks (Robert-Lachaine et al. 2017; Karatsidis et al. 2019). The kinematic data were collected at a frequency frame rate of 60 Hz, using the Xsens MVN Analyse software package. The MVN Awinda system comprises the following (see Figure 15):

- 1 Awinda station.
- 17 wireless IMU motion trackers (MTw).

- MTw full-body Velcro straps, including three shirts, a headband, footpads, and two pairs of gloves.

Figure 15 Suitcase containing the MVN Awinda System

The participants' measurements of body segment lengths were taken to create the biomechanical models according to the Xsens manual guidelines (Xsens Technologies B.V. 2021): see Table 5. These measurements were taken using the Xsens measuring tape (Xsens Technologies, Enschede, The Netherlands) and then entered into the MVN software. This data was necessary for creating a body configuration model in the MVN software to allow quantification of the body segment (Roetenberg et al. 2009). Measurements included shoulder width, shoulder height, arm span, elbow span, wrist span, hip width, hip height, knee height, ankle height and foot length.

Table 5 Measurements needed for subject Dimension Input

Dimensions	Description
Foot size	Top of shoe nose to end of the heel
Shoulder width	Right to left distal tip of acromion (acromial angle)
Arm span	Top of right fingers to top of left fingers in T-pose
Elbow span	From the right elbow olecranon to the left one
Hip height	Ground to most lateral bony prominence of greater trochanter
Knee height	Ground to lateral epicondyle on the femoral bone
Hip width	Right to left anterior sup. iliac spine
Ankle height	Ground to distal tip of lateral malleolus
Body height	Ground to top of head when standing upright

Then, seventeen wireless Xsens MTw2 IMU sensors (MVN BIOMECH Awinda; Xsens Technologies, Enschede, The Netherlands) were placed on the participant's body by adhering to the Xsens guidelines (Xsens Technologies B.V. 2021). Each participant was asked to wear a zip-fastening T-shirt over their own T-shirt and a headband and gloves to ensure reliable and easy placement of the head, shoulder, and hand sensors. Elasticated Velcro straps were used to secure the sensor in position and reduce movement. The sensors were positioned between the two external layers of the strap, adhered to the Velcro in the internal layer, and distributed as follows:

- One on the head.
- Two on both scapulas (shoulder blades).
- One on the chest (sternum).
- Two on both upper arms (on the lateral side above the elbow).
- Two on both forearms (lateral and flat on the wrist).
- Two on both hands (flat on the backside of the hands).
- One flat on the sacrum (the upper boundary of the sensor in line and centred with the right and left posterior superior iliac spine) (A 3M Tegaderm Transparent Film Roll dressing was used to keep the sacral sensor in position).
- Two on both upper legs (in the centre between the greater trochanter and lateral epicondyle).
- Two on both lower legs (flat on the shin bone proximally and medially to the surface of the tibia); and
- Two in the middle and over the bridge of both feet, as in Figure 16.

Figure 16 MVN Straps, according to Xsens Technologies B.V. (2021)

Following manufacturer guidelines, a dynamic calibration process was implemented. Calibration is essential for initialising the orientation of the Motion Trackers and ensuring magnetic immunity (Xsens Technologies B.V. 2021). Effective calibration can significantly enhance the quality of Motion Capture data. First, participants maintained a neutral standing position (N-pose) for 20 seconds as in Figure 17, with their body upright, head forward, feet parallel, and arms at their sides (Xsens Technologies B.V. 2021). Next, participants walked at their natural speed along a system-specified path, including a turn-around, before returning to the N-pose. The system then automatically evaluated calibration quality (ranging from “Good” to “Fail”) and processed the results (Xsens Technologies B.V. 2021).

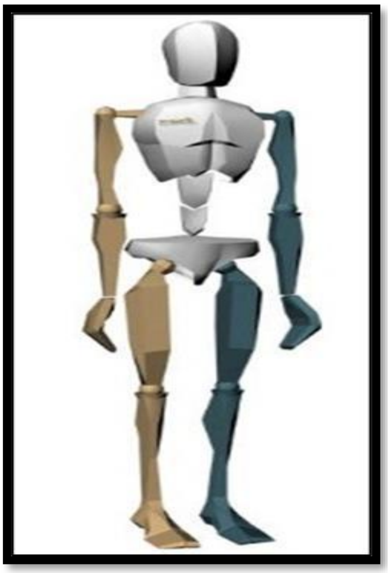


Figure 17 Statice N-pose, Xsens Technologies B.V. (2021)

4.4.3.3 The Trigno Research System

This study employed electromyography (EMG) to measure muscle activation patterns during the VR exercises. For precise data collection, the Trigno Research System (Delsys Inc., Natick, MA, USA) was utilised, which provided synchronised, wireless EMG recordings with high signal fidelity (Figure 15). This system has been validated in multiple studies for its reliability in capturing muscle activation during dynamic movements (Merletti and Muceli 2019). The wireless sensors enabled participants to move naturally without restriction while still delivering EMG data. The EMG sensors were placed according to the recommendations of the Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) project. This technology was crucial for accurately quantifying the neuromuscular demands of the exercises and confirming the targeted muscle engagement during the VR protocols.

Figure 18 The Trigno Research System

4.4.3.4 Force Platform

In this study, a BTS PODIUM force platform system was used to measure the COP and COM trajectories during the experimental tasks (BTS Bioengineering Corp., Milan, Italy). The COP represents the point of application of the ground reaction force vector and offers valuable insights into postural control strategies. The COM, calculated from the force platform data, represents the point at which the entire body mass can be concentrated. The platform's high sampling frequency (960 Hz) and precision allowed accurate tracking of these parameters throughout the movement trials.

4.4.3.5 The Polar T31

The Polar T31 is a chest-strap heart rate monitor that uses ECG (electrocardiogram)-based technology for heart rate detection (Figure 19). The participants' heart rates were continuously monitored using a Polar T31 chest-band heart rate transmitter and accompanying wrist receiver (Polar Electro Oy, Kempele, Finland). The chest strap was positioned horizontally just below the pectoral muscles, with the transmitter unit centred on the sternum. The electrode areas were moistened with water to ensure optimal conductivity and signal quality. The accompanying wrist receiver was worn on the participant's preferred wrist and positioned within one metre of the chest transmitter to maintain consistent signal reception. This system operates at a transmission frequency of 5 kHz and provides ECG-accurate heart rate measurements with a sampling rate of 1,000 Hz (Terbizan et al. 2002).

Figure 19: Polar T31

4.5 Study Design and Methods

4.5.1 Sampling Method

In this study, a non-probability purposive sampling technique was used to select participants who could provide valuable insights into the effectiveness of VR games for managing CKP. Unlike random sampling, this approach allowed intentional selection of individuals experiencing CKP who would benefit from and engage with the VR games in the laboratory setting (Vehovar et al. 2016). This method was particularly suitable for this study, as individuals with CKP represent a specific population with unique rehabilitation needs that our VR toolkit could address. Purposive sampling's main goal is to improve the accuracy and reliability of the research findings by focusing on the most relevant participants (Vehovar et al. 2016). This helps researchers to make better conclusions about the population they are studying and leads to more effective solutions or interventions based on their results.

4.5.2 Sample Size

The sample size was determined using G Power software (version 3) and based on an estimated effect size of 0.5 from a pilot study conducted by our research team. This value is considered medium and was chosen to represent the expected difference or association the study aimed to detect. Following standard statistical parameters in health research, the alpha level (α) was set at 0.05, and the power (1-β) was set at 0.8 (Noordzij et al. 2010). This calculation resulted in a required sample size of 28 participants. To account for potential dropouts, an additional 10% was added, bringing the final participant count to 30. This method aligns with recommended practices for sample size calculations in clinical studies (Faul et al. 2007).

The chosen power of 0.8 is a commonly accepted standard in health research, indicating an 80% probability of detecting an effect if one exists (Noordzij et al. 2010).

The medium effect size of 0.5 was selected because it reflects what would be considered clinically meaningful in rehabilitation interventions for knee OA (Bennell et al. 2016). The sample size is consistent with similar studies examining movement-based interventions for individuals with knee conditions (Dobson et al. 2016).

4.5.3 Recruitment

Participants were recruited using various approaches. Firstly, an advertising flyer with a brief description of the research project was distributed on the notice boards of the School of Healthcare Sciences, Cardiff University. For internal recruitment, information was shared electronically with staff and students at Cardiff University through the Yammer social network. For external community recruitment, the study information was posted in local community Facebook groups, including the Central Library Hub account. The administrators of these community groups were asked to share the research information, allowing potential participants from the wider community to contact the research team if they were interested in taking part.

4.5.4 Study Participants

Subjects with CKP from the university and the community were recruited to play the rehabilitation games in the laboratory.

Inclusion criteria:

1- Adults aged 18+ years.
2- Individuals complaining of knee pain for more than three months and on most days of the previous month (National Institute for Care and Health Excellence 2014).
3- Have activity-related knee joint pain (National Institute for Care and Health Excellence 2014)
4- Have either no morning knee joint-related stiffness or morning stiffness that lasts no longer than 30 minutes (National Institute for Care and Health Excellence 2014)
5- Able to give written informed consent.

Exclusion criteria

1- Inability to understand written or spoken English.
2- History of lower extremity, pelvis or back disorder that may impair the individual's performance of functional activities during the last 12 months.

3- Any neurological or cardiovascular pathology that would influence motion.
4- History of lower extremity surgery during the last 12 months.
5- Individuals who suffer from vertigo, as this vestibular disorder can cause dizziness, balance disturbances, and visual disorientation that could be aggravated by visual tracking elements in non-immersive VR games (Meldrum et al. 2015).

4.5.5 Study Setting

The study was conducted at Cardiff University in the UK, specifically in the School of Health Care Sciences (HCARE).

4.6 Data Collection Protocol

4.6.1 Venue Preparation

Before the participants arrived, thorough preparations were made in the lab to ensure their safety during the trial. All the equipment mentioned previously was set up in the designated section.

4.6.2 Data Collection Tools

A digital weighing scale (Model 862, SECA Ltd., Medical Scales, Birmingham, UK) was used to record participants' weight in kilograms (kg), while a stadiometer (Marsden HM-250P Leicester Portable Height Measure, UK) was employed to measure their height in centimetres (cm). A high-quality Wireless Lavalier Microphone featuring Lightning/USB-A adapters and plug-and-play functionality for video recording was used for clear audio capture during the sessions (Model CL-K3A-UK, Quanlex, UK). Additionally, an HP Envy x360 laptop (HP Inc., Palo Alto, California, USA) was utilised for data collection and MVN and Delsys systems setup.

4.7 Pilot Study

A pilot study was conducted with nine participants experiencing CKP to assess the data collection procedures and equipment setup protocols. The testing session followed a structured sequence: initially, anthropometric measurements were taken to calibrate the MVN motion capture system, followed by the placement of EMG electrodes in accordance with SENIAM guidelines. Subsequently, participants were fitted with the MVN sensors, and with the Polar T31 chest band and watch. System calibration was performed for both the MVN system and the force platform. Although each game in the VR-based physiotherapy system featured 15 difficulty levels, participants completed only the easy and hard levels due to time constraints.

Several technical challenges emerged during the pilot study, prompting revisions to the protocol. The first involved the Kinect camera's requirement for a two-metre distance between participants and the screen. This positioning conflicted with force plate boundaries, resulting in unreliable COP data. Therefore, COP was excluded, and COM was estimated from the MVN data.

The second challenge involved the Polar T31 watch, which presented several practical difficulties. Recording measurements before and after each scenario disrupted engagement and the watch's positioning interfered with the MVN wrist strap. Relocating the device on the forearm proved impractical for some participants, and the one-metre spacing requirement between the chest band and watch further complicated the setup. Based on these challenges, the Polar T31 was also removed from the protocol.

4.8 Refined Data Collection Procedure

Figure 20 shows the flowchart sequence of data collection. Participants were contacted by phone using the VR phone screening form to check their eligibility; they were also free to ask any questions regarding the study (see Appendix 3). In addition, an email with a participant information sheet was sent to the eligible participants who satisfied the stated inclusion criteria and agreed to participate in the study. Then, an appointment was made for them to attend the School of Healthcare Science, Cardiff, and they were asked to wear shorts and a t-shirt for the session.

Upon arrival, participants were asked to sign the consent form (Appendix 4) and complete the self-reported measures questionnaires: the WOMAC Osteoarthritis Index (Appendix 5), Health-related Quality of Life (EQ-5D-5L questionnaire) (Appendix 6), Self-Efficacy for Managing Chronic Diseases (Appendix 7), the PHQ-9 (Patient Health Questionnaire-9) (Appendix 8) and the Tampa Scale for Kinesiophobia (TSK) (Appendix 9) at the beginning of the session. After that, demographic details for each participant, such as their height, weight, gender, and age, were collected. Then, the study was verbally explained to the participants by introducing the systems used and what the session would include.

A high-quality microphone was attached to the participants to record their voices via Bluetooth. Then, the participants were instructed to verbalise their thoughts, emotions, and difficulties while completing tasks related to the VR toolkit games. Then, the EMG sensors were fixed on the following muscles on both lower limbs: the Rectus Femoris, Vastus Medialis, Medial Gastrocnemius, and Biceps Femoris. Then, the seventeen wireless Xsens MTw2 sensors were placed according to Xsens guidelines (Xsens Technologies B.V. 2021). To set up the Tringo system, the Base Station was connected to the computer using a USB cable. All sensors were fully charged before the session. Next, the Trigno Avanti Sensors were applied to the relevant muscles using the provided adhesive or Velcro straps after checking that the skin was clean, dry, and free from oils to get proper EMG signals.

The next step was starting the MVN Awinda software and integrating the EMG sensors into the MVN Awinda to record the muscle activity within the system. Then the MVN Awinda was calibrated by following the audio instructions from the software. Participant stood in front of the monitor to play the five VR scenarios: marching, high stepping, weight-shifting, step forward, and sit-to-stand. Each scenario had fifteen levels, starting with easy and assessment levels and progressing to hard levels. Only two trials from each scenario (one easy level and one hard level) were played because of the time constraints. At the end of the session, the participants were given the SUS and an open-ended questionnaire to answer, either in writing or by recording their answers using the audio recorder.

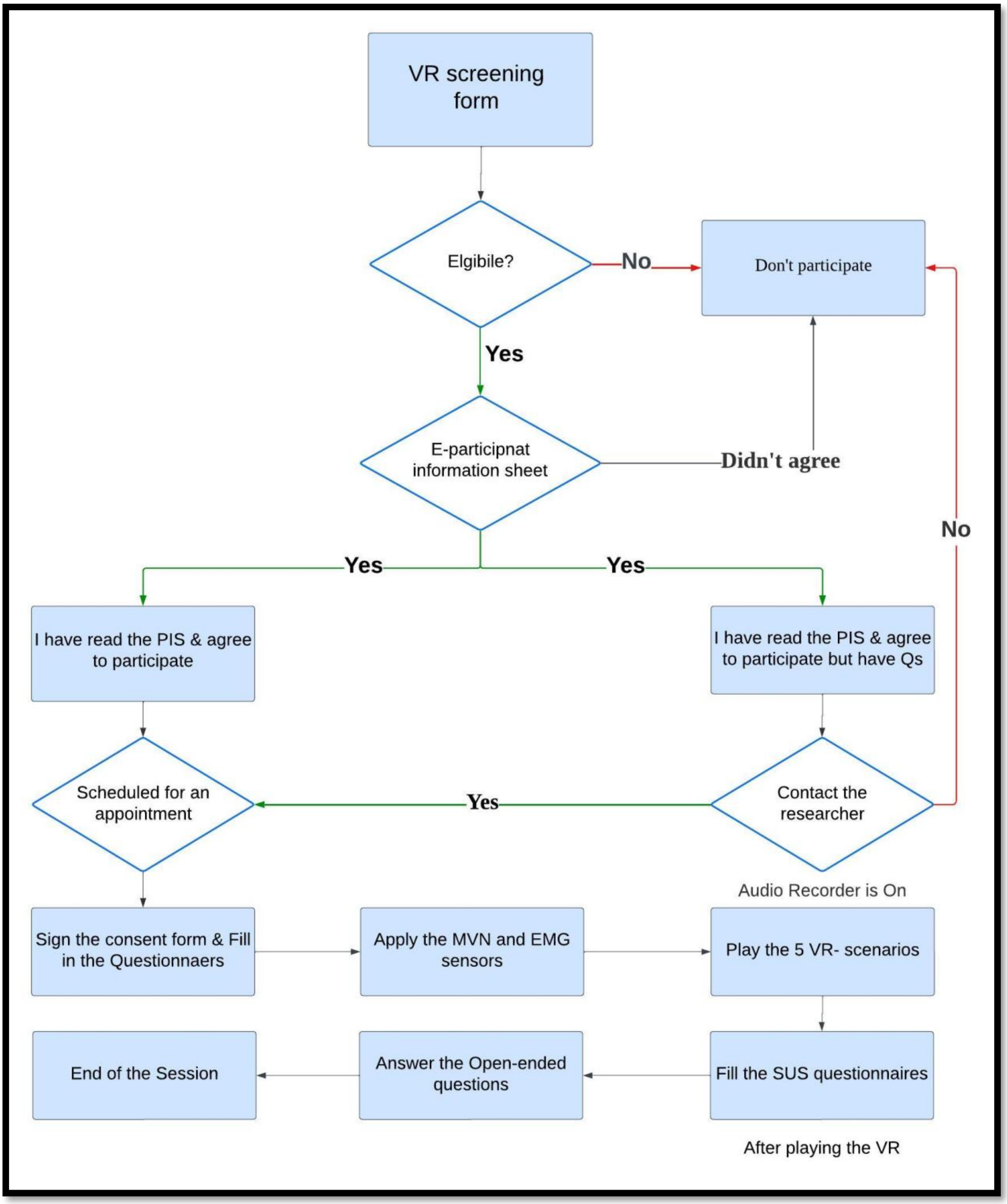


Figure 20 Flowchart Sequence of Data Collection.

4.9 Outcome Variables

This study assessed several kinematic variables, including joint ROM, muscle activity, and the trajectory of COM. These objective measures provide insight into movement patterns, muscle function during rehabilitation activities, improved movement control and reduced compensatory patterns in people with CKP (Knudson

2009). They also helped to identify compensation strategies and muscle recruitment patterns often observed in individuals with CKP.

In addition to kinematic measures, several validated self-reported assessments were collected at the beginning of the data collection. These included the impact of OA through the WOMAC Osteoarthritis Index (McConnell et al. 2001), followed by the EQ-5D-5L questionnaire to assess health-related quality of life (Herdman et al. 2011), and the Self-Efficacy for Managing Chronic Disease Scale to measure self-efficacy in managing chronic conditions (Lorig et al. 2001). In addition to these, the PHQ-9 questionnaire was used to assess depression (Kroenke et al. 2001), and the TSK to evaluate fear of movement (Miller et al. 1991). At the end of the session, the user experience with the VR games was assessed using the SUS (Brooke 1996), supplemented by open-ended questions to gather feedback on game usability and participant experience (Patton 2014).

Together, these outcome measures provide a comprehensive assessment of physical function and the psychosocial factors that influence rehabilitation outcomes in individuals with CKP. The following sections of the study will cover further details regarding these outcome measures.

4.9.1 Kinematic Variables

4.9.1.1 ROM Measurement

ROM is the degree of movement that a joint can make in different directions. It is a key factor in assessing joint health and function (Hyodo et al. 2017). The MVN Awinda uses sensors to track the movement of the joints and provide feedback on the performance. It can measure the lower limb's ROM in several specific directions, including flexion, extension, and limited internal and external rotation degrees.

The system can also provide feedback on the quality of the movements by analysing motion data to evaluate characteristics such as the smoothness of acceleration/deceleration patterns, consistency of movement speed, precision in reaching target positions, and overall movement efficiency compared to expected norms or previous measurements. After performing the functional movements (virtual games), the system captures the movement data and provides feedback on the performance to measure ROM and identify areas that need improvement. Table 6 will show the kinematic variables that were assessed from each scenario in the sagittal and frontal planes.

Table 6 Kinematic Variables

Scenario	**Kinematic variables**
Marching/stepping in place	Hip, knee, and ankle ROM
High stepping	Flexion/extension of the hip, knee, and ankle ROM (sagittal plane) Abduction and adduction ROM of the hip and knee, and ankle eversion and inversion ROM (frontal plane)
Weight-shifting	The total excursion of the COM
Step forward	<u>From the Sagittal Plane:</u> hip, knee, and ankle ROM angles. <u>From the Frontal Plane:</u> Abduction and adduction ROM of the hip and knee, and ankle eversion and inversion ROM.
Sit-to-stand	<u>From the Sagittal Plane:</u> Hip, knee and ankle flexion and extension ROM <u>From the Frontal Plane:</u> Abduction and adduction ROM of the hip and knee, and ankle eversion and inversion ROM.

4.9.1.2 Muscle activity measurement

Muscle activity was assessed during virtual gameplay using the Delsys EMG system. The focus was on four key muscles: Rectus Femoris, Vastus Medialis, Medial Gastrocnemius, and Biceps Femoris. The muscles selected for this study are essential for controlling knee joint movement and stability (Ghazwan et al. 2022). Specifically, the Rectus Femoris and Vastus Medialis are part of the quadriceps group, which primarily functions to extend the knee (Ghazwan et al. 2022). The Medial Gastrocnemius contributes to both plantar flexion and knee flexion, while the Biceps Femoris, which belongs to the hamstring group, is primarily responsible for knee flexion and assists with rotational stability (Ghazwan et al. 2022). The Delsys system recorded the electrical activity of these muscles through EMG signals during gameplay, measuring various variables such as signal amplitude (which indicates the intensity of muscle activation) and coordination patterns among muscle groups throughout different game activities.

4.9.2 Self-Reported Measures

4.9.2.1 The WOMAC Osteoarthritis Index

The WOMAC is a self-administered health status measure that assesses physical disability and symptoms experienced by individuals with knee OA (WOMAC - AUSCAN - Osteoarthritis Global Index). The WOMAC assessment tool, originally developed by Bellamy et al. (1988), measures three dimensions – pain, stiffness, and physical function – through a series of questions. There are five questions for pain, two for stiffness, and 17 for physical function (McConnell et al. 2001). The Likert version of the WOMAC uses a scale from 0 to 4, where lower scores indicate lower levels of symptoms or physical disability (McConnell et al. 2001). The three subscales are added up to maximum scores of 20, 8, and 68, respectively. Additionally, there is a global or index score (Table 7), which is typically obtained by summing up the scores for the three subscales, and the score ranges include 0–240 (derived from the VAS 0–10 or NRS scale), or 0–2400 (derived from the VAS 0–100) or 0-96 (derived from a 0–4 Likert scale) (McConnell et al. 2001).

In interpreting WOMAC scores, it is important to note that lower scores signify better outcomes, indicating less pain, reduced stiffness, and improved physical function, whereas higher scores reflect worse symptoms and greater functional limitations. There are no universally accepted cutoff scores to distinguish "good" from "bad," as interpretation is highly dependent on each individual's baseline and clinical context. Nonetheless, a 12% to 18% reduction from baseline is generally recognised as the minimal clinically important difference (MCID) when assessing treatment outcomes (Angst et al. 2001).

The WOMAC has undergone extensive validation and showcases strong psychometric properties, including high test-retest reliability (with ICC values typically exceeding 0.80), excellent internal consistency (Cronbach's alpha greater than 0.90), and construct validity when compared to other measures of pain and function. It has been specifically validated for populations with CKP, such as OA, making it a fitting and dependable tool for this demographic (Bellamy et al. 1988; McConnell et al. 2001; Thumboo et al. 2001).

Table 7 The Expected Range of Scores for the WOMAC

Form of WOMAC used	WOMAC pain score range	WOMAC index range
VAS 0–10	0–50	0–240
VAS 0–100	0–500	0–2400
NRS 0–10	0–50	0–240
Likert scale (0–4)	0–20	0–96

4.9.2.2 Health-Related Quality of Life (EQ-5D-5L questionnaire)

The EQ-5D-5L is a tool that has undergone extensive testing and has been used both in the general population and among patients. It describes and assesses an individual's health in a generic way (Herdman et al. 2011). It measures health in five dimensions, namely mobility, self-care, usual activities, pain or discomfort, and anxiety or depression. Each dimension has five response categories that indicate the level of problems experienced: no problems, slight problems, moderate problems, severe problems, complete inability/extreme problems. The participants are asked to indicate their health state by checking the box next to the most appropriate response level of each of the five dimensions (van Hout et al. 2012).

Responses are expressed as single-digit numbers for each dimension to describe the participant's health state. The digits for the five dimensions can be combined into a five-digit code that describes the participant's health state that often represent national or regional values, and in this study, the England value set was used (Devlin et al. 2018). A single summary number or index value is assigned to each health state, which helps in calculating quality-adjusted life years (QALYs) used in economic evaluations of healthcare interventions.

The EQ-5D-5L index values range from -0.594 to 1. A score of 1 indicates perfect health, 0 represents death, and negative values signify health states considered worse than death. In patients with CKP, scores generally fall between 0.3 and 0.7, with higher scores reflecting better health status. The minimal clinically important difference (MCID) for the EQ-5D-5L index has been estimated at 0.074 for patients with OA (Nolan et al. 2016).

The EQ-5D-5L has shown strong validity and reliability among patients with CKP. Its test–retest reliability is high, with Intraclass Correlation Coefficient (ICC) values typically exceeding 0.70. Additionally, it displays good construct validity when compared to condition-specific measures, such as the WOMAC (Conner-Spady et al. 2015). The instrument is also responsive to changes following interventions, making it an effective tool for evaluating treatment outcomes in this patient population.

Then, the participants completed the EuroQol Visual Analogue Scale, which provides a quantitative measure of the patient's perception of their overall health, rated on a scale from 0 to 100 using a vertical visual analogue scale where the endpoints are labelled "The best health you can imagine" and "The worst health you can imagine," summarised using the mean, standard deviation (SD), minimum, median and maximum scores (EuroQol Group 1990).

4.9.2.3 Self-Efficacy for Managing Chronic Diseases questionnaire

The Self-Efficacy for Managing Chronic Diseases is a questionnaire designed to measure how confident patients are in managing chronic diseases (Lorig et al. 2001). This scale consists of six items, each rated on a visual analogue scale, ranging from 1 (not at all confident) to 10 (totally confident). The scale has been evaluated in several studies and has proven to have good psychometric properties, including high reliability and validity (Ritter and Lorig 2014).

The scale demonstrates strong internal consistency, with Cronbach's alpha values ranging from 0.88 to 0.95 across various chronic disease populations, including those with arthritis and knee pain (Lorig et al. 2001). Additionally, it exhibits robust test-retest reliability, with correlation coefficients typically surpassing 0.80 over intervals of 2 to 3 weeks (Brady 2011). In terms of construct validity, the scale correlates well with other measures of self-management behaviours ($r = 0.43$ to 0.58) and with health outcomes such as pain intensity and functional limitations ($r =$ 0.38 to 0.54) in patients with chronic musculoskeletal conditions (Freund et al. 2013).

To analyse the questionnaire, the mean scores of the six items were calculated to obtain an overall measure of self-efficacy for managing chronic diseases. A mean score closes to 10 (the maximum) indicates high self-efficacy, a mean score between 6 and 9 suggests moderate self-efficacy and a mean score below 6 indicates low self-efficacy (Ritter and Lorig 2014). In patients with CKP, baseline mean scores typically range from 5.2 to 6.8. An increase of 1.0 to 1.5 points is generally regarded as a clinically meaningful improvement following an intervention (Marks 2012). Higher self-efficacy scores in this population have been linked to better adherence to exercise programmes, enhanced physical function, and reduced pain intensity (Nicholas et al. 2013).

4.9.2.4 The Patient Health Questionnaire-9 (PHQ-9)

The PHQ-9 is a nine-item instrument used to assess depression (Kroenke et al. 2001). It screens for the presence and severity of depressive symptoms, making it valuable in primary care settings (Costantini et al. 2021). The PHQ-9 incorporates DSM-IV depression diagnostic criteria and rates the frequency of symptoms to determine a severity index (Kroenke et al. 2001). It consists of nine items; each scored on a scale of 0 (not at all) to 3 (nearly every day), and the total score ranges from 0 to 27.

The PHQ-9 demonstrates strong internal consistency, with Cronbach's alpha values ranging from 0.86 to 0.89 across diverse populations, including those with chronic pain conditions (Kroenke et al. 2001). Additionally, it showcases impressive test-retest reliability, with correlation coefficients between 0.84 and 0.96 over intervals of 7 to 14 days (Löwe et al. 2004). The scale also possesses good criterion validity when compared to structured clinical interviews, achieving a sensitivity and specificity of 88% for diagnosing major depression at a cutoff score of ≥10 (Kroenke et al. 2001).

The PHQ-9 has been validated in CKP patients and reveals significant correlations with pain intensity ($r = 0.40$ to 0.52), functional disability ($r = 0.45$ to 0.57), and quality of life measures ($r = -0.48$ to -0.65) (Riddle et al. 2010). Depressive symptoms are common in this demographic, with approximately 20% of patients with knee OA exhibiting clinically significant depression, as indicated by a PHQ-9 score of ≥ 10 (Stubbs et al. 2016).

To analyse PHQ-9 data, the scores of all the items can be added up to obtain an overall depression severity score. This total score can then be categorised into severity levels: minimal (0–4), mild (5–9), moderate (10–14), moderately severe (15–19), and severe (20–27). A change of 5 points or more is typically considered clinically significant, with a minimum clinically important difference (MCID) estimated between 3-5 points in chronic pain populations (Löwe et al. 2004; Kroenke et al. 2010).

4.11.2.5 The TSK

The TSK was originally developed in 1991 by Miller, Kopri and Todd. A year earlier, the developers introduced the term "Kinesiophobia" at the Ninth Annual Scientific Meeting of the American Pain Society to describe circumstances in patients characterised by an "excessive, irrational, and debilitating fear of physical movement and activity resulting from a feeling of vulnerability to painful injury or reinjury" (Miller et al. 1991).

Initially used to differentiate between non-excessive fear and phobia in patients with chronic musculoskeletal pain, such as the fear of movement in older people with chronic low back pain, the TSK's application later expanded to encompass other conditions and body parts, including the neck, lower extremities, temporomandibular disorders, cardiac conditions, and fibromyalgia (Larsson et al. 2014; Kortlever et al. 2020; Dupuis et al. 2023). Additionally, certain factors of the scale have been recommended for use in adolescents with idiopathic scoliosis undergoing spinal surgery (Archer et al. 2012).

The TSK is a 17-item self-administered questionnaire designed to assess fear of movement objectively. It uses a four-point Likert scale (ranging from “Strongly Disagree” to “Strongly Agree”) with items linked to fear-avoidance, fear of work-related activities, fear of movement, and fear of re-injury (French et al. 2007). Each item is scored from 1 to 4, with negatively worded items (4, 8, 12, 16) being reverse scored (from 4 to 1). Total TSK scores range from 17 to 68, with a score of 17 indicating no or negligible kinesiophobia and higher scores indicating increasing Kinesiophobia (Roelofs et al. 2011). Scores above 37 on the 17-item scale generally suggest Kinesiophobia. However, it is worth noting that gender and pain diagnosis may impact TSK scoring, affecting the norming of this scale (Roelofs et al. 2011).

For patients suffering from CKP, the TSK shows strong psychometric properties. The scale's internal consistency is high, with Cronbach's alpha values ranging from 0.68 to 0.80 (Koho et al. 2001; Heuts et al. 2004). Additionally, its test-retest reliability is good, with intraclass correlation coefficients between 0.72 and 0.82 over two weeks (Lundberg et al. 2011).

The TSK also demonstrates good construct validity, showing significant correlations with measures of pain intensity (r = 0.30 to 0.45), disability (r = 0.33 to 0.59), and other factors such as catastrophising (r = 0.51 to 0.59) in patients with knee OA (Vlaeyen et al. 1995; Heuts et al. 2004).

Mean TSK scores typically range from 35.1 to 42.6 in populations with knee OA. Higher scores are linked to lower physical activity levels, poorer physical performance, and less favourable treatment outcomes (Somers et al. 2009). A reduction of 4 to 8 points in TSK scores after an intervention is generally considered clinically meaningful (Swinkels-Meewisse et al. 2003; Lundberg et al. 2011). Kinesiophobia is a significant predictor of functional limitations in patients with knee OA, independent of pain intensity. Therefore, it is important to assess and address in treatment (Somers et al. 2009).

4.9.2.6 The SUS

The SUS is a widely used questionnaire with ten items designed to assess system usability across various industries (Brooke 1996). Participants rate different aspects of usability on a five-point scale, ranging from "Strongly Agree" to "Strongly Disagree." After participants complete the questionnaire, their responses are converted into a score ranging from 0 to 100, where higher scores indicate greater usability.

The SUS demonstrates excellent reliability, with Cronbach's alpha consistently ranging from 0.85 to 0.91 across various studies and applications. This indicates strong internal consistency (Bangor et al. 2008; Lewis and Sauro 2009). The scale also exhibits good test-retest reliability, with correlation coefficients of 0.85 obtained over two- to three-week intervals (Sauro 2011). Additionally, the SUS shows strong construct validity, as it correlates significantly with other usability measures and user performance metrics, with correlation values ranging from 0.56 to 0.76 (Tullis and Stetson 2004).

To calculate the SUS score, the contribution of each item is considered. For items 1, 3, 5, 7, and 9, the score is derived by subtracting one from the participant's response. For items 2, 4, 6, 8, and 10, the score is calculated by subtracting the response from 5. The final SUS score is obtained by multiplying the total sum of these values by 2.5 (Barnum 2021).

For interpretation, Bangor et al. (2008) established widely accepted benchmark criteria for usability scores. A score of 100% indicates a system with no usability issues. Scores above 80.3 are considered excellent usability (Grade A), while scores between 68 and 80.3 suggest good usability (Grade B), scores between 51 and 68 represent acceptable usability (Grade C), and scores below 51 highlight major usability concerns (Grade F). The average SUS score across over 500 evaluations is approximately 68, marking the threshold between acceptable and unacceptable systems (Sauro 2011).

Specifically in healthcare technology applications, SUS scores typically range from 64 to 70, while rehabilitation technologies often score between 70 and 75 for patients with chronic conditions (Parmanto et al. 2016). For VR rehabilitation platforms, such as those used for CKP, the minimum acceptable score is generally considered to be 70. Scores of 85 and above indicate an excellent user experience and are likely to result in high engagement with therapy (Shah et al. 2021).

4.10 Open-Ended Questions

The open-ended questions used in this study were designed based on Barnum's (2021) book, which emphasises the importance of crafting questions that produce meaningful insights into participants' experiences and preferences. When creating open-ended questions, it is best to focus on prompting participants to reflect on their experiences without leading them towards a specific answer (Barnum 2021).

The questionnaire comprised eight questions designed to gather detailed, personal feedback to enhance the design, functionality, and effectiveness of the VR-based physiotherapy exercises. The questions covered the following areas: experience with the system, the impact on pain levels, engagement, preferences and suggestions for improvements, challenges or discomfort, future recommendations, and any additional feedback (Appendix 10). These types of questions are effective in gathering detailed feedback, which is particularly valuable for understanding user motivations, preferences, and pain points.

For interpretation, quantitative content analysis was used, which provides a systematic and objective means of describing and quantifying phenomena (Krippendorff 2018). This method allowed for converting qualitative responses into measurable frequency data: this was particularly useful for CKP patients, whose experiences can vary widely.

4.11 Data Processing

The data collected through MVN Analyse software was exported as *.MVNx files, which integrated two data components: external data sheets containing EMG measurements and joint angle data. Individual files were created for each participant, containing raw data from all 11 recorded trials. High-definition processing was applied to the MVN analysis data to combine sensor information with advanced biomechanical models. This determines human body segment positioning and orientation (Schepers et al. 2018). The *.MVNx files were accessed using MATLAB software to extract various measurements calculated using MVN Analyse, including joint angles, segment orientations, positions, and EMG data.

The data obtained from the think-aloud approach was securely stored in individual files, each labelled with a unique participant ID to ensure anonymity and facilitate easy identification. These files were then uploaded to an online OneDrive server for secure and centralised access. The open-ended questions were documented in hard-copy files, which were stored securely in a locked cupboard. Access to these files was restricted to the main researcher only. Subsequently, the recordings and hard-copy files were transcribed and saved as written documents, capturing all the original recorded information, and then saved again on OneDrive.

4.12 Data Analysis

4.12.1 Descriptive Analysis

Descriptive statistics (mean and SD) for participants' demographics (height, weights, age, and gender), the WOMAC and EQ-5D-5L scores, Self-Efficacy for Managing Chronic Diseases, the PHQ-9, the TSK and the SUS scores were calculated.

4.12.2 Kinematic Analysis

All data were analysed using the Statistical Package for Social Sciences (SPSS) version 29 (IBM Corp. in Armonk, NY) for Windows. The analysis approach included descriptive and inferential statistical methods, with all statistical tests performed at a significance level of .05.

For all the VR scenarios, two levels were recorded and analysed for high-stepping, weight-shifting, and step forward. For the marching scenario, the data processing affected the second level data, which was counted as missing data in this study. Three levels were recorded and analysed for the sit-to-stand scenario. In the sit-to-stand scenario, the Symmetry Index (SI) for the hip, knee, and ankle joints was calculated to assess the symmetry with which individuals used both limbs during this movement by using the following formula (Błażkiewicz and Wit 2012):

$$SI = \frac{X_R - X_L}{0.5 * (X_R + X_L)} . 100\%$$

In this formula, "R" represents the measurement from the right limb, while "L" represents the measurement from the left limb (Błażkiewicz and Wit 2012). The outcome indicates which limb uses more effort. A positive value signifies that the left limb is working harder, whereas a negative value indicates that the right limb is doing more work. A result of zero indicates a perfect balance between the limbs.

The SI identifies differences that may not be apparent to the naked eye. It is particularly beneficial in therapeutic settings, as it can reveal imbalances in movement. This approach serves several important functions. First, it identifies which joints (hip, knee, or ankle) exhibit the greatest imbalances during the sit-to-stand movement. Second, it aids in tracking rehabilitation progress by measuring whether movements become more challenging over time. By measuring symmetry across three progressively challenging levels in VR, observers can see how balance changes as the task becomes more difficult.

The first step of kinematic analysis involved assessing the normality of each variable across different scenarios using the Shapiro-Wilk test. Box plots were also used to visually inspect the distribution of residuals for outliers. Based on the distribution of data, descriptive statistics were calculated and presented as follows: mean and SD for normally distributed variables, and median and interquartile range (IQR) for non-normally distributed data.

The mean and SD were selected as appropriate measures for normally distributed variables (Field 2024). This approach aligns with Fisher's foundational work on parametric statistics, which demonstrated that the mean provides maximum likelihood estimation for normally distributed data (Edwards 2005). The SD offers precise quantification of variability around the central tendency: in kinematic analyses specifically, Winter (2009) substantiated that these measures efficiently characterise movement patterns when data satisfy normality assumptions.

For non-normally distributed variables, the median and interquartile range were employed in accordance with robust statistical guidelines (Demir 2022). In the biomechanics literature, Knudson (2009) specifically advocated for median-based statistics when analysing movement data that violates normality assumptions, as they better represent the central tendency without being unduly influenced by extreme values often present in kinematic recordings.

The data's distribution determined the selection of inferential statistical tests. For normally distributed data, repeated measures ANOVA was conducted to examine differences in ROM between limbs, across VR levels (Level 1 vs. Level 2), and between joints (hip, knee, and ankle) in the sagittal and frontal plane. When using repeated-measures ANOVA, the sphericity assumption was evaluated using Mauchly's test. If this assumption was violated (indicated by significant results), corrections were applied based on the Greenhouse and Geisser measure (ε):

- If $\varepsilon < 0.75$: Greenhouse and Geisser correction was used
- If $\varepsilon > 0.75$: Huynh and Feldt correction was applied

Following significant ANOVA results ($p < 0.05$), pairwise comparisons with Bonferroni adjustment were conducted to pinpoint specific differences among limbs, VR levels, joints, and their interactions. A difference was considered statistically significant when the p-value was less than 0.05 following the adjustment for multiple comparisons.

The Friedman test was employed as a non-parametric alternative to one-way repeated measures ANOVA for non-normally distributed data. This test analysed differences in muscle activity (EMG data) across the two limbs and VR levels (Level 1 vs. Level 2). When the Friedman test revealed statistically significant differences ($p < 0.05$), post-hoc Wilcoxon signed-rank tests with Bonferroni correction were conducted to identify specific pairwise differences between limbs and VR levels.

Adjusted p-values less than 0.05 were considered statistically significant for these post-hoc comparisons.

4.12.3 Usability Analysis

The think-aloud and open-ended questions data were examined using quantitative content analysis, as outlined by Krippendorff (2018). This method involves systematically classifying and counting specific verbal elements or themes to produce measurable results. The principal researcher coded the transcripts based on a predetermined coding framework, which a second researcher verified to maintain coding consistency. Inter-coder reliability was achieved through consensus discussions among the research team, resolving any coding discrepancies through collaborative dialogue, as Lombard et al. (2002) suggested, ensuring reliability in content analysis.

Quantitative content analysis is a research method that systematically categorises and measures textual data to identify patterns, themes, or relationships within a set of texts (Boettger and Palmer 2010). It differs from qualitative content analysis in that it requires predefined categories and coding schemes, allowing researchers to objectively quantify the presence of specific words, phrases, or concepts (Boettger and Palmer 2010).

The quantitative content analysis in this study followed a structured process based on Krippendorff's (2018) methodology. First, all participants' textual data describing the VR system were transferred and collected in a Microsoft Word document (version 16.56). Any word or phrase that described the VR system was considered a unit of analysis. The lead researcher (A.AL) read all transcripts multiple times to gain initial insight into the content. Following the research objectives and initial review, a preliminary coding scheme was developed to categorise descriptions of the VR toolkit (Appendix 11).

The lead researcher and second reviewer held three meetings to discuss and refine the initial codes and categories. Any discrepancies were resolved through consensus discussions. Following this collaborative refinement, all transcripts were systematically coded according to the finalised coding framework. The coded data were then transferred to Microsoft Excel spreadsheets, with separate sheets for each participant's data. This organisation enabled systematic quantification of the data, where the frequency of each repeated code was counted for individual participants and across the entire sample. The occurrences of each code were converted to percentages to identify the predominant themes in participants' descriptions of the VR system. A third researcher reviewed the Excel spreadsheets to validate the consistency of the coding application. This structured approach ensured that the data analysis remained systematic and aligned with the established principles of quantitative content analysis (Krippendorff 2018).

4.13 Ethical Considerations

The study prioritised participant safety throughout the research process. A thorough risk assessment of the lab environment was conducted before beginning data collection to eliminate potential hazards. Participants received clear information about sensor attachment methods (adhesive tape for sacral trackers and elastic straps for other locations), possible discomfort during removal of both MVN Xsensors and EMG sensors, and the potential for temporary joint pain or muscle soreness during VR gaming. Regular rest periods were incorporated between games for participant comfort. A qualified physiotherapist provided constant supervision during all activities to ensure safety. Privacy was maintained by securing the research space exclusively for study purposes with a "Research is Ongoing" notice displayed on the door and providing a separate changing facility in an adjacent room.

To protect participant information, comprehensive data security measures were implemented. Personal data was stored on password-protected university computers, with access limited to the research team. Each participant provided written consent and received a unique identification number that was used throughout the study. Electronic records were maintained on Cardiff University's secure servers, while anonymised copies were stored on OneDrive, accessible only to the researcher. Physical copies of data were secured in a locked cabinet with access restricted to the researcher. All data will be preserved for five years after the completion of the study before deletion, following Cardiff University's Research Governance Guidelines, GDPR 2018 regulations, and clinical research standards.

The Ethics Committee of the School of Healthcare at Cardiff University approved this study on December 20, 2022 (SREC reference: REC894). Following pilot study observations, the protocol was amended to remove problematic equipment measurements and incorporate think-aloud methodology to capture participant feedback. This amendment received ethical approval on November 2, 2023 (Appendix 12). Think-aloud recordings were anonymised, securely stored, and will be deleted after five years according to the university's retention schedules. Participants were informed of their right to withdraw from the study at any time, with the assurance that all personally identifiable data would be permanently deleted upon withdrawal.

CHAPTER 5: Results

5.1 Overview of the Chapter

This chapter presents the results of an evaluation of an in-house VR-based physiotherapy toolkit developed for home use by individuals with CKP. The analysis addressed two key objectives:

- It evaluated whether the VR games were ‘fit-for-purpose' by providing an appropriate level of challenge and accurately mirroring exercises, assessed through joint ROM and muscle activity to ensure that they met the physical therapy needs.
- It explored the toolkit's usability and acceptability for participants with CKP.

To address these objectives, five VR scenarios (marching, high stepping, weight-shifting, step forward, and sit-to-stand) were analysed through a detailed biomechanical analysis. These scenarios were evaluated based on their ability to promote strength and balance adaptation, using the ROM, EMG amplitude and COM trajectory in both the sagittal and the frontal plane across different difficulty levels. The evaluation incorporated a comprehensive biomechanical assessment using motion capture technology to evaluate joint kinematics and EMG measurements to assess muscle activity. It also gathered feedback from participants during VR gameplay through a think-aloud approach and the SUS.

This chapter begins with an overview of participant demographics, followed by the presentation of self-reported outcome measures, statistical analysis of the VR scenarios, and findings from the think-aloud feedback. It concludes with a summary of key findings.

5.2 Participants’ Demographic Data

The data was gathered from a total of 40 participants, comprising 52.5% males and 47.5% females. Age was distributed across various categories: 35% were between 18 and 25 years old, 12.5% were 26–35, 15% were 36–45, 17.5% were 46–55, and 20% were 56 and above. Regarding the distribution of the affected knee, most participants (70%) had left knee involvement, while 15% each had right knee and bilateral knee involvement (Table 8).

Table 8: Participants' Gender Distribution, Age Group, and Affected Knee

Parameters	Category	Frequency	Percentage
Gender	Male Female	21 19	52.5% 47.5%
Age (years)	18–25 26–35 36–45 46–55 ≥ 56	14 5 6 7 8	35% 12.5% 15% 17.5% 20%
Affected knee	Right Left Bilateral	6 28 6	15% 70% 15%

The group had an average age of 39.33 (SD ±16.78), indicating a broad age range. The average height of the participants was 173.28 cm, while the average weight was 80.65 kg (Table 9). These statistics demonstrate variability in the participants' physical characteristics, notably in weight and age.

Table 9: Descriptive Statistics for Participants' Height, Weight, and Age

Variables	Mean (SD)
Height	173.28 (± 8.9) cm
Weight	80.65 (±17.65) Kg
Age	39.33 (±16.78) years

5.3 Self-Reported Outcome Measures

The analysis of self-reported measures among participants with CKP provides insights into their health-related quality of life, physical function, and well-being (Table 10).

Table 10: Self-Reported Outcome Measures

Self-reported measures	Mean ± SD
EQ-5DL-5L Index	0.78 ± 0.15
EQ-5DL-5L VAS	71.36 ± 19.19
WOMAC	0.29 ± 0.19
TSK	37.59 ± 7.38
SECD	6.55± 1.88
PHQ-9	9.56 ± 6.98

5.4 SUS Questionnaire

All 40 participants completed the SUS questionnaire, and Table 11 presents the overall SUS results for each questionnaire. The overall SUS score was 76 ± 12.54. According to Brooke (1996), values between 60% and 80% are interpreted as borderline-to-good.

Table 11: SUS questionnaire results

Subject ID	SUS score	Subject ID	SUS score
VR10KNEE	95	VR29KNEE	75
VR11KNEE	72.5	VR30KNEE	92.5
VR12KNEE	85	VR31KNEE	65
VR13KNEE	65	VR32KNEE	80
VR14KNEE	75	VR33KNEE	65
VR15KNEE	67.5	VR34KNEE	87.5
VR16KNEE	80	VR35KNEE	75
VR17KNEE	80	VR36KNEE	70
VR18KNEE	87.5	VR37KNEE	65
VR19KNEE	80	VR38KNEE	95
VR20KNEE	65	VR39KNEE	55
VR21KNEE	80	VR40KNEE	72.5
VR22KNEE	72.5	VR41KNEE	70
VR23KNEE	85	VR42KNEE	32
VR24KNEE	82.5	VR43KNEE	77.5
VR25KNEE	92.5	VR44KNEE	77.5
VR26KNEE	90	VR45KNEE	75
VR27KNEE	87.5	VR46KNEE	85
VR28KNEE	80	VR47KNEE	70
		VR48KNEE	87.5

5.5 Statistical Analysis of the Kinematic Measurements

The normality tests for the ROM measures across the sagittal and frontal planes and EMG measures for all VR scenarios are detailed in Appendix 13. The following sections present the descriptive statistics, and the results of inferential statistical tests used to evaluate the data.

5.5.1 Marching Scenario

5.5.1.1 Descriptive Statistics

As the average ROM data was normally distributed in the sagittal and frontal planes, the mean and SD were used to describe the data for the lower limb joints (hip, knee, and ankle). Table 12 presents the mean and SD values for the ROM across both the sagittal and the frontal plane for the right and left limbs. Table 13 presents the median and IQR for the EMG amplitude across the lower limb muscles (Rectus

Femoris, Vastus Medialis, Medial Gastrocnemius, and Biceps Femoris) on the right and left limbs.

Table 12: ROM Descriptive Statistics for Sagittal and Frontal Plane

Joints	Sagittal Plane	Mean ± SD	Frontal plane	Mean ± SD
Hip	Right Hip Flexion Extension ROM	34.20° ± 7.23	Right Hip Abduction Adduction ROM	4.62° ± 4.78
	Left Hip Flexion Extension ROM	33.78° ± 8.51	Left Hip Abduction Adduction ROM	2.75° ± 4.52
Knee	Right Knee Flexion Extension ROM	57.25 ° ± 12.25	Right Knee Abduction Adduction ROM	-2.63° ± 7.74
	Left Knee Flexion Extension ROM	57.46° ± 14.70	Left Knee Abduction Adduction ROM	0.11° ± 6.48
Ankle	Right Ankle ROM Dorsiflexion Plantarflexion	-3.68° ± 7.90	Right Ankle Eversion-Inversion ROM	-10.35° ± 6.43
	Left Ankle ROM Dorsiflexion Plantarflexion	-3.14° ± 7.85	Left Ankle Eversion-Inversion ROM	-9.31° ± 5.77

Table 13: EMG Amplitude Descriptive Statistics

Muscles	Limb	Median	IQR
RF	Left	.0017 μV	.00 μV
	Right	.0015 μV	.00 μV
VM	Left	.0020 μV	.00 μV
	Right	.0024 μV	.00 μV
MG	Left	.0043 μV	.01 μV
	Right	.0040 μV	.01 μV
BF	Left	.0027 μV	.00 μV
	Right	.0029 μV	.00 μV

(μV = microvolts, RF = Rectus Femoris, VM = Vastus Medialis, MG = Medial Gastrocnemius, BF = Biceps Femoris)

5.5.1.2 Inferential Statistical Tests

Repeated Measures ANOVA for ROM Measures in Sagittal Plane

A repeated measures ANOVA was conducted to examine the effects of Limbs, Joints, and their interaction (Limbs × Joints) on lower limb joint ROM. Mauchly's test of sphericity was used to evaluate the sphericity assumption for each factor (Table 14). For the Limbs factor, Mauchly's W was 1.000, indicating no violation of sphericity;

thus, sphericity was assumed for this factor. However, significant violations of sphericity were detected for the Joints factor (W = 0.726, p = 0.004) and the Limbs × Joints interaction (W = 0.414, p < 0.001). Therefore, the Greenhouse-Geisser correction was applied to adjust the degrees of freedom for these effects.

Table 14: A repeated measures ANOVA of ROM across lower limb joints in sagittal plane.

Measures	**Mauchly's W**	**Sig.**	**Greenhouse-Geisser**	**Huynh-Feldt**
Joints	.726	.004	.785	.814
Limbs * Joints	.414	<.001	.631	.643

Table 15: Within-Subjects Effect of Average ROM across Lower Limb Joints

Measure	**Sphericity condition**	**F**	**Sig.**
Limb	Sphericity Assumed	.047	.830
Joints	Greenhouse-Geisser correction	654.041	<.001
Limb x Joints	Greenhouse-Geisser correction	.373	.593

The analysis of the Limbs factor using sphericity-assumed degrees of freedom revealed a non-significant effect (F = 0.047, p = 0.830), indicating that there were no statistically significant differences in average ROM between limbs (Table 15). For the Joints factor, the Greenhouse-Geisser corrected analysis showed a highly significant effect (F = 654.041, p < 0.001), indicating substantial differences in ROM among the lower limb joints.

The interaction between Limbs × Joints, analysed using the Greenhouse-Geisser correction, yielded a non-significant result (F = 0.373, p = 0.593). This suggests that the relationship between average ROM and joints did not differ significantly across the VR levels.

Repeated Measures ANOVA for ROM Measures in the Frontal Plane

The frontal plane ROM analysis began with evaluating the assumption of sphericity using Mauchly's test. The results demonstrated that the assumption of sphericity was met for both the Joints factor (p = .382) and the interaction between Limbs and Joints (p = .919). Mauchly's test was not computed for the Limbs factor, as it contained only two levels. These results indicate that the variance of the differences between all possible pairs of tested factors (Joints and Limbs) was approximately equal, allowing for standard repeated measures ANOVA without corrections (Table 16).

Table 16: A repeated measures ANOVA of ROM across lower limb joints in frontal plane.

Within Subjects Effect	**Sig.**	**Epsilon**	
		Greenhouse-Geisser	Huynh-Feldt
Joints	.382	.949	1.000
Limbs x Joints	.919	.995	1.000

The repeated measures ANOVA revealed significant findings across all main effects and interactions (Table 17).

Table 17: Tests of Within-Subjects Effects

Measures		**F**	**Sig.**
Limbs	Sphericity Assumed	4.365	.044
Joints	Sphericity Assumed	58.415	<.001
Limbs x Joints	Sphericity Assumed	6.877	.002

Nonparametric Test of EMG Activity

The Wilcoxon signed-rank test was employed to compare EMG activity between the left and right limbs for each muscle, as the data violated normality assumptions (Shapiro-Wilk test, $p < 0.001$) (Table 18).

Table 18: Wilcoxon Signed-Rank Test for EMG Muscle Activity between Limbs

Measures	Right–Left RF	Right–Left VM	Right–Left MG	Right– Left BF
Z	-1.373	-1.654	-.681	-1.308
Asymp. Sig. (2-tailed)	.170	.098	.496	.191

5.5.2 High-Stepping Scenario

5.5.2.1 Descriptive Statistics

Table 19 and 20 present the mean and SD for the ROM across the sagittal and the frontal plane respectively for the lower limb joints (hip, knee, and ankle) in both limbs and at two levels of difficulty in the VR scenario (L1 and L2).

Table 19: Descriptive Statistics for ROM in Sagittal Plane

Joints	Level 1	Mean ± SD	Level 2	Mean ± SD
Hip	Right Hip Flexion–Extension ROM	45.57° ± 9.18	Right Hip Flexion–Extension ROM	63.25° ± 9.59
	Left Hip Flexion–Extension ROM	48.84° ± 9.24	Left Hip Flexion–Extension ROM	60.35° ± 10.09
Knee	Right Knee Flexion–Extension ROM	72.84° ± 12.99	Right Knee Flexion–Extension ROM	87.26° ± 11.20
	Left Knee Flexion–Extension ROM	77.78° ± 13.09	Left Knee Flexion–Extension ROM	86.87° ± 11.96
Ankle	Right Ankle ROM Dorsiflexion–Plantarflexion	4.51° ± 10.62	Right Ankle ROM Dorsiflexion–Plantarflexion	-.10° ± 13.57
	Left Ankle ROM Dorsiflexion–Plantarflexion	3.05° ± 9.91	Left Ankle ROM Dorsiflexion–Plantarflexion	2.29° ± 10.87

Table 20: Descriptive Statistics for ROM in Frontal Plane

Joints	Level 1	Mean ± SD	Level 2	Mean ± SD
Hip	Right Hip Abduction–Adduction ROM	2.32° ± 5.17	Right Hip Abduction–Adduction ROM	2.62° ± 6.55
	Left Hip Abduction–Adduction ROM	1.25° ± 6.37	Left Hip Abduction–Adduction ROM	1.38° ± 5.54
Knee	Right Knee Abduction–Adduction ROM	-5.01° ± 7.19	Right Knee Abduction–Adduction ROM	-7.33° ± 8.10
	Left Knee Abduction–Adduction ROM	-2.17° ± 7.77	Left Knee Abduction–Adduction ROM	-4.58° ± 7.95

Ankle	Right Ankle Eversion–Inversion ROM	-10.49° ± 6.67	Right Ankle Eversion–inversion ROM	-9.12° ± 6.35
	Left Ankle Eversion–Inversion ROM	-12.76° ± 8.17	Left Ankle Eversion–Inversion ROM	-9.88° ± 7.67

Table 21 presents the median and IQR for the EMG amplitude across the lower limb muscles (Rectus Femoris, Vastus Medialis, Medial Gastrocnemius and Biceps Femoris) in both limbs and at two levels (L1 and L2).

Table 21 EMG Amplitude Descriptive Statistics

Limb	Level 1	Median	IQR	Level 2	Median	IQR
Left	RF	.0019 μV	.00 μV	RF	.0019 μV	.00 μV
	VM	.0016 μV	.00 μV	VM	.0023 μV	.00 μV
	MG	.0048 μV	.01 μV	MG	.0062 μV	.01 μV
	BF	.0022 μV	.00 μV	BF	.0023 μV	.00 μV
Right	RF	.0019 μV	.00 μV	RF	.0026 μV	.00 μV
	VM	.0019 μV	.00 μV	VM	.0024 μV	.00 μV
	MG	.0035 μV	.00 μV	MG	.0046 μV	.00 μV
	BF	.0021 μV	.00 μV	BF	.0023 μV	.00 μV

(μV = Microvolts, RF = Rectus Femoris, VM = Vastus Medialis, MG = Medial Gastrocnemius, BF = Biceps Femoris)

5.5.2.2 Inferential Statistics

Repeated Measures ANOVA for ROM Measures in Sagittal Plane

A repeated measures ANOVA was conducted to examine the effects of Levels, Limbs, and Joints, as well as their interactions, on ROM measures in the sagittal plane. Mauchly's test of sphericity was used to assess the assumption of sphericity for each factor (Table 22). For most effects, including Levels, Limbs, and Joints, as well as the Levels × Limb's interaction, Mauchly's W indicated no violations of sphericity ($W = 1.000$, $p > 0.05$). Therefore, sphericity was assumed for these factors.

However, as shown in Table 22, significant violations of sphericity were detected for the interactions: Levels × Joints ($W = 0.692$, $p = 0.003$), Limbs × Joints ($W = 0.791$, $p = 0.024$), and Levels × Limb × Joints ($W = 0.622$, $p < 0.001$). For these interactions, sphericity corrections were applied using the Greenhouse-Geisser adjustments.

Table 22: Mauchly's Test of Sphericity

Within Subjects Effect	**Mauchly's W**	**Sig.**		
			Greenhouse-Geisser	Huynh-Feldt
Levels x Joints	.692	.003	.765	.794
Limb x Joints	.791	.024	.827	.866
Levels x Limb x Joints	.622	<.001	.726	.750

The analysis revealed several significant findings regarding movement patterns. While the main effect of Limbs was not significant (F = 2.052, p = .161), the Levels × Limb's interaction (f = 8.347, p = .007) was significant. This means that the effect of difficulty levels on performance differed between the left and right limbs. Furthermore, the three-way interaction between Levels, Limbs, and Joints (F = 9.503, p = .001) showed a significant finding. This indicates that the relationship between difficulty levels and limb (left/right) varied depending on which joint was being measured (Table 23).

Table 23: Within-Subjects Effect of Average ROM

Measure	**Sphericity condition**	**F**	**Sig.**
Levels	Sphericity Assumed	40.49	<.001
Limb	Sphericity Assumed	2.05	.161
Joints	Sphericity Assumed	1069.22	<.001
Levels x Limb	Sphericity Assumed	8.34	.007
Levels x Joints	Sphericity Assumed	39.92	<.001
Limb x Joints	Greenhouse-Geisser	1.21	.299
Levels x Limb x Joints	Greenhouse-Geisser	9.50	.001

Repeated-Measures ANOVA for ROM Measures in the Frontal Plane

The analysis began with Mauchly's test of sphericity to examine the assumptions for the repeated measures ANOVA (Table 24). The results showed that the sphericity assumption was met for the main effects of Joints (p = .563). However, significant violations of sphericity were found for the Joints x Levels interaction (p = .002) and the three-way interaction of Joints x Levels x Limbs (p < .001). The Joints x Limbs interaction met the sphericity assumption (p = .161). Greenhouse-Geisser corrections were applied to adjust the degrees of freedom for the factors where sphericity was violated.

Table 24: Mauchly's Test of Sphericity

Within Subjects Effect	**Sig.**		
		Greenhouse-Geisser	**Huynh-Feldt**
Joints	**.563**	**.966**	**1.000**
Joints x Levels	**.002**	**.758**	**.786**
Joints x Limb	**.161**	**.903**	**.952**
Joints x Levels x Limb	**<.001**	**.631**	**.644**

The subsequent repeated measures ANOVA (Table 25) revealed a significant main effect for Joints (F = 30.377, p < .001), indicating substantial differences in movement patterns across the three joints. However, no significant main effects were found for either Levels (F = 0.001, p = .979) or Limbs (F = 0.009, p = .925). Significant two-way interactions were observed for Joints x Levels (F = 9.255, p = .001, using Greenhouse-Geisser correction) and Joints x Limbs (F = 4.983, p = .010). The Levels x Limbs interaction was not significant (F = 1.588, p = .216). The three-way interaction of Joints x Levels x Limbs was also non-significant (F = 1.021, p = .337, using Greenhouse-Geisser correction).

Table 25 Tests of Within-Subjects Effects

Measures		**F**	**Sig.**
Joint	**Sphericity Assumed**	**30.37**	**<.001**
levels	**Sphericity Assumed**	**.001**	**.979**
Limb	**Sphericity Assumed**	**.009**	**.925**
Joint x Levels	**Greenhouse-Geisser**	**9.25**	**<.001**
Joint * Limb	**Sphericity Assumed**	**4.98**	**.010**

levels x Limb	**Sphericity Assumed**	**1.58**	**.216**
Joint x Levels x Limb	**Greenhouse-Geisser**	**1.02**	**.337**

Inferential Analysis for EMG Amplitude

The Friedman test was employed to compare EMG activity across two levels and two limbs for each muscle. This test was selected due to the related sample design and non-normal data distribution. If the results were significant, then post-hoc analyses were performed using Wilcoxon signed-ranks tests to determine specific differences between conditions.

Statistical Analysis of Rectus Femoris Muscle Activity

The Friedman Test was conducted to assess whether there were significant differences in Rectus Femoris muscle activity across the measurement conditions (two limbs and two levels). The results indicated that muscle activity remained consistent among the different conditions ($p = 0.37$). Therefore, no additional statistical tests were needed, as the initial Friedman Test revealed no significant variations.

Statistical Analysis of Vastus Medialis Muscle Activity

A Friedman test examined Vastus Medialis muscle activity differences across multiple conditions. The test revealed a statistically significant difference ($p = .005$), indicating that Vastus Medialis muscle activation patterns varied significantly across the tested conditions. Given these critical findings, post-hoc analyses were performed using the Wilcoxon signed-ranks tests to determine specific differences between conditions.

The Wilcoxon signed-ranks test was selected as the appropriate post-hoc analysis due to its ability to compare paired measurements in non-parametric data. Two specific comparisons were analysed. The first comparison examined the left limb, revealing a significant increase in Vastus Medialis muscle activity from L1 to L2 ($p = .038$). The second comparison focused on the right limb, demonstrating an even more pronounced significant increase from L1 to L2 ($p = .004$).

Statistical analysis of Medial Gastrocnemius muscle activity

A Friedman test examined the differences in Medial Gastrocnemius muscle activity across multiple conditions. The test revealed no statistically significant differences ($p = .199$), indicating that Medial Gastrocnemius muscle activation patterns did not vary significantly across the tested conditions.

Statistical analysis of Biceps Femoris muscle activity

A Friedman test examined the differences in Biceps Femoris muscle activity across multiple conditions. The test revealed no statistically significant differences ($p = .175$), indicating that Biceps Femoris muscle activation patterns did not vary significantly across the tested conditions.

5.5.3 Weight Shifting Scenario

5.5.3.1 Descriptive Statistics

As the data was not normally distributed, Table 26 represents the median and IQR for the total excursion of COM across the levels during the weight-shifting scenario.

Table 26: Descriptive Statistics for Total Excursion of COM

Measures	Median	IQR
TotExc_L1	**0.49**	**0.78**
TotExc_L2	**1.96**	**3.03**

Table 27 presents the median and the Interquartile Range (IQR) for the EMG activity for the four muscles (Rectus Femoris, Vastus Medialis, Medial Gastrocnemius, Biceps Femoris) for both sides.

Table *27*: Descriptive *S*tatistics for EMG Amplitude.

Limb	Level 1		Statistic	Level 2		Statistic
Left	RF	Median	.0013 µV	RF	Median	.0021 µV
		- IQR	.00 µV		IQR	.00 µV
	VM	Median	.0014 µV	VM	Median	.0020 µV
		IQR	.00 µV		IQR	.00 µV
	MG	Median	.0019 µV	MG	Median	.0023 µV
		IQR	.00 µV		IQR	.00 µV
	BF	Median	.0015 µV	BF	Median	.0018 µV

		IQR	.00 µV		IQR	.00 µV
Right	RF	Median	.0010 µV	RF	Median	.0017 µV
		IQR	.00 µV		IQR	.00 µV
	VM	Median	.0014 µV	VM	Median	.0023 µV
		IQR	.00 µV		IQR	.00 µV
	MG	Median	.0023 µV	MG	Median	.0026 µV
		IQR	.00 µV		IQR	.00 µV
	BF	Median	.0018 µV	BF	Median	.0018 µV
		IQR	.00 µV		IQR	.00 µV

(µV = microvolts, RF = Rectus Femoris, VM = Vastus Medialis, MG = Medial Gastrocnemius, BF = Biceps Femoris)

5.5.3.2 Inferential Statistics

Inferential Analysis for Total Excursion of COM

A Wilcoxon signed-rank test was conducted to examine the difference in total excursion (TotExc) between two levels of weight-shifting exercises (L1 and L2). The test revealed a statistically significant difference in excursion levels between L1 and L2 ($Z = -4.579$, $p < .001$).

Table 28: Wilcoxon Signed-Rank Test

Wilcoxon signed-rank test	
	TotExc_L2 - TotExc_L1
Z	-4.579
Asymp. Sig. (2-tailed)	<.001

Inferential Analysis for EMG Amplitude

The Friedman test was employed to compare EMG activity across two levels and two limbs for each muscle. This test was selected due to the related sample design and non-normal data distribution. If the results were significant, then post-hoc analyses were performed using Wilcoxon signed-ranks tests to determine specific differences between conditions.

The analysis of muscle activity yielded varying results across different muscle groups. For the Rectus Femoris muscle, the Friedman test revealed significant differences across conditions ($p < .001$), which led to follow-up Wilcoxon signed-rank tests with a Bonferroni correction, setting the significance threshold at 0.0083 to prevent Type I errors. Similarly, for the Vastus Medialis, significant differences were observed across conditions ($p < .001$), with follow-up Wilcoxon signed-rank tests conducted using the same Bonferroni correction ($\alpha = 0.0083$), and detailed results are presented in Table 29.

In contrast, the Medial Gastrocnemius demonstrated no significant differences across conditions ($p = .096$), so no post-hoc tests were necessary, and neither the difference between left and right limbs nor the interaction between level and limb was statistically significant. For the Biceps Femoris, significant differences were detected across conditions ($p = .005$), leading to Wilcoxon signed-rank tests with Bonferroni correction ($\alpha = 0.0083$), with complete results available in Table 29.

Table 29: Wilcoxon Signed-Rank Tests

Comparison	RF	VM	BF
Level comparison in left limb (L2 vs L1)	Z = -2.983 p = .003	Z = -2.966 p = .003	Z = -3.342 p < .001
Level comparison in right limb (L2 vs L1)	Z = -2.983 p = .003	Z = -2.812 p = .005	Z = -2.077 p = .038*
Between limbs comparison at L1	Z = -2.795 p = .005	Z = -.180 p = .858	Z = -.880 p = .379*
Between limbs comparison at L2	Z = -2.009 p = .045	Z = -.778 p = .437	Z = -.863 p = .388*

*(not significant after Bonferroni correction)

Overall Summary

The Rectus Femoris exhibited significantly higher activation during Level 2 compared to Level 1 in both limbs. An important finding was the asymmetry at Level 1, where the right RF showed significantly lower activation than the left RF ($Z = -2.795$, $p = .005$). For the Vastus Medialis, both the left and right sides demonstrated significantly higher activation during Level 2 compared to Level 1, with no significant differences between the limbs at either level. The MG muscle showed consistent activation across both difficulty levels, with no significant differences observed between the left and right limbs. The Biceps Femoris revealed notable limb asymmetry, with the left Biceps Femoris showing a significant increase in activation from Level 1 to Level 2 ($Z = -3.342$, $p < .001$), while the right Biceps Femoris activation remained unchanged between levels.

5.5.4 Step-Forward Scenario

5.5.4.1 Descriptive Statistics

After conducting the normality tests for all variables and finding that the results were not normally distributed, Table 30 represents the median and IQR for the ROM across the sagittal plane for the lower limb joints (hip, knee, and ankle) in both limbs. Table 31 represents the mean and SD for the frontal plane for the lower limb joints (hip, knee, and ankle) in both limbs.

Table 30: Descriptive Statistics for ROM Average in Sagittal Plane.

Joints	Level 1	Median (IQR)	Level 2	Median (IQR)
Hip	Right Hip Flexion–Extension ROM	11.74° (11.16)	Right Hip Flexion–Extension ROM	13.86° (7.14)
	Left Hip Flexion–Extension ROM	10.06° (8.29)	Left Hip Flexion–Extension ROM	13.58° (7.31)
Knee	Right Knee Flexion–Extension ROM	43.91° (5.46)	Right Knee Flexion–Extension ROM	44.08° (5.43)
	Left Knee Flexion–Extension ROM	44.02° (5.90)	Left Knee Flexion–Extension ROM	44.93° (5.91)
Ankle	Right Ankle ROM Dorsiflexion–Plantarflexion	7.88° (8.90)	Right Ankle ROM Dorsiflexion–Plantarflexion	8.2° (8.25)
	Left Ankle ROM Dorsiflexion–Plantarflexion	9.48° (8.90)	Left Ankle ROM Dorsiflexion–Plantarflexion	5.70° (9.51)

Table 31: Descriptive Statistics for ROM Average in Frontal Plane.

Joints	Level 1	Mean ± SD	Level 2	Mean ± SD
Hip	Right Hip Abduction–Adduction ROM	1.81° ± 3.55	Right Hip Abduction–Adduction ROM	2.45° ± 3.18
	Left Hip Abduction–Adduction ROM	1.04° ± 3.13	Left Hip Abduction–Adduction ROM	2.30° ± 2.63
Knee	Right Knee Abduction–Adduction ROM	-1.87° ± 4.56	Right Knee Abduction--Adduction ROM	-1.98° ± 4.19
	Left Knee Abduction–Adduction ROM	0.30° ± 4.11	Left Knee Abduction–Adduction ROM	0.37° ± 3.98
Ankle	Right Ankle Eversion--Inversion ROM	0.81° ± 3.81	Right Ankle Eversion–Inversion ROM	-1.37° ± 3.76
	Left Ankle Eversion--inversion ROM	0.20° ± 4.35	Left Ankle Eversion–Inversion ROM	-1.26° ± 3.28

Based on the non-normal distribution of the data, median and interquartile ranges were used to describe the EMG activity (Table 32).

Table 32: Descriptive statistics for EMG amplitude

Limb	Level 1		Statistic	Level 2		Statistic
Left	RF	Median	.0023 μV	RF	Median	.0019 μV
		- IQR	.00 μV		IQR	.00 μV
	VM	Median	.0028 μV	VM	Median	.0023 μV
		IQR	.00 μV		IQR	.00 μV
	MG	Median	.0043 μV	MG	Median	.0042 μV
		IQR	.00 μV		IQR	.01 μV
	BF	Median	.0020 μV	BF	Median	.0017 μV
		IQR	.00 μV		IQR	.00 μV
Right	RF	Median	.0030 μV	RF	Median	.0018 μV
		IQR	.00 μV		IQR	.00 μV
	VM	Median	.0022 μV	VM	Median	.0024 μV
		IQR	.00 μV		IQR	.00 μV
	MG	Median	.0066 μV	MG	Median	.0032 μV
		IQR	.00 μV		IQR	.01 μV
	BF	Median	.0019 μV	BF	Median	.0017 μV
		IQR	.00 μV		IQR	.00 μV

(μV = microvolts, RF = Rectus Femoris, VM = Vastus Medialis, MG = Medial Gastrocnemius, BF = Biceps Femoris)

5.5.4.2 Inferential Statistics

Non-Parametric Test of ROM Measures in the Sagittal Plane

Wilcoxon signed-rank tests revealed significant bilateral changes in hip flexion-extension between L1 and L2. Specifically, on the right limb, the p-value was 0.028, and on the left limb, it was 0.006, indicating that most participants showed increased values at L2 (Table 33).

Table 33: Wilcoxon Signed-Rank Test Results for Hip Joint

Wilcoxon signed-rank tests	Right Hip L2 – L1	Left Hip L2 – L1
Z	-2.197	-2.744
Asymp. Sig. (2-tailed)	.028	.006

In contrast, knee movements did not show significant changes between levels on the right limb (p = 0.180) and exhibited borderline significance on the left limb (p = 0.054) (Table 34). Additionally, ankle movements displayed an interesting asymmetry: while the right ankle showed no significant changes (p = 0.765), the left ankle demonstrated a considerable decrease in the dorsiflexion-plantarflexion range in the L2 condition (p = 0.004) (Table 35).

Table 34: Wilcoxon Signed-Rank Test Results for Knee Joint

Wilcoxon signed-rank tests	Right Knee L2 – L1	Left Knee L2 – L1
Z	-1.342	-1.923
Asymp. Sig. (2-tailed)	.180	.054

Table 35: Wilcoxon Signed-Rank Test Results for Ankle Joint

Wilcoxon signed-rank tests	Right Ankle L2 – L1	Left Ankle L2 – L1
Z	-.299	-2.915
Asymp. Sig. (2-tailed)	.765	.004

Parametric Statistical Tests for ROM Measures in the Frontal Plane

A three-way repeated measures ANOVA was conducted to examine the effects of Levels, Limbs, and Joints (hip, knee, ankle) on abduction/adduction measurements in the frontal plane. The analysis revealed significant main effects for Level (F = 4.198, p = .049), Limbs (F = 4.382, p = .044), and Joints (F = 6.837, p = .002). Significant interaction effects were observed between Levels and Joints (F = 8.889, p = .002) (Greenhouse-Geisser corrected) and between Limbs and Joints (F = 6.812, p = .003), as set out in Table 36. The Levels-by-Limb interaction approached but did not reach statistical significance (F = 3.026, p = .091), while the three-way interaction between Levels, Limbs, and Joints was not significant (F = .219, p = .740).

Table 36: Within-Subjects Effect

Source		F	Sig.
Level	Sphericity Assumed	4.198	.049
Limb	Sphericity Assumed	4.382	.044
Joint	Sphericity Assumed	6.837	.002
Level x Limb	Sphericity Assumed	3.026	.091
Level x Joint	Greenhouse-Geisser	8.889	.002
Limb x Joint	Sphericity Assumed	6.812	.003
Level x Limb x Joint	Greenhouse-Geisser	.219	.740

Post-hoc analyses using Bonferroni correction for multiple comparisons revealed that hip movements were significantly greater than knee and ankle movements. No significant difference was found between knee and ankle movements. The contrast analysis further supported these findings, showing significant differences between joint levels (Table 37).

Table 37: Pairwise Comparison

(I) Joint	(J) Joint	Mean Difference (I-J)	Std. Error	Sig.
1 (Hip)	2	2.701*	.781	.005
	3	2.310*	.705	.007
2 (Knee)	1	-2.701*	.781	.005
	3	-.391	.873	1.000
3 (Ankle)	1	-2.310*	.705	.007
	2	.391	.873	1.000

Inferential analysis of EMG amplitude

The Wilcoxon Signed Ranks Test was conducted to examine changes in muscle activity across the four muscles (Rectus Femoris, Vastus Medialis, Medial

Gastrocnemius, and Biceps Femoris) between two different levels, comparing the left and right limbs.

The results for the RF muscle revealed an interesting asymmetry (Table 38). The right limb showed a statistically significant difference between the two levels (p = 0.019). In contrast, the left RF muscle did not demonstrate a statistically significant change (p = 0.126).

Table 38: Wilcoxon Signed Ranks Test for RF muscle

	Left RF **L2 - L1**	**Right RF** **L2 - L1**
Z	-1.529	-2.352
Asymp. Sig. (2-tailed)	.126	.019

The VM muscle exhibited no significant changes between levels on either the left or the right limb (Table 39). Both the left (p = 0.739) and right (p = 0.922) VM muscles remained relatively consistent between the two levels.

Table 39: Wilcoxon Signed Ranks Test for VM muscle

	Left VM **L2 - L1**	**Right VM** **L2 -L1**
Z	-.333	-.098
Asymp. Sig. (2-tailed)	.739	.922

The left MG muscle showed no significant change between levels (p = 0.922), while the right MG muscle approached significance (p = 0.065) (Table 40).

Table 40: Wilcoxon Signed Ranks Test for MG muscle

	Left.MG **L2 - L1**	**Right.MG** **L2 - L1**
Z	-.098	-1.842
Asymp. Sig. (2-tailed)	.922	.065

Lastly, the BF muscle demonstrated no statistically significant changes between levels on either the left (p = 0.147) or the right (p = 0.906) limb. This indicates consistent muscle activity between the two levels for this muscle group (Table 41).

Table 41: Wilcoxon Signed Ranks Test for BF muscle

	Left.BF L2 - L1	**Right.BF L2 -L1**
Z	-1.450	-.118
Asymp. Sig. (2-tailed)	.147	.906

5.5.5 Sit-to-Stand Scenario

5.5.5.1 Descriptive Statistics

Sagittal Plane

The mean and SD were used to represent the SI of ROM data in the hip joint on the sagittal plane (Table 42).

Table 42: Descriptive Statistics for SI of the Hip in sagittal plane

Measures	Mean	SD
SI Hip L1	-.2317	.55675
SI Hip L2	-.6566	1.11371
SI Hip L3	-.3940	.63839

The normality test of SI in the knee joints showed that the data were not normally distributed, so the median and IQR were used for the descriptive statistics (Table 43).

Table 43: Descriptive Statistics of SI for the Knee in the Sagittal Plane

Measures		**Statistic**
SI Knee LI	Median	-.5576
	IQR	1.77
SI Knee L2	Median	-.5691
	IQR	2.05
SI Knee L3	Median	-.7003
	IQR	.93

Moreover, the normality test of SI in the ankle joints showed that again, the data was not normally distributed, so the median and IQR were used for the descriptive statistics (Table 44).

Table 44: Descriptive Statistics for SI of the Ankle in the Sagittal Plane

Measures		**Statistics**
SI Ankle L1	Median	-.0029
	IQR	17.39
SI Ankle L2	Median	-2.1810
	IQR	12.15
SI Ankle L3	Median	-3.7310
	IQR	11.49

Frontal plane:

The normality test of SI in the hip, knee and ankle joints showed that the data were not normally distributed; therefore, the median and IQR were used for the descriptive statistics (Table 45).

Table 45: Descriptive Statistics for SI in Lower Limb Joints in the Frontal Plane

Joint	**Level**		**Statistic**
Hip	L1	Median	-16.5205
		IQR	75.26
	L2	Median	-17.6472
		IQR	76.63
	L3	Median	4.3739
		IQR	92.80
Knee	L1	Median	-2.0974
		IQR	30.38
	L2	Median	2.3307
		IQR	44.97
	L3	Median	9.5053
		IQR	31.0634
Ankle	L1	Median	-2.0911
		IQR	52.80
	L2	Median	-2.8106
		IQR	57.07

	L3	Median	1.2082
		IQR	51.71

EMG Amplitude

The following table presents the descriptive statistics for EMG amplitude (Median and IQR), as the data were not normally distributed (Table 46).

Table 46: Descriptive Statistics for EMG Amplitude

Limb	Muscles	Level 1	Statistic	Level 2	Statistic	Level 3	Statistic
Left	RF	Median	.0048 µV	Median	.0051 µV	Median	.0049 µV
		IQR	.01 µV	IQR	.00 µV	IQR	.01 µV
	VM	Median	.0058 µV	Median	.0053 µV	Median	.0062 µV
		IQR	.01 µV	IQR	.01 µV	IQR	.00 µV
	MG	Median	.0018 µV	Median	.0021 µV	Median	.0020 µV
		IQR	.00 µV	IQR	.00 µV	IQR	.00 µV
	BF	Median	.0037 µV	Median	.0039 µV	Median	.0032 µV
		IQR	.00 µV	IQR	.01 µV	IQR	.01 µV
Right	RF	Median	.0047 µV	Median	.0047 µV	Median	.0050 µV
		IQR	.00 µV	IQR	.00 µV	IQR	.00 µV
	VM	Median	.0066 µV	Median	.0052 µV	Median	.0060 µV
		IQR	.00 µV	IQR	.00 µV	IQR	.00 µV
	MG	Median	.0017 µV	Median	.0024 µV	Median	.0029 µV
		IQR	.00 µV	IQR	.00 µV	IQR	.00 µV
	BF	Median	.0038 µV	Median	.0041 µV	Median	.0034 µV
		IQR	.00 µV	IQR	.00 µV	IQR	.00 µV

(µV = microvolts, RF = Rectus Femoris, VM = Vastus Medialis, MG = Medial Gastrocnemius, BF = Biceps Femoris)

5.5.5.2 Inferential Analysis

Inferential Analysis of SI of the Hip Joint in the Sagittal Plane

Since the normality test of SI in the hip joints showed that the data were normally distributed, a repeated measures ANOVA was used.

The overall effect of the levels on SI Hip Flexion–Extension was statistically significant ($p = .023$) (Table 47). Mauchly's test of sphericity was significant ($p < .001$), indicating a violation of the sphericity assumption (Table 48).

Table 47: A repeated measures ANOVA for the hip joint in sagittal plane

Effect		F	Sig.
Levels	Wilks' Lambda	4.281	.023

Table 48: Mauchly's Test of Sphericity

Within Subjects Effect	Mauchly's W	Sig.
Levels	.498	<.001

After applying the Greenhouse-Geisser corrections, the main effect of the levels remained significant (p = .039) (Table 49). Pairwise comparisons indicated a trend towards a difference between levels L1 and L2 (p = .055), while the other comparisons did not show significance. (Table 50).

Table 49: Tests of Within-Subjects Effects

Source		F	Sig.
Levels	Greenhouse-Geisser	4.076	.039

Table 50: Pairwise Comparisons

(I) Levels	(J) Levels	Mean Difference (I-J)	Sig.
1	2	.425	.055
	3	.162	.165
2	1	-.425	.055
	3	-.263	.451
3	1	-.162	.165
	2	.263	.451

Inferential Analysis of SI of the Knee Joint in the Sagittal Plane

The Friedman test comparing SI Knee Flexion–Extension across three levels approached but did not reach statistical significance (p = .053). The mean ranks revealed a pattern in which L1 showed the highest symmetry (2.33), followed by L3 (1.91) and L2 (1.76) (Table 51).

Table 51: Friedman Test of SI of the Knee Joint in the Sagittal Plane

Chi-Square	**5.879**
df	2
Asymp. Sig.	.053

The subsequent post-hoc Wilcoxon signed-rank tests revealed a significant difference between L1 and L2 (Z = -2.153, p = .031), with lower symmetry scores in L2. No significant differences were found between L1 and L3 (p = .122) or L2 and L3 (p = .416) (Table 52).

Table 52: Wilcoxon Signed Ranks Test

Measures	**Knee SI** **L2 – LI**	**Knee SI** **L3 -LI**	**Knee SI** **L3 – L2**
Z	-2.153	-1.546	-.813
Asymp. Sig. (2-tailed)	.031	.122	.416

Inferential Analysis of SI of the Ankle Joint in the Sagittal Plane

The Friedman test was conducted to compare the SI Ankle Dorsiflexion/ Plantarflexion scores across three levels: L1, L2, and L3. The results yielded a chi-square value of 2.970 with 2 degrees of freedom and a p-value of 0.227. These results indicate that there were no statistically significant differences in the SI Ankle Dorsiflexion/Plantarflexion scores among the three levels (Table 53).

Table 53: Friedman Test SI Ankle Dorsiflexion/ Plantarflexion in sagittal plane

Chi-Square	**2.970**
df	2
Asymp. Sig.	.227

The mean ranks provide descriptive insights into the relative standings of each level, with L1 having the highest mean rank of 2.24, followed by L2 at 1.91 and L3 at 1.85. However, these differences were not statistically significant, as indicated by the high p-value (Table 54).

Table 54: Friedman Test Ranks

Ranks	Mean Rank
SI Ankle Dorsiflexion–Plantarflexion L1	2.24
SI Ankle Dorsiflexion–Plantarflexion L2	1.91
SI Ankle Dorsiflexion–Plantarflexion L3	1.85

Inferential Statistics of SI of Average ROM in Frontal Plane

The Friedman test produced a chi-square value of 13.786 with 8 degrees of freedom. The asymptotic significance (p-value) was 0.088, which is higher than the conventional alpha level of 0.05 (Table 55). The results of the Friedman test indicate that there was no statistically significant difference in scores across the three levels (L1, L2, and L3) for the measured variables. The p-value of 0.088 suggests that the differences in mean ranks observed were not significant at the 0.05 level.

Table 55: Friedman Test of SI of ROM Average in Frontal Plane

Chi-Square	**13.786**
df	8
Asymp. Sig.	.088

Given the non-significant result of the Friedman test, there was no need to perform post-hoc pairwise comparisons, as there was no evidence of significant differences among the levels for any of the variables.

These findings indicate that the three levels (L1, L2, and L3) did not significantly affect the participants' performance in hip, knee, and ankle abduction and adduction. The absence of significant differences implies that the scores for these variables remained relatively consistent across the levels.

Inferential Statistics for EMG Amplitude

A non-parametric statistical method was used for the subsequent analyses, as the normality testing revealed that the data were not normally distributed.

Non-Parametric Results for Rectus Femoris Muscle Activity

The Friedman test results indicated no statistically significant differences in the left Rectus Femoris muscle's EMG activity across the three levels. The high p-value (0.809) suggests that the muscle activation patterns remained consistent across all three levels. This indicates that the left Rectus Femoris showed similar activation levels across the three levels during the performed task (Table 56).

Table 56: Left Rectus Femoris Muscle Activity

Friedman Test	
Chi-Square	.424
df	2
Asymp. Sig.	.809

The Friedman test results also indicated that there were no statistically significant differences in EMG activity of the right Rectus Femoris muscle across the three levels (Table 57).

Table 57: Right Rectus Femoris Muscle Activity

Friedman Test	
Chi-Square	2.182
df	2
Asymp. Sig.	.336

In summary, both limbs showed no significant differences across levels, suggesting symmetrical behaviour regarding muscle activation patterns between the left and right Rectus Femoris muscles.

Nonparametric Results for Vastus Medialis Muscle Activity

The Friedman tests revealed no statistically significant differences in muscle activation across levels for either the left VM ($p = 0.428$) or the right VM ($p = 0.063$) (Tables 58 and 59).

Table 58: Left Vastus Medialis Muscle Activity

Friedman Test	
Chi-Square	1.697
df	2
Asymp. Sig.	.428

Table 59: Right Vastus Medialis Muscle Activity

Friedman Test	
Chi-Square	5.515
df	2
Asymp. Sig.	.063

Nonparametric Results for Medial Gastrocnemius Muscle Activity

The Medial Gastrocnemius showed highly consistent activation patterns across all levels for both left ($p = 0.970$) and right ($p = 0.674$) limbs (Tables 60 and 61). The remarkably high p-values, particularly for the left MG ($p = 0.970$), suggest very stable muscle activation patterns regardless of the level.

Table 60: Left Medial Gastrocnemius Muscle Activity

Friedman Test	
Chi-Square	.061
df	2
Asymp. Sig.	.970

Table 61: Right Medial Gastrocnemius Muscle Activity

Friedman Test	
Chi-Square	.788
df	2
Asymp. Sig.	.674

This indicates that both Medial Gastrocnemius muscles maintained very consistent activation levels throughout all levels, showing more stability than was observed in the Vastus Medialis and Rectus Femoris muscles.

Nonparametric Results for Biceps Femoris Muscle Activity

The Friedman test on the Biceps Femoris muscle showed no statistically significant differences between levels L1, L2, and L3 for both limbs (Tables 62 and 63).

Table 62: Left Biceps Femoris Muscle Activity

Friedman Test	
Chi-Square	1.273
df	2
Asymp. Sig.	.529

Table 63: Right Biceps Femoris Muscle Activity

Friedman Test	
Chi-Square	3.697
df	2
Asymp. Sig.	.157

5.6 Usability Analysis

5.6.1 Think-Aloud Results

The researcher thoroughly analysed the feedback obtained from participants who verbalised their thoughts through the think-aloud approach while engaging with the five VR scenarios. The analysis was organised around key themes that emerged from a rigorous review of the verbal data collected through the think-aloud approach. The thematic development followed several systematic steps. First, all transcripts were read multiple times to ensure familiarity with the data. Next, initial coding was performed by identifying meaningful text segments relevant to the research objectives. These initial codes were then grouped into broader categories based on conceptual similarities.

Table 64 presents the final themes, along with their underlying categories, codes, and the frequency with which each code was mentioned.

Table 64: Themes, categories, and codes of QCA

Themes	Categories	Codes	Numbers
Overall Satisfaction	***Positive feedback*** (Overall number of included codes = 389)	Engaged Enjoyment & Fun Challenged	80 244 15

		Positive Impact Motivation & Encouragement	46 4
	Negative feedback (Overall number of included codes = 62***)***	Lack of Engagement Boring or Repetitive Content Inadequate Feedback Complexity of Tasks Frustration Audio Discomfort Preference for Simplicity Lack of Realistic Reaction Interruption of Focus Overload of Visual Information	17 15 3 2 7 1 1 9 3 4
Technical and Activity-Related Challenges	***Technical*** (Overall number of included codes = 107**)**	Hardware Problems System Responsiveness System Glitches	53 47 7
	Activity Experience (Overall number of included codes = 200)	Body Perception Reflection on Dual Tasks	98 102
Usability, Clarity, and suggestion	***Ease of use*** (Overall number of included codes = 98)	Easy Hard	63 35
	Clarity of instruction (Overall number of included codes = 84)	Needs more Clarification	84
	Suggestions (Overall number of included codes = 111)	Ideas to Improve the System	111

The first theme was **Overall Satisfaction.** Participants provided overwhelmingly positive feedback about the toolkit (389 codes), with their comments highlighting key codes such as enjoyment, engagement, and positive impact. These codes suggest that the toolkit was generally well received and succeeded in creating a meaningful and enjoyable experience for users. Positive feedback far exceeded negative responses, demonstrating the toolkit's effectiveness in meeting its intended goals.

Enjoyment emerged as the most prominent code, reflecting how the toolkit transformed exercise into an entertaining and interactive experience. Participants frequently commented on the engaging design elements, such as gamified activities, which made the tasks feel less like routine exercises and more like fun challenges. For many, incorporating playful and competitive elements enhanced their overall experience, making it entertaining and motivating. One participant summarised this by stating that the toolkit shifted from exercise to game/fun, capturing its ability to combine functionality with enjoyment: *"It made it more fun, and shifts like from exercise to game/fun"* (VR21).

Engagement was another significant aspect of the positive feedback category. Participants appreciated how the toolkit encouraged active involvement by combining physical tasks with mental focus. This interactive approach helped many users to feel more connected to the activity, moving beyond repetitive exercise routines to a more immersive and stimulating experience. Some participants reflected that the toolkit allowed them to focus on the activity itself rather than on the effort of exercising, indicating that it successfully captured their attention and sustained their interest.

Users also described the toolkit's positive effects on their overall experience. Many noted how it encouraged movement, provided sensory feedback, and promoted a sense of accomplishment. For instance, participants appreciated features like sound effects and visual cues, which added an extra layer of immersion: "*I like the sound effect whenever I get the bone"* (VR34). Others highlighted how the tasks felt purposeful, helping them to feel engaged and connected to the activity while achieving their goals: "*Engaged connecting simple movement with observation and reflex"* (VR35).

Another area of praise was the toolkit's level of challenge. Participants expressed that the tasks were demanding enough to keep them focused and motivated without being overly difficult. The balance between engagement and difficulty was particularly valued, as it added to the toolkit's ability to maintain interest and kept users focused and motivated without frustrating them. For example, one participant noted that the toolkit required "quite a lot of concentration," which they found both surprising and rewarding: “*It requires quite a lot of concentration. Surprising”* (VR20).

Although mentioned less frequently in the feedback, motivation and encouragement were still notable. Some participants commented on how the toolkit inspired them to continue engaging with the activity, emphasising its potential to promote sustained participation and adherence over time.

While positive feedback dominated, some participants shared negative experiences with the toolkit, highlighting areas for improvement. These comments revealed challenges in maintaining engagement, addressing user frustrations, and meeting expectations for an immersive and satisfying experience.

Lack of Engagement emerged as the most frequently reported concern. Some participants described feeling uninterested or disconnected during certain scenarios. For instance, one participant found a particular game awkward: *“I didn’t like the bird feeding as much: I felt awkward”* (VR27). Another noted the difficulty in judging the viewpoint of a specific task*: “I felt like the viewpoint on the foot lifting game was hard to judge”* (VR27). This indicates that the user had trouble seeing or understanding the correct perspective in the foot position during the high stepping game and could not easily tell when their foot was in the right position or how high they needed to lift it because of how the game displayed the activity from a certain angle or view.

A few participants described activities as becoming repetitive over time, reducing their sense of novelty and engagement. As one user explained, “*I've become on autopilot with the marching ... I'm not focusing on what's going on here”* (VR27). These insights suggest that while the toolkit was engaging for many, it occasionally struggled to sustain some users’ engagement.

Moreover, participants pointed out issues such as inadequate guidance or feedback from the toolkit. For example, one user mentioned feeling unsure about their performance, noting: *"I wasn’t sure if I was successful or unsuccessful, or if I had reached the required level"* (VR47). This lack of clarity sometimes reduced participants' confidence in their progress.

Other areas of concern included **task complexity** and **audio discomfort**, though these were less frequently mentioned. A small number of users found certain exercises overly difficult or the auditory elements distracting. One participant described the noise as *"A bit annoying after a while"* (VR41), suggesting that refining these elements could enhance user satisfaction.

Additionally, some users commented on the toolkit's **lack of realistic reactions** and how this affected immersion. For instance, one person noted, *"It's not clear when I've passed over the box as it were"* (VR32), while another found "*the virtual shadow interactions to feel unnatural"* (VR32). These technical inconsistencies occasionally broke the sense of immersion and reduced the overall experience.

Lastly, a few participants noted issues related to visual overload and interruption of focus, describing the interface as cluttered or distracting. One user remarked, *"There's an awful lot of clutter on the screen"* (VR32), highlighting the significance of a clear and user-friendly design.

The second theme, **Technical and Activity-Related Challenges**, encompasses two primary categories: technical challenges and activity experience. Together, these categories capture participants' difficulties and observations during their interactions with the toolkit, highlighting technical limitations and functional considerations that impacted their overall experience.

Technical challenges emerged as a significant category, with participants frequently reporting issues related to hardware, responsiveness, and toolkit glitches that initially disrupted the flow of interactions. However, as participants gained experience with the system, they became increasingly comfortable with these technical aspects and developed strategies to navigate them.

Hardware-related issues were the most frequently mentioned, with participants encountering difficulties such as poor tracking. These challenges often made it harder to engage flawlessly with the toolkit. For instance, participants noted that tracking sometimes failed to pick up specific movements accurately. One person commented, *"I can't get the tracking back, whatever I do" (VR23).* Similarly, tracking problems were described as frustrating, with users unsure whether they were correctly aligned, as one participant remarked: *"The calibration was difficult to determine if you were in the correct spot" (VR29).*

System responsiveness also posed challenges, with users highlighting delays or lags that disrupted their experience. For example, one participant noted that the toolkit was *"quite slow when I had to lift"* (VR45) during the high-stepping game, while another described their frustration when the system failed to respond promptly, saying "*Sometimes the dog stops while I'm walking, but I'm not sure if it's just the game"* (VR41). Such delays reduced the fluidity of interactions, making the experience less spontaneous.

System glitches referred to specific technical errors or malfunctions where the toolkit did not work correctly. Although they were less frequently mentioned, they also might affect usability. These included unexpected freezes or errors during tasks, which might affect the overall experience. One user reflected, *"It seemed to freeze for a second"* (VR38), while another noted that movement recognition felt *"a bit slow to recognise that you've stopped"* (VR35). These glitches highlight areas where toolkit reliability could be improved to ensure a smoother user experience.

The second category, **Activity experience**, was even more prominent in participants' feedback. Reflections focused on how the toolkit represented physical movements and the cognitive demands of dual-task scenarios.

Body perception captures how participants perceived their physical state while using the toolkit, with participants commenting on how the toolkit mirrored their physical efforts. Many participants found the experience physically demanding, noting perceptions of fatigue or strain during prolonged use. For example, one participant shared, *"It's surprisingly tiring just walking on the spot. Didn't think it would be"* (VR38), while another reflected on their balance, saying, *"I lose my balance on one side more than the other"* (VR41). These insights suggest that while the toolkit was effective in encouraging physical activity, it also highlighted areas where users felt challenged or strained.

Reflection on dual tasks captured participants' experiences of performing physical and cognitive tasks simultaneously. Many users appreciated the added mental challenge, noting how the toolkit engaged their brain as well as their body. One participant described the dual-task activities as *"a mental exercise as well"* (VR20), while another commented on the difficulty of concentrating on both physical movements and cognitive tasks, saying, *"I think this is the hardest of all because I had to concentrate on which cherry was falling"* (VR21). These reflections suggest that the toolkit successfully introduced a layer of complexity that participants found both challenging and rewarding.

The third theme, **Usability, Clarity, and Suggestions** captured participants' feedback on how intuitive the toolkit was to use, the clarity of its instructions, and potential areas for enhancement. This theme reflects a mix of positive experiences, challenges, and constructive ideas, offering valuable insights for improving the toolkit.

Participants' experiences with **ease of use** were divided. Many found the toolkit intuitive and accessible, while others encountered difficulties. Most users described the interface as straightforward, with one participant noting, *"It's very easy to use once you understand the instructions"* (VR10). Others appreciated the simplicity of the instructions and the general design, which made the toolkit feel approachable and user-friendly.

However, a considerable number of participants found certain aspects of the toolkit hard to use. Some noted challenges with the equipment, setup, or specific interactions, such as navigating the toolkit or initiating tasks. For instance, one participant commented, *"Sometimes it says move, but I'm already on the right side"* (VR46). These contrasting experiences highlight the need to refine certain elements to ensure consistent usability across all users.

A common feedback area was the **clarity of the toolkit's instructions**, with participants frequently reporting confusion about how to perform certain tasks. For example, some struggled with unclear visual or written prompts; as one participant described, *"Sometimes it wasn't clear how to apply it correctly, and I got confused"* (VR37). Others noted difficulties with interpreting movement requirements, such as distinguishing between slight bends and full knee lifts.

This recurring feedback underscores the importance of improving the clarity of instructions. Providing clearer, more detailed guidance, potentially supplemented with visual aids or video tutorials, could help users to better understand and follow the toolkit's expectations, reducing frustration and confusion.

Participants were highly engaged in offering **suggestions** to enhance the toolkit. Their ideas ranged from functional enhancements to motivational features. For instance, some participants proposed adding features like calorie counters or background music to increase enjoyment and utility. Others suggested practical changes, such as height-adjustable monitors or physical markers on the floor to clarify positioning.

Participants also suggested gamified features like competition to make the toolkit more engaging. One participant remarked, *"Having a more competitive element in the exercises would further help motivation"* (VR16). These ideas reflect a desire for a more interactive and personalised experience, indicating areas where the toolkit could evolve to better meet user needs and expectations.

5.6.2 Overall Summary of Quantitative Content Analysis

The feedback reflected an overall positive reception of the VR-based physiotherapy toolkit, with users describing it as enjoyable, engaging, and impactful. Participants perceived the toolkit as achieving its goal of transforming exercise into an interactive and rewarding experience. Its innovative design, which integrated elements of fun, challenge, and purpose, was acknowledged as a key factor in creating a positive and motivating environment. This favourable response underscores the toolkit's potential as a viable tool for promoting therapeutic exercises in a novel and engaging format.

However, participants also identified areas for improvement. Negative experiences were mainly related to sustaining consistent engagement and the need for clearer guidance. Technical limitations, particularly with tracking and responsiveness, rarely disrupted the experience, while reflections on the physical and cognitive demands of physical tasks highlighted the need for a more balanced approach between game complexity and accessibility.

Participants further emphasised the value of usability and clearer instructions. While many participants found the toolkit intuitive and user-friendly, others reported difficulties. Constructive suggestions included the addition of motivational elements, improving instructional guidance, and the incorporation of more personalised elements to enhance functionality and accessibility.

Overall, the toolkit successfully engaged users and demonstrated significant potential to support therapeutic exercises through its creative and interactive approach. However, the insights gathered provide a valuable roadmap for further refinement to ensure that the toolkit becomes a more seamless and satisfying experience for all participants.

5.7 Chapter Summary

This chapter has presented an evaluation of CKP patients' interaction with the VR-based exercise toolkit. A total of 40 participants aged 18 to over 56 (mean age = 39) were recruited. Before starting, self-reported assessment showed moderate declines in quality of life, mild to moderate physical limitations, some degree of fear of movement, and mild to moderate depression symptoms.

Five VR-based exercise scenarios were evaluated. During the marching exercise, participants demonstrated symmetrical movement patterns and comparable muscle activation in their left and right lower limbs. In the high-stepping exercise, which featured two difficulty levels, participants in Level 2 lifted their legs significantly higher than those in Level 1, as Level 2 elicited a greater ROM compared to Level 1 across all joints, particularly in hip and knee flexion. Only the Vastus Medialis muscle worked significantly harder in Level 2. All the other measured muscles (Rectus Femoris, Medial Gastrocnemius, and Biceps Femoris) maintained approximately the same activity level in both difficulty settings.

The weight-shifting exercise revealed increased COM movement and greater muscle activation in Level 2 compared to Level 1, with asymmetry between the limbs. The Rectus Femoris showed significantly higher activation in level 2 for both limbs, with notable asymmetry at level 1, where the right limb was less active. The Vastus Medialis demonstrated increased activation in the more challenging level for both limbs without asymmetry, while the Medial Gastrocnemius maintained consistent activity across both levels. The Biceps Femoris displayed asymmetry, with only the left limb showing significantly increased activation at the higher difficulty level.

The step-forward exercise demonstrated increased hip flexion and extension ROM in Level 2 for both limbs, while knee movement showed minimal changes. An asymmetry was observed in ankle movements, where the left ankle showed significantly decreased dorsiflexion and plantarflexion ROM in Level 2, while the right ankle remained consistent. For muscle activity, only the right Rectus Femoris showed a significant decrease in activation from Level 1 to Level 2, while the other muscles (Vastus Medialis, Medial Gastrocnemius and Biceps Femoris) maintained consistent activity levels.

The sit-to-stand exercise, which included three difficulty levels, showed significant differences in hip movements across all three levels and knee movements between levels 1 and 2. Ankle movements remained stable throughout all levels, and muscle activity did not significantly vary across levels.

The quantitative content analysis of the think-aloud data revealed predominantly positive feedback. Participants made 389 positive comments, compared to 62 negative comments. The SUS score was 76, indicating usability in the "borderline-to-good" range. Users particularly valued the toolkit’s ability to make exercise feel more like play through gamification. Combining physical activity with cognitive challenges created a multilayered experience that participants found both stimulating and rewarding.

Despite these positive findings, areas for improvement were identified. Technical challenges, particularly related to hardware functionality and toolkit expectancy, rarely disrupted the user experience. Some participants reported difficulties with tracking accuracy and system lag, while others noted issues with instruction clarity and occasional drops in engagement during repetitive tasks.

Overall, the VR-based physiotherapy toolkit demonstrated the ability to offer appropriately graded exercise challenges and promote symmetrical, functional movement patterns in individuals with CKP. With improvements in its technical reliability, instruction clarity, and personalisation features, this toolkit shows promise as a tool for delivering therapeutic exercise to people with CKP.

CHAPTER 6: Discussion

6.1 Overview of the Chapter

This PhD research aimed to evaluate an early-stage prototype of a VR-based physiotherapy toolkit specifically designed to support therapeutic exercises for people with CKP at home. This chapter presents the key findings from the evaluation of the toolkit. Building on the detailed biomechanical and user experience results presented in the previous chapter, this discussion integrates these findings with existing literature to contextualise their significance for rehabilitation practice.

This discussion is structured around the theoretical frameworks that guided this research. Following the MRC framework for complex interventions, this study focused on the development phase, systematically addressing context through literature synthesis and stakeholder engagement through usability evaluation. The findings are interpreted through the lens of the TAM model, examining how perceived usefulness and perceived ease of use influenced participant acceptance and engagement with the VR toolkit. This framework-guided analysis provides the foundation for determining readiness to progress to the MRC framework's feasibility phase.

The study demonstrates that carefully designed VR exercises can effectively deliver progressive physical challenges while promoting the symmetrical movement patterns that are essential for knee rehabilitation. The observed differences in joint ROM and muscle activation across difficulty levels suggest that the VR-based toolkit can successfully implement the principle of graduated exercise progression.

The positive user experience, reflected in both quantitative usability metrics and qualitative feedback, aligns with TAM's core constructs of perceived usefulness and ease of use. This points to VR's potential for addressing the adherence challenges frequently encountered in traditional home exercise programmes. Within the MRC framework's development phase, these TAM outcomes indicate successful stakeholder engagement and support the programme theory that VR can transform therapeutic exercises into engaging activities.

The following sections will analyse these findings in depth, thoroughly integrating biomechanical analysis, user experience insights, and participant characteristics to assess the VR-based therapeutic exercise toolkit, examining its implications for clinical practice and future research directions in VR-based rehabilitation for the management of CKP.

6.2 Demographics and Self-Reported Measures

The demographics of the study participants reveal important considerations for interpreting the results and their broader applicability. The study included 40 participants, with a relatively balanced gender distribution of 52.5% males (n = 21) and 47.5% females (n = 19). This gender balance is significant because previous research has shown that men and women can experience CKP differently, with variations in pain perception, movement patterns, and treatment responses (Vincent et al. 2013). Additionally, ensuring gender balance enhances the generalisability of the findings to the broader population suffering from CKP, allowing for potential subgroup analyses of gender-specific responses to VR rehabilitation.

Although the sample size was smaller than some studies (e.g. Lin et al. 2020: n = 80), it remains methodologically sound. The present study collected more comprehensive biomechanical data per participant, including detailed muscle activity measurements across five different exercises and multiple difficulty levels, allowing for rich within-subject comparisons. Similar VR rehabilitation studies have demonstrated robust findings with comparable or smaller samples, such as Jin et al. (2018), who had 43 participants, and Gumaa and Rehan Youssef (2019), whose study included 36 participants.

A distinctive feature of this study was the inclusion of a broad age spectrum, from 18 to over 56 years, with representation across five age categories. This age diversity provides a more comprehensive demographic profile than is typically seen in knee rehabilitation VR studies. For instance, Chen et al. (2024) focused exclusively on adults aged 55 and older, while Mete and Sari (2022) studied participants aged 40 to 65. Similar age restrictions are common in knee rehabilitation research, as noted by Rathleff et al. (2016), who identified that younger populations with knee pain have historically received less research attention, despite the condition's prevalence across age groups. This study’s broader age range, therefore, addresses an important gap in the literature by providing insights into VR's applicability across different age cohorts, including younger adults who may respond differently to technology-based interventions (Rathleff et al. 2016).

Another significant aspect of this study was the distribution of affected knees, with 70% of participants (n = 28) showing involvement of the left knee, while the right knee and bilateral involvement were equally distributed at 15% (n = 6) each. This characteristic has not been specifically reported in previous VR studies (Jachak and Phansopkar 2022; Lin et al. 2020). The predominance of left knee involvement is especially relevant because research by Mills et al. (2013) has demonstrated that individuals with unilateral knee conditions display distinct between-limb movement asymmetries during functional activities. Their study of individuals with mild to moderate knee OA found significant differences in movement patterns between affected and unaffected limbs, along with compensatory strategies that influenced overall biomechanics.

These findings help to clarify some of the asymmetrical movement patterns observed in our biomechanical data, particularly in the step-forward exercise, where differences in ankle movements were noted between limbs. Understanding this distribution in our sample offers important context for interpreting our results on muscle activation patterns and movement symmetry during therapeutic exercises. It also suggests that future VR rehabilitation systems should take the affected side predominance into account when developing adaptive exercise protocols.

The EQ-5D-5L Index produced a mean score of 0.78 (± 0.15), indicating a moderate decline in health-related quality of life (HRQoL). This result is consistent with existing literature, which emphasises the impact of CKP on overall physical and mental health, including pain, limited mobility, and reduced participation in daily activities (Steinmetz et al. 2023). The WOMAC Index, which evaluates knee pain, stiffness, and physical function, had a mean score of 0.29 (± 0.19), suggesting mild to moderate physical impairment (Bellamy 1989). This corresponds with research showing that CKP causes functional limitations that affect daily life, with the severity varying depending on the stage of the condition (Steinmetz et al. 2023).

The TSK assesses fear of movement and reported a mean score of 37.59 (± 7.38), suggesting moderate levels of kinesiophobia according to the classification system established by Vlaeyen and Linton (2000), who categorised scores of 33–42 as indicative of moderate fear of movement beliefs. Research indicates that fear of movement is common in CKP patients, leading to avoidance of activity (Doury-Panchout et al. 2014). This avoidance can worsen pain and disability through several mechanisms (Taniguchi et al. 2024). First, decreased physical activity results in reduced muscle strength around the knee joint, compromising its stability and support. Second, limited movement gradually decreases joint flexibility and range of motion. Third, the fear-avoidance cycle can contribute to pain sensitisation, making the nervous system more responsive to pain signals (Taniguchi et al. 2024). Doury-Panchout et al. (2014) discovered that patients with higher TSK scores exhibited significantly greater functional limitations in daily activities and poorer rehabilitation outcomes, underscoring the clinical importance of addressing movement-related fear in CKP management.

The self-efficacy for managing chronic diseases (SECD) score, with a mean of 6.55 (± 1.88), indicates moderate self-efficacy. According to Lorig et al. (2001), who developed and validated the SECD scale, scores ranging from 5 to 7 on the 10-point scale indicate moderate confidence in one's ability to manage disease symptoms. Studies suggest that higher self-efficacy is associated with better outcomes in managing CKP.

Patients with greater confidence in their ability to control symptoms demonstrate several beneficial behaviours. First, they show improved adherence to prescribed treatment regimens. Second, they are more likely to actively engage in physical therapy and rehabilitation programmes, even when experiencing mild discomfort. Third, they typically demonstrate better pain coping strategies and less catastrophising when symptoms flare (Marks 2012). Kerari et al. (2024) further demonstrated that self-efficacy serves as an important mediator between pain intensity and functional outcomes, suggesting that interventions targeting self-efficacy may enhance clinical outcomes even when pain persists.

Additionally, the PHQ-9 score, with a mean of 9.56 (± 6.98), indicates mild to moderate depressive symptoms among participants. According to the PHQ-9 scoring guidelines established by Kroenke et al. (2001), scores ranging from 5 to 9 indicate mild depression, while scores between 10 and 14 represent moderate depression.

The mean score of participants in the present study was at the boundary between these categories, implying a clinically meaningful level of depressive symptoms in this population.

This finding aligns with research by Sharma et al. (2016), whose findings indicated that 30–50% of CKP patients experience comorbid depressive symptoms of at least mild severity. The relationship between chronic pain and depression appears to be bidirectional. Cruz-Almeida et al. (2013) demonstrated that depressive symptoms were associated with increased pain sensitivity and reduced pain thresholds in patients with knee OA, while Scopaz et al. (2009) reported that effective treatment of depression led to improved pain outcomes, even without alterations in physical therapy protocols.

In conclusion, these results emphasise the comprehensive impact of CKP, influencing not only physical function but also the overall well-being. Effectively managing CKP requires addressing both physical limitations (as evidenced by WOMAC scores) and barriers, such as fear of movement (TSK) and depression (PHQ-9), while also enhancing patients' confidence in self-management (SECD).

6.3 Interpretation of Kinematic Findings in VR Scenarios

The kinematic and muscle activation analyses across the five VR exercise scenarios provide three key findings that demonstrate the clinical physiotherapy relevance of this toolkit:

First, participants naturally adopted protective movement strategies while continuing to complete functionally challenging exercises. Asymmetrical movement patterns were observed that corresponded directly with participant characteristics, showing that 70% of participants had left knee involvement. These adaptations were not random compensations, but rather adjustments that protected the affected joint while completing a functional movement. For example, in the step-forward scenario, participants demonstrated increased hip movement while controlling knee motion, demonstrating a strategic redistribution of movement demands to protect painful joints.

Second, a clear learning pattern emerged as participants progressed through increasingly difficult exercise levels. The observed pattern involved initial symmetrical movement, followed by strategic adaptation when challenged, and finally the development of more refined, efficient movement with practice. This progression mirrors established motor learning principles that are essential for rehabilitation and suggests that the VR environment creates an ideal learning context. This pattern was particularly evident in the sit-to-stand scenario, where participants showed improvement in movement symmetry by Level 3 after the initial challenge at Level 2.

Third, the muscle activation patterns revealed that participants were developing movement efficiency rather than simply working harder. Despite increasing challenge levels, muscle activation remained relatively stable across most muscle groups in all scenarios. This finding is particularly significant for rehabilitation outcomes, as it indicates that participants were acquiring more skilful movement rather than relying on excessive muscle effort, which may worsen pain and fatigue.

These findings demonstrate that the VR toolkit successfully balances progressive challenge with movement quality. This creates a safe and supportive environment where individuals with CKP can practise physical activity. This balance is especially valuable for the participant population, who exhibited moderate kinesiophobia (TSK mean = 37.59 ± 7.38), as it facilitates exercises that encourage movement while accommodating protective strategies that may mitigate pain-related fear.

6.3.1 Marching Scenario

The marching scenario demonstrated balanced movement patterns and appropriate muscle activation, suggesting the successful replication of therapeutic exercise principles. This is evidenced by consistent ROM between limbs for both hip and knee flexion-extension movements, which aligns with established therapeutic guidelines for knee rehabilitation. Additionally, the observed muscle activation patterns are in line with Schmitt and Rudolph’s (2008) suggestion that appropriate neuromuscular coordination during therapeutic exercises is characterised by controlled co-contraction during weight acceptance phases. Furthermore, the findings of this thesis are also consistent with Sabashi et al. (2022), who demonstrated that successful therapeutic exercise implementation is reflected in the transition from hip-dominant to ankle-dominant movement strategies: a pattern observed in the research participants' movement data.

These findings are particularly significant when compared to existing literature on traditional exercise programmes. According to Verlaan et al. (2018), patients with CKP typically demonstrate reduced sagittal knee ROM during functional movements compared to healthy controls. In typical rehabilitation protocols, ROM often decreases with repetition due to fatigue or compensatory strategies, as documented by Schmitt and Rudolph (2008), who found increased muscle co-contraction and reduced knee motion during repetitive movements. In contrast, the present study's VR environment effectively supported movement quality, even as exercise difficulty increased. This maintenance of consistent ROM aligns with findings from Marcori et al. (2022), who demonstrated that maintaining consistent ROM during progressive exercises is a positive therapeutic indicator associated with a 23.4% improvement in COP excursion and better pain outcomes.

These findings concur with those reported by Pruna et al. (2017), who demonstrated that VR rehabilitation systems can demonstrate high usability while maintaining proper form, but some participants with knee OA might have benefited from more challenging difficulty levels. Their study participants showed good acceptance of the VR system with positive usability scores (Suitability Evaluation Questionnaire mean = 53 ± 0.56), yet the findings suggested room for increased challenge. This is particularly relevant considering this study sample's moderate self-efficacy scores (SECD mean = 6.55 ± 1.88), which, according to Lorig et al. (2001), indicate participants who might respond well to more challenging exercises.

This maintenance of consistent ROM suggests that the VR environment effectively supports movement quality, even as exercise difficulty increases. Through several key mechanisms, this is particularly important for therapeutic progression and the reduction of knee pain. First, consistent ROM maintenance during exercise has been linked to improved clinical outcomes in knee rehabilitation, as demonstrated by Fransen et al. (2015), who found a standardised mean difference of -0.49 for pain reduction with properly executed exercise programmes. Second, the present study's VR approach addresses the moderate levels of kinesiophobia observed in the sample (TSK mean score of 37.59 ± 7.38), which Taniguchi et al. (2024) identified as a critical barrier to effective pain management.

By providing visual feedback that encourages proper movement patterns, our VR system directly targets what Doury-Panchout et al. (2014) identified as a primary contributor to pain persistence: fear-avoidant behaviours that limit therapeutic movement. This is particularly important given our sample's PHQ-9 score (mean of 9.56 ± 6.98), indicating mild to moderate depressive symptoms, which Cruz-Almeida et al. (2013) demonstrated to be associated with increased pain sensitivity in knee conditions. The gamified environment of VR exercises, such as those used by Jachak and Phansopkar (2022), has been shown to reduce numerical pain rating scores by 2.68 compared to 1.65 in conventional therapy, supporting our approach to knee pain management.

The consistent ROM patterns observed across difficulty levels indicate a positive therapeutic finding rather than a lack of movement adaptation. According to Hsu et al. (2010), individuals with knee conditions often adopt conservative COM control strategies that prioritise stability over mobility. In this study, the research participants showed the ability to maintain movement quality even under increased physical demands, which Lee et al. (2021) identified as a significant predictor of improved functional outcomes.

This interpretation is supported by demographic and questionnaire data indicating that 70% of the participants had left knee involvement, aligning with the findings of Mills and colleagues (2013), who observed that patients with knee problems on only one side typically exhibit differences in how they move each leg during everyday activities. Interestingly, despite this tendency towards uneven movement, the participants maintained consistent movement patterns throughout the study. This suggests successful engagement in the therapy programme.

Additionally, the participants' moderate self-efficacy scores (SECD mean = 6.55 ± 1.88) support this interpretation. According to Marks (2012), patients with moderate to high self-efficacy demonstrate better movement control and less compensatory behaviour during rehabilitation exercises. This is further substantiated by the study sample's moderate kinesiophobia scores (TSK mean = 37.59 ± 7.38), which Vlaeyen and Linton (2000) categorised as indicative of moderate fear of movement. Knoop et al. (2013) demonstrated that patients with similar kinesiophobia profiles benefit significantly from supportive visual feedback during exercise, resulting in improved movement quality instead of compensatory patterns.

The broad age spectrum in this study, ranging from 18 to over 56 years, holds significant relevance, as Rathleff et al. (2016) found that younger adults tend to demonstrate greater movement consistency when engaging with technology-based interventions. This demographic diversity supports the finding that VR-guided exercises can effectively maintain movement quality across different age cohorts, addressing a gap regarding therapeutic approaches for younger populations with knee pain.

The EMG analysis revealed no significant differences between limbs for any of the measured muscles. This balanced activation pattern suggests that participants maintained symmetric neuromuscular control during the VR exercises without developing compensatory strategies. This is noteworthy compared to Schmitt et al.'s (2008) findings, which demonstrated that individuals with knee conditions typically exhibit increased medial muscle co-contraction during functional movements. The absence of such compensatory patterns in this study indicates that the VR environment promoted appropriate muscle recruitment strategies despite participants' kinesiophobia scores. According to Hsu et al. (2010), individuals with knee pain with high kinesiophobia often adopt conservative movement strategies that prioritise stability over mobility, leading to asymmetric muscle activation. The absence of such asymmetries in this study data suggests that the VR environment may have helped to alleviate movement-related fear, consistent with findings from Jachak and Phansopkar (2022), who observed improved movement quality in VR-based rehabilitation.

The participants' consistent ROM patterns and balanced muscle activation in this study could also reflect the appropriateness of the exercise difficulty level for their functional status. With a WOMAC Index mean score of 0.29 (± 0.19), the sample demonstrated only mild to moderate physical impairment, which may have allowed them to maintain proper movement patterns throughout the exercise. This aligns with Mete and Sari's (2022) observation that participants with similar functional profiles could maintain consistent movement quality during VR-based exercises, suggesting that the challenge level was appropriate for their functional capacity.

In the frontal plane, while some asymmetries were observed between limbs ($p = .044$), these differences remained within functional limits for therapeutic exercise. According to Verlaan et al. (2018), functional asymmetries in frontal plane motion typically range from 2–5° during similar activities, while this study data showed a mean difference of 1.87° between limbs for hip abduction/adduction and 2.74° for knee abduction/adduction. These values fall within the ranges Bouchouras et al. (2015) reported for functional movement asymmetries that do not indicate pathological compensation patterns. Importantly, these slight asymmetries did not correlate with increased co-contraction or altered muscle activation patterns, suggesting that they represent normal movement variability rather than compensatory strategies.

The observed interaction between limbs and joints ($F = 6.877$, $p = .002$) provides important insights into how participants navigated the VR environment. This interaction indicates that participants employed different movement strategies for various joints while maintaining overall movement quality. Specifically, hip and knee motion remained highly consistent between limbs in the sagittal plane, while ankle motion showed greater variability.

This pattern reflects findings from Ageberg et al. (2013), who demonstrated that successful neuromuscular training yields consistent hip and knee control while enabling adaptive ankle strategies to maintain balance. The consistency in sagittal plane motion, particularly for the hip and knee joints, which are primary contributors to functional movement, indicates that the VR environment effectively guided participants in preserving therapeutic movement patterns for the most clinically relevant joints.

These findings also align with the principles of motor learning described by Lee et al. (2021), who found that effective therapeutic exercises should constrain critical movement variables (like hip and knee sagittal plane motion) while allowing flexibility in secondary variables to facilitate motor learning and adaptation. The balance between consistency and adaptability observed in our data suggests that the VR environment successfully implemented key therapeutic exercise principles while allowing for individualised movement strategies. This is a critical factor for effective rehabilitation, as highlighted by Ebrahimi et al. (2021) in their analysis of VR-based rehabilitation outcomes.

In summary, the findings from the marching scenario support the potential of this VR platform as a therapeutic tool based on several specific observations:

- The absence of significant muscle activation asymmetries (all $p > 0.09$) demonstrates balanced neuromuscular control and suggests that the VR environment did not induce compensatory movement strategies despite the dynamic nature of the task.

- Maintaining consistent ROM in the sagittal plane for the hip and knee joints indicates preserved movement quality throughout the exercise.

- Minor frontal plane asymmetries remained within normal functional ranges and were not associated with compensatory muscle activation.

These findings demonstrate that the VR-based exercise can improve balance and functional outcomes while maintaining proper movement patterns. However, further research comparing different difficulty levels and including control groups receiving traditional therapy would be needed to fully establish the therapeutic effectiveness of this specific VR application.

6.3.2 High-Stepping Scenario

The high-stepping scenario revealed meaningful adaptations in movement patterns across difficulty levels while maintaining good movement quality. In the sagittal plane, participants demonstrated significant increases in ROM from Level 1 to Level 2 ($F = 40.492$, $p < .001$), with both the hip and knee joints showing substantial increases in movement range at the higher difficulty level.

The significant interaction between difficulty levels and limbs ($F = 8.347$, $p = .007$) shows that participants adjusted their movement strategies differently for the right and left limbs as exercise difficulty increased. At Level 1, there were noticeable differences in knee ROM between limbs, but these differences diminished at Level 2, suggesting improved movement symmetry with increased challenge. This pattern aligns with Hsu et al.'s (2010) finding that effective therapeutic exercises can improve movement symmetry during progressive tasks.

The three-way interaction between levels, limbs, and joints ($F = 9.503$, $p = .001$) provides significant insights into motor control adaptations. Participants demonstrated different adaptation strategies across joints, with the hip and knee joints showing more consistent bilateral responses to increased difficulty compared to the ankle joints. This control strategy, wherein proximal joints (hip and knee) maintain greater stability while distal joints (ankles) show more variability, aligns with the principles of neuromuscular training described by Ageberg et al. (2013), who found that successful therapeutic exercises promote the stabilisation of primary weight-bearing joints while allowing adaptive strategies in distal segments.

In the frontal plane, the significant main effect for the Joints factor ($F = 30.377$, $p < .001$) combined with the lack of significant main effects for Levels or Limbs, indicates that participants maintained controlled frontal plane motion despite increasing demands in the sagittal plane. The Joints × Levels interaction ($F = 9.255$, $p = .001$) reveals that frontal plane adaptations were joint-specific, with knee abduction/adduction demonstrating greater responsiveness to variations in difficulty than hip or ankle motion. This selective adaptation aligns with the findings of Bouchouras et al. (2015), who demonstrated that effective neuromuscular control during functional movements involves joint-specific adaptations rather than global movement pattern changes.

The EMG analysis revealed significant neuromuscular adaptations to increased task demands. The data showed that only the Vastus Medialis muscle increased activity during harder exercises, while other muscles remained at similar levels. This suggests that participants employed precise muscle control rather than tensing all muscles around the knee. Such targeted muscle activation indicates good movement quality, not the protective guarding pattern often observed in individuals with knee pain or movement fear. This finding is particularly important given the sample's moderate kinesiophobia scores (TSK mean = 37.59 ± 7.38), as it indicates that the VR environment facilitated appropriate increases in muscle activation without triggering excessive co-contraction, which is often seen in individuals with movement-related fear, as described by Taniguchi et al. (2024).

Maintaining consistent activation in the Rectus Femoris, Medial Gastrocnemius, and Biceps Femoris across difficulty levels suggests that participants could meet the increased movement demands primarily through more efficient Vastus Medialis recruitment instead of global increases in muscle activation. This pattern aligns with the findings of Brenneman et al. (2016), who demonstrated that effective therapeutic exercises promote selective muscle recruitment strategies rather than general increases in muscle activation.

These movement and muscle activation patterns are particularly significant given the participants' demographic characteristics. With a mean WOMAC Index score of 0.29 (± 0.19), indicating mild to moderate physical impairment, participants demonstrated appropriate functional adaptations without relying on compensatory strategies. Despite 70% of participants having left knee involvement, the balanced activation patterns observed suggest that the VR environment successfully guided movements without triggering the asymmetric compensatory patterns often seen in clinical populations, as documented by Mills et al. (2013).

The quality of movement was assessed through several objective parameters: (1) the preservation of symmetric ROM patterns between limbs at both difficulty levels, (2) the coordinated increase in ROM across joints with increased difficulty, (3) the selective activation of key stabilising muscles (Vastus Medialis) without tensing all muscles around the knee, and (4) the controlled frontal plane motion despite increasing sagittal plane demands. These metrics indicate that participants maintained therapeutic movement quality while adapting to increased task difficulty. This finding aligns with Mete and Sari's (2022) criteria for effective therapeutic exercise progression, where movement quality is preserved while functional demands increase.

Participants' ability to adapt successfully to increased difficulty levels while maintaining movement quality suggests that the VR environment effectively implements progressive therapeutic challenge principles. The high-stepping scenario demonstrates potential as a therapeutic exercise that can challenge patients while preserving movement control by facilitating appropriate adaptations in both kinematics (ROM) and muscle activation (selective Vastus Medialis recruitment) without triggering compensatory strategies.

6.3.3 Weight Shifting Scenario

The weight-shifting scenario revealed significant differences in both movement patterns and muscle activation strategies as participants progressed from easy to advance levels. The total excursion of the COM increased substantially from Level 1 (median = 0.49, IQR = 0.78) to Level 2 (median = 1.96, IQR = 3.03), with statistical analysis confirming this difference ($Z = -4.579$, $p < .001$). This increase in COM excursion demonstrates that the VR system successfully increased postural control demands while allowing participants to maintain controlled movements.

The significant increase in COM excursion aligns with research by Hsu et al. (2010), who demonstrated that individuals with knee OA adopt specific COM control strategies during functional activities, prioritising stability over mobility. Our findings suggest that the VR environment challenged participants to expand their stability limits beyond their typical conservative movement patterns, which is particularly valuable for a population with moderate kinesiophobia (mean TSK score of 37.59 ± 7.38). As Doury-Panchout et al. (2014) noted, higher kinesiophobia scores often correlate with greater functional limitations, making controlled exposure to increased movement demands potentially beneficial.

The muscle activation patterns presented complex neuromuscular strategies among different muscle groups. The quadriceps muscles (Rectus Femoris and Vastus Medialis) showed a clear increase in activation levels, with both demonstrating increased activation in Level 2 compared to Level 1 across both limbs. However, a notable asymmetry emerged in the Rectus Femoris muscle during Level 1, as the right muscle showed lower activation than the left ($Z = -2.795$, $p = .005$). This asymmetry is particularly significant considering the demographic data, which indicated that 70% of participants (n = 28) had left knee involvement. This suggests that participants might have developed compensatory strategies, involving decreased activation of the right Rectus Femoris to alleviate stress on the compromised left knee.

Unlike the asymmetrical pattern seen in the Rectus Femoris, the Vastus Medialis showed symmetrical activation between limbs at both difficulty levels, while still showing significant increases from Level 1 to Level 2 on both the left ($Z = -2.966$, $p = .003$) and right sides ($Z = -2.812$, $p = .005$). The Vastus Medialis symmetry, despite increased task demands and Rectus Femoris asymmetry, suggests an advanced neuromuscular control strategy. This aligns with Mills et al.'s (2013) finding that individuals with unilateral knee conditions displayed distinct between-limb movement asymmetries and compensatory strategies that influenced overall biomechanics.

The ankle stabilisers showed different adaptation patterns. The Medial Gastrocnemius maintained consistent activation levels across both difficulty levels and between limbs ($p = .096$), suggesting that ankle control strategies remained stable despite increased challenges. This finding supports Lee et al.'s (2021) research on dynamic balance control, which found that neuromuscular training focused on COM control specifically improved weight transfer during walking. The consistent Medial Gastrocnemius activation might indicate that participants sustained stable ankle strategies while adapting to increased demands through other muscle groups.

As measured by Biceps Femoris activation, the hamstring response revealed another significant asymmetry. The left Biceps Femoris showed a significant increase in activation from Level 1 to Level 2 ($Z = -3.342$, $p < .001$), while the right Biceps Femoris activation remained constant. This limb-specific adaptation further supports the asymmetrical movement strategies related to the predominance of left knee involvement in this sample. The increased activation of the left Biceps Femoris during more challenging tasks may indicate a protective mechanism to enhance knee stability on the affected side.

These findings have important clinical implications for VR-based rehabilitation. The observed increase in COM excursion, coupled with appropriate muscle activation adaptations, suggests that the weight-shifting scenario successfully challenges postural control while accommodating individual compensatory strategies. This is particularly important for patients with CKP, who often exhibit kinesiophobia. As noted by Taniguchi et al. (2024), kinesiophobia can lead to activity avoidance, which worsens pain through decreased muscle strength, reduced joint flexibility, and pain sensitisation. Our VR system appears to effectively encourage movement while allowing participants to maintain control, potentially helping them to overcome kinesiophobia.

The asymmetrical muscle activation patterns observed also highlight the importance of personalised approaches in rehabilitation. As Dell'Isola et al. (2016) emphasised, there is a significant research gap in understanding how to tailor strengthening protocols to individual needs, and our findings support the concept that different patient populations may require specific movement strategies and exercise modifications. The predominance of left knee involvement in the present study's sample (70%) helps to explain some of the observed asymmetrical patterns and underscores the need for rehabilitation systems to accommodate individual differences.

These results also support Howard's (2017) meta-analysis findings on the mechanisms behind successful VR rehabilitation, particularly regarding physical fidelity. The weight-shifting scenario effectively mimics real-life activities while allowing for controlled progression of difficulty. This could eliminate patients' need to translate practised behaviours into real-world contexts, making the rehabilitation process more intuitive and effective.

While the findings demonstrate the VR system's ability to challenge participants while maintaining movement quality progressively, several limitations must be acknowledged. The standardised approach to difficulty levels may not have been optimal for all participants, given their varying degrees of knee involvement and functional capacity. Furthermore, although significant differences in muscle activation patterns were observed, these cannot be directly attributed to pain reduction mechanisms without additional longitudinal data. Finally, the increased COM excursion and muscle activation in Level 2 suggest an appropriate progression of challenge; however, further research is needed to determine whether these changes translate to improved functional outcomes in daily activities.

In conclusion, the weight-shifting scenario demonstrated effective progression of challenges while allowing for individual movement adaptations. The significant increases in COM excursion and appropriate muscle activation patterns suggest that the VR tool successfully challenges postural control while accommodating the specific needs of individuals with CKP. These findings contribute to our understanding of how VR-based rehabilitation can be designed to effectively challenge patients while respecting their individual movement strategies and limitations.

6.3.4 Step-Forward Scenario

The step-forward scenario showed clear movement patterns and muscle activation changes as participants faced various difficulty levels. Analysing sagittal plane movement indicated a significant increase in hip flexion–extension from Level 1 to Level 2 for both limbs, with more marked changes in the left limb (left: $p = 0.006$; right: $p = 0.028$). This bilateral adaptation indicates that participants adapted well to the increased challenge by broadening their hip movement range.

This increase in hip movement is particularly significant when considering the demographic data, which showed that 70% of participants had left knee involvement. The greater adaptation in the left hip may represent a compensatory strategy to protect the affected knee while still accomplishing the task. This aligns with Segal et al.'s (2013) finding that higher-functioning individuals with knee problems use different movement strategies based on gender: men tend to use increased hip ROM to maintain function, while women with stronger hip abductors and controlled knee movement achieve better outcomes.

Unlike the hip, the knee movement showed only modest changes between difficulty levels. Data for the left knee approached but did not reach statistical significance ($p = 0.054$), while the right knee showed no significant change ($p = 0.180$). This limited knee adaptation suggests that participants maintained controlled knee movements despite the increased challenge, which may reflect a protective strategy. As Wood et al. (2016) noted in their research, patellofemoral joint forces increase with knee flexion, and patients with knee pain are advised to limit knee flexion during exercises like squats and lunges to reduce joint loading. The minimal change in knee movement across difficulty levels suggests that participants naturally adopted movement patterns that protected their affected joints.

The ankle movement revealed an interesting asymmetry. While the right ankle maintained consistent movement across both levels ($p = 0.765$), the left ankle displayed a significant decrease in dorsiflexion-plantarflexion range from Level 1 to Level 2 ($p = 0.004$). This reduction in left ankle movement, combined with the increased hip movement on the same side, suggests a shift in movement strategy that may protect the affected knee. By reducing ankle movement and increasing hip movement, participants may have been redistributing movement demands to minimise stress on the painful joint.

The frontal plane analysis provided additional insights, revealing significant main effects for Level ($F = 4.198$, $p = 0.049$), Limb ($F = 4.382$, $p = 0.044$), and Joint ($F = 6.837$, $p = 0.002$). The significant interaction between Level and Joint ($F = 8.889$, $p = 0.002$) indicates that different joints responded differently to the increased challenge. Post-hoc analysis demonstrated that hip movements were significantly greater than both knee and ankle movements, supporting the idea that participants were using hip strategies to accomplish the task while protecting their knees.

The muscle activation patterns support these movement adaptations. The Rectus Femoris showed a significant decrease in activation on the right side from Level 1 to Level 2 ($p = 0.019$), whereas the left side maintained consistent activation ($p = 0.126$). This asymmetrical adaptation may reflect an effort to reduce load on the predominantly affected left knee by decreasing muscular effort on the opposite side. This finding aligns with Brenneman et al.'s (2016) research, which showed that pain can influence muscle activation patterns during functional exercises like lunges.

The Vastus Medialis showed consistent activation across difficulty levels in both limbs (left: $p = 0.739$; right: $p = 0.922$), suggesting stable quadriceps control despite the increased challenge. Similarly, the Biceps Femoris maintained consistent activation in both limbs across all levels. The Medial Gastrocnemius showed a trend toward decreased activation on the right side ($p = 0.065$), which corresponds with the stable right ankle movement and may indicate a shift toward a more hip-dominant movement strategy as difficulty increased.

These findings have important clinical implications when viewed in the context of the participants' characteristics. The moderate kinesiophobia scores (mean TSK = 37.59 ± 7.38) suggest that many participants experienced some fear of movement; however, they were able to adapt their movement strategies to meet the increased challenge. The VR system appears to have created an environment where participants felt comfortable exploring movement adaptations despite this fear, which could be valuable for rehabilitation. As mentioned above, fear of movement can worsen pain through decreased physical activity, reduced joint flexibility, and pain sensitisation (Taniguchi et al. 2024). The VR step-forward scenario allowed participants to engage in functional movement while naturally adopting protective strategies.

The modest self-efficacy scores (mean SECD = 6.55 ± 1.88) offer important context for these results. Participants who exhibited moderate confidence in managing their symptoms displayed sophisticated movement adaptations that effectively balanced task completion and joint protection. This supports the findings of Kerari et al. (2024), which indicate that self-efficacy plays a crucial role in mediating the relationship between pain intensity and functional outcomes. The VR system seems to facilitate these individual adaptations while ensuring an appropriate level of challenge.

The combination of increased hip movement, stable knee control, and reduced ankle movement on the affected side, along with corresponding changes in muscle activation, suggests that the step-forward scenario successfully facilitated functional movement while allowing participants to adopt protective strategies. This aligns with the principles of effective rehabilitation, which aim to improve function while minimising pain and preventing further tissue damage (Howard 2017).

These findings support the use of VR for knee rehabilitation, as it appears to facilitate natural movement adaptations while maintaining an appropriate challenge. The observed movement strategies align with research by Bouchouras et al. (2015) on neuromuscular adaptations that help to protect the knee joint during functional movements. The VR system seems to create an environment where participants can develop and practise these protective strategies in a controlled and engaging manner.

However, some limitations should be noted. While significant movement adaptations were observed, these cannot be directly attributed to pain reduction mechanisms without additional data. Further research should investigate whether these movement adaptations improve functional outcomes and reduce pain in daily activities.

In conclusion, the step-forward scenario demonstrated that participants naturally adopted protective movement strategies while successfully progressing through increasingly difficult levels. The observed adaptations in movement patterns and muscle activation suggest that the VR system effectively challenged participants while allowing them to maintain movement quality and protect their affected joints. These findings contribute to our understanding of how VR-based rehabilitation can accommodate individual movement strategies while providing an appropriate challenge progression.

6.3.5 Sit-to-Stand Scenario

In the sagittal plane, hip movement symmetry showed significant differences across the three difficulty levels ($p = .039$). The SI progressively changed from Level 1 (SI = -0.232) to Level 2 (SI = -0.657), and then partially recovered at Level 3 (SI = -0.394). This pattern suggests that participants began with relatively balanced hip movement, then adopted more asymmetrical strategies when challenged at Level 2, before developing more effective movement patterns by Level 3.

This pattern of adaptation is particularly meaningful when considered alongside the demographic data, which show that 70% of participants had left knee involvement. The negative symmetry values indicate greater movement on the right side, suggesting that participants were shifting weight away from their affected left knee. This protective strategy aligns with Segal et al.'s (2013) research, which found that individuals with knee problems develop distinct movement patterns based on functional needs and pain avoidance.

Knee movement symmetry showed a near-significant difference across the three levels ($p = .053$), with a significant decrease in symmetry from Level 1 to Level 2 ($p = .031$). Like the hip pattern, knee symmetry was highest at Level 1, decreased at Level 2, and then showed some recovery at Level 3. This suggests that participants initially used a balanced strategy, then shifted to protect the affected knee when challenged, before developing more effective movement patterns through practice.

The decrease in knee symmetry at Level 2 mirrors findings by Verlaan et al. (2018), who discovered that individuals with knee OA showed significantly reduced knee ROM during sit-to-stand movements compared to both lean patients and healthy controls. The participants appeared to naturally adopt protective movement strategies that reduced stress on their affected knees while still accomplishing the task.

In contrast to hip and knee movements, ankle symmetry remained consistent across all three levels ($p = .227$). This stability in the ankle strategy suggests that participants maintained consistent foot positioning and ankle control throughout the exercise, even as they modified their hip and knee movements to manage the increasing difficulty. This finding is important because stable ankle positioning provides a solid base for more complex adjustments occurring at the knee and hip.

The EMG analysis revealed remarkably consistent muscle activation patterns across all three difficulty levels. None of the four muscles studied showed statistically significant changes in activation between levels on either limb. The right Vastus Medialis muscle showed nearly significant changes in activation ($p = .063$). While not quite reaching the standard threshold for significance ($p < .05$), this suggests that there might be fundamental changes in how participants used this muscle as they progressed through different difficulty levels. This could be part of how participants adapted their movement to protect their affected knee, particularly on the left side for 70% of participants.

This consistency in muscle activation is interesting when contrasted with the significant changes observed in movement patterns. It suggests that participants maintained similar muscle recruitment strategies even as they modified their movement patterns. This finding aligns with Bouchouras et al.'s (2015) research on neuromuscular adaptations during sit-to-stand movements, which found that individuals with knee problems developed specific muscle coordination strategies that they maintained despite varying task demands.

The stable Medial Gastrocnemius activation across all levels (left: $p = .970$; right: $p = .674$) corresponds with our kinematic finding of a consistent ankle strategy. Together, these results suggest that participants maintained a stable base of support through consistent ankle positioning and calf muscle activation while adapting their movement primarily through hip and knee strategies.

These findings have important clinical implications when considered alongside the participants' characteristics. The moderate kinesiophobia scores (mean TSK = 37.59 ± 7.38) indicate a degree of fear of movement among participants. According to Taniguchi et al. (2024), such fear often leads to activity avoidance, which exacerbates pain by decreasing muscle strength and reducing joint flexibility. The VR sit-to-stand scenario appears to have created an environment where participants felt comfortable exploring different movement strategies despite this fear.

The progression pattern across the three difficulty levels demonstrates the effectiveness of the VR system in providing suitable challenges. At Level 1, participants exhibited relatively symmetrical movement patterns, establishing baseline performance. The increased asymmetry at Level 2 indicates how the game effectively challenged participants' movement control, requiring them to adapt their strategies. The improved symmetry at Level 3 suggests successful adaptation to these challenges, indicating that participants were learning more efficient movement patterns as they advanced.

This pattern of initial symmetry, followed by increased asymmetry when challenged, and then improved symmetry with practice, follows normal motor learning principles. It suggests that the VR system successfully implemented progressive difficulty while allowing participants to develop effective movement strategies. This is particularly valuable for rehabilitation, where the goal is to gradually increase challenge while maintaining movement quality.

The stable muscle activation patterns across difficulty levels, combined with the adaptive movement strategies, indicate that participants were developing more efficient movement patterns rather than simply increasing muscle effort. This is an important distinction in rehabilitation, as efficient movement is often more sustainable and less likely to cause pain or fatigue than strategies that rely on increased muscle effort.

These findings support the use of VR for knee rehabilitation, as it seems to create an environment where participants naturally adopt protective movement strategies while still engaging in functional exercises. The sit-to-stand task is especially valuable, as it directly translates to an essential daily activity, making improvements in this movement pattern particularly meaningful for quality of life.

While the findings indicate promising adaptive patterns, some limitations should be acknowledged. Although significant movement adaptations were observed, these cannot be directly attributed to pain reduction mechanisms without additional data.

The lack of significant changes in muscle activation patterns across levels could be interpreted in several ways. It might suggest that the challenge progression was insufficient to necessitate increased muscle effort, or it could imply that participants were developing more efficient movement strategies that relied on improved coordination rather than increased muscle activation.

The sit-to-stand scenario demonstrated that participants naturally adopted and refined protective movement strategies as they progressed through increasing difficulty levels. The observed pattern of initial symmetry, followed by asymmetry when challenged, and then improved symmetry with practice, suggests effective motor learning, as described by Sabashi et al. (2022), who found that balance training leads to changes in movement strategies that relate to pain reduction. Meanwhile, the consistent muscle activation patterns indicate that participants were developing more efficient movement strategies rather than simply increasing muscle effort, as Brenneman et al. (2016) observed in their research on muscle activation during functional exercises.

These findings suggest that the VR system effectively challenged participants while allowing them to develop movement strategies that protected their affected joints. This balance between challenge and protection aligns with Howard's (2017) research on successful VR rehabilitation mechanisms, particularly regarding physical fidelity and appropriate cognitive challenges.

This balanced approach is essential for the effective rehabilitation of individuals with CKP, especially considering their moderate kinesiophobia scores (mean TSK = 37.59 ± 7.38), which, according to Taniguchi et al. (2024), can lead to avoidance behaviours that worsen pain. The VR sit-to-stand scenario appears to create an environment where participants can safely practice and refine this important functional movement, like the benefits observed by Jachak and Phansopkar (2022) in their study of VR therapy for knee OA.

6.4 Interpretation of Usability Findings

The usability evaluation of the VR prototype toolkit for therapeutic exercise revealed several key findings that both align with and diverge from existing research. The overall SUS score of 76 indicates good usability, comparable with similar technology-assisted exercise systems. This section explores how the findings relate to the broader literature on VR rehabilitation, focusing particularly on engagement factors, technical challenges, instruction clarity, feedback mechanisms, and functional outcomes.

The quantitative content analysis of the think-aloud data revealed a predominance of positive feedback (389 codes) over negative feedback (62 codes), with enjoyment and engagement emerging as the dominant themes. This is consistent with findings from Manlapaz et al. (2022), who reported that participants described their gamified VR experience as "enjoyable, engaging, and motivating," and Lin et al. (2020), who demonstrated higher adherence rates (100%) in VR-based exercise groups compared to 93% in traditional exercise groups. Krepkovich et al. (2022) also reported that patients using video-game-based systems exercised for longer periods and reported higher levels of engagement.

The consistency between the usability findings and the published studies strengthens the argument that VR's primary advantage in rehabilitation is its ability to transform therapeutic exercises into engaging experiences. As one participant noted, *" the system shifts from exercise to game/fun"* (VR21), capturing the essence of how VR can reframe rehabilitation from a medical necessity to an enjoyable activity. This transformation may be particularly valuable for home-based rehabilitation, where maintaining motivation without direct professional supervision presents a significant challenge.

The high engagement levels observed in the study suggest that VR systems can sustain user interest even without the external motivation provided by therapists in supervised settings. This addresses a critical gap identified by Nicolson et al. (2017), who found that participation rates in exercise programmes dropped significantly after the conclusion of supervised intervention periods, with fewer than 50% of patients maintaining recommended activity levels at six-month follow-up.

Technical challenges emerged as a significant theme in the study, with hardware problems (53 codes) and system responsiveness (47 codes) being particularly challenging. These findings mirror concerns raised throughout the literature on VR rehabilitation. Guo et al. (2024) highlighted technological and usability issues as major limitations, particularly for older adults, who often face difficulties navigating these systems without additional support. Similarly, early work by Fitzgerald et al. (2007) noted complex calibration processes as significant barriers to implementation.

The usability findings revealed that tracking accuracy and system lag were more prominent concerns than calibration issues. Participants expressed frustration when the system failed to accurately track their movements, with one participant noting, *"I can't get the tracking back, whatever I do"* (VR23). This differs somewhat from the findings of Chen et al. (2024), who identified camera calibration as the most significant difficulty for users. This difference may reflect the evolution of VR technology over time, with newer systems potentially offering improved calibration but real-time tracking still posing limitations.

The persistence of technical challenges across both this study and the broader literature suggests that these issues are not entirely limitations of a specific prototype but represent fundamental challenges in the field of VR rehabilitation. As emphasised by Hamilton et al. (2023), technical reliability is crucial for acceptance, particularly in home-based applications where users cannot receive immediate technical support.

Another key theme was the importance of instruction clarity, particularly in unsupervised settings. Without the guidance of a therapist, users rely entirely on the system's instructions to understand proper execution of exercises. Comments like *"Sometimes it wasn't clear how to apply it correctly, and I got confused"* (VR37) highlight the importance of developing intuitive, unambiguous guidance for home-based applications.

The evaluation of real-time feedback mechanisms indicated high user appreciation for visual feedback, aligning with the Brennan et al.'s (2020) finding that visual feedback is the predominant and most effective mode in digital biofeedback systems. However, while Brennan's (2020) review suggested that combining multiple feedback modes could enhance effectiveness, the participants in this study preferred simpler, more focused feedback approaches. This difference indicates that, in home-based settings, clarity may be more important than comprehensive feedback.

The preference for simplified feedback is aligned with research from Pruna et al. (2017), which found that real-time visual and auditory feedback helped to ensure accurate completion of exercises during unsupervised rehabilitation. However, participant feedback reveals that an overload of information can be harmful, as noted in comments like *"There's an awful lot of clutter on the screen"* (VR32). This highlights the necessity for home-based VR systems to find a balance between providing sufficient guidance and avoiding overwhelming users with too much information.

This insight contributes to a relatively underexplored aspect of VR-based physiotherapy research, specifically the importance of feedback design in home settings. While most existing research primarily emphasises comprehensive feedback systems for clinical environments, findings indicate that home-based applications benefit more from clear, simplified language that supports users' autonomous learning and independent exercise progression.

A particularly novel insight emerged around dual-task performance. With 102 codes related to this theme, participants frequently commended the combined physical and cognitive components. For instance, one participant noted that the activities felt like "*a mental exercise as well"* (VR20). This aligns with Howard's (2017) identification of realistic cognitive challenges as a key mechanism behind the success of VR rehabilitation, as these challenges enhance patients' preparation for multitasking in real-world functional scenarios.

However, the findings also revealed that while participants demonstrated high engagement with these cognitive–physical tasks, they encountered difficulties maintaining proper form during complex exercises. This suggests that engagement alone does not guarantee the correct execution of therapeutic movements, which could potentially limit clinical outcomes. This observation aligns with the findings of Hribernik et al. (2022) regarding the need to balance between user experience and therapeutic outcomes.

The challenge of maintaining proper form during engaging yet complex exercises represents a critical consideration for VR rehabilitation system design. As demonstrated by Ebrahimi et al. (2021), VR training can improve both physical outcomes and brain activity, suggesting that the dual-task nature of VR exercises provides unique benefits. However, the findings indicate that system designers must carefully calibrate the cognitive load to ensure that it enhances rather than detracts from movement quality.

The usability evaluation revealed five important considerations for developing an effective VR rehabilitation toolkit for home use. These findings, as set out below, highlight both the potential and challenges of this emerging technology.

VR technology shows great promise for increasing patient engagement with rehabilitation exercises. Users responded positively to its interactive nature, finding the exercises more enjoyable than traditional methods. This enhanced engagement could lead to better long-term adherence, as patients are more likely to consistently perform exercises that they find interesting and motivating.

Technical reliability is crucial for home-based systems where users lack professional support. The evaluation identified that even minor technical issues like tracking errors or system crashes significantly impacted the user experience. Since patients do not have therapists present to troubleshoot problems, consistent performance is essential to prevent frustration and neglect of the rehabilitation programme.

Instructional design requires special attention in home settings. Unlike clinical environments where therapists provide guidance, home users rely entirely on the system for instruction. Future VR rehabilitation platforms should incorporate clearer visual demonstrations, simpler language, and progressive complexity that builds user confidence gradually. Instructions that work well in supervised settings may be insufficient for independent home use.

Feedback mechanisms should emphasise simplicity rather than comprehensiveness. While detailed performance data might seem beneficial, the findings show that users prefer focused, easily understood feedback on the most important aspects of their exercise. Overwhelming users with too much information can distract from the physical activity and reduce the overall effectiveness of the rehabilitation session.

The balance between engaging gameplay and therapeutic quality represents a fundamental design challenge. While game-like elements enhance motivation, they must not compromise proper movement patterns or therapeutic benefits. Designers need to carefully manage cognitive demands while maintaining appropriate physical challenge and correct exercise form, ensuring that entertainment value does not override clinical effectiveness.

In conclusion, this usability evaluation provides valuable insights for developing effective VR-based home rehabilitation systems. The findings suggest that VR technology offers promising potential for improving rehabilitation outcomes by increasing patient engagement and exercise adherence. However, successful implementation requires careful attention to technical reliability, instructional clarity, the design of appropriate feedback, and a balance between engagement and therapeutic quality. As VR rehabilitation technology continues to evolve, addressing these considerations will be essential for creating systems that not only engage patients but also deliver meaningful clinical benefits in home-based settings. Future research should focus on implementing these improvements and evaluating their impact on patient outcomes across different rehabilitation contexts.

6.5 Implications of the findings

The findings indicate that VR-based rehabilitation presents promising potential for enhancing patient engagement and adherence in rehabilitation programmes, with features that may facilitate future home-based applications. The main benefits include enhancing patient engagement, promoting appropriate motor learning patterns, and effectively balancing physical and cognitive challenges. The system transforms conventional therapeutic exercises into enjoyable activities while minimising the focus on pain.

Patient engagement emerged as the most significant strength of the VR rehabilitation toolkit. Participants consistently described their experience as enjoyable and engaging, with many noting how the system successfully transformed therapeutic exercise from a medical necessity into an enjoyable activity. This transformation is particularly valuable for individuals with moderate kinesiophobia (fear of movement) and mild to moderate depressive symptoms, as the engaging nature of VR exercises helped shift focus away from pain concerns towards the enjoyment of movement.

The relationship between movement quality and system design is crucial in clinical practice. The biomechanical analysis showed that participants naturally adopted protective movement strategies while completing functionally challenging exercises. These adaptations were not random compensations; they were strategic adjustments aimed at protecting affected joints while maintaining functional movement.

A clear learning pattern emerged as participants progressed through increasingly difficult exercise levels. Typically, this pattern involves initial symmetrical movement, followed by strategic adaptations when faced with challenges, and ultimately the development of more refined and efficient movements with practice. This progression aligns with established motor learning principles and suggests that the VR environment effectively supports rehabilitation exercises.

The study emphasised the importance of providing clear instructions and guidance in VR rehabilitation, especially for independent home use. Participants expressed a preference for simple, focused feedback instead of comprehensive information that could be overwhelming. This insight implies that rehabilitation professionals should emphasise initial training sessions and set clear expectations regarding the system's capabilities when implementing VR tools.

The design of the instructional elements should prioritise clarity and gradually build user confidence, as home users rely heavily on the system for guidance through visual demonstrations and simple language. The VR system effectively combines cognitive challenges with physical exercises, creating a dual-task approach that enhances motor learning and engagement. This method better prepares patients for real-world situations where multitasking is a common requirement.

The user experience involved dealing with technical elements such as system responsiveness and tracking accuracy. As participants gained experience with the system, they became increasingly comfortable with these elements. Tracking accuracy and movement recognition were part of the learning curve for users, who developed strategies to optimise their interactions with the system over time.

Integrating technical elements into the rehabilitation experience represents an evolving aspect of digital health interventions. As users become more familiar with the system, they adapted their approaches to work effectively within its parameters, demonstrating the flexibility of human-technology interaction in therapeutic contexts.

6.6 Limitations of the Study

Despite the important insights gained, several limitations must be acknowledged. First, the study focused on immediate usability and movement patterns instead of long-term clinical outcomes. While positive engagement and suitable movement strategies were observed, their long-term influence on pain reduction and functional improvement cannot be determined. Longitudinal studies are necessary to determine whether these immediate benefits lead to sustained clinical improvements.

Second, the sample size of 40 participants, while methodologically sound and comparable to similar studies, may limit the generalisability of the findings to the broader population with CKP. Additionally, although participants from a wide age range were included, the sample may not fully represent individuals with varying levels of technological knowledge or comfort with virtual environments.

Third, the usability assessment was conducted in a controlled environment rather than in participants' homes. While this approach provided consistency in evaluation conditions, it may not fully capture the challenges that users might face when implementing the system in their own living spaces without technical assistance.

The research has demonstrated that the VR system is suitable for its intended purpose and is both acceptable and usable in controlled environments. However, its feasibility for independent use at home has not yet been established. The controlled testing conditions probably provided advantages that may not be available in-home settings, such as consistent lighting, sufficient space, absence of distractions, and immediate technical support.

6.7 Future Recommendations

Based on this study's findings, several recommendations can be made for the future development and implementation of VR-based rehabilitation systems. Future research should evaluate the long-term effectiveness of VR rehabilitation compared to traditional approaches. Studies should assess various outcomes, including physical results, adherence rates, pain reduction, functional improvement, and quality of life measures, over extended periods. This would provide more substantial evidence regarding the clinical value of VR-based interventions for managing CKP.

Home-based feasibility studies are an important area for future research. Investigations should explore the implementation of VR rehabilitation systems in participants' homes over extended periods. These studies should identify specific environmental, technical, and user-related factors that impact the feasibility of this approach. Documenting space requirements, technical support needs, adherence patterns in unsupervised settings, and adaptations for diverse home environments is essential. This research bridges the findings on acceptability and usability in controlled settings with the practical challenges of implementing home-based rehabilitation.

Efforts should be made to develop systems that accommodate a wider range of users, including those with limited experience of technology. Simplified setup procedures can help ensure that VR rehabilitation remains accessible to diverse patient populations who could benefit from this approach.

Additionally, incorporating optional social features such as virtual group exercises or friendly competition could enhance motivation for some users. These elements could help reduce the isolation that sometimes accompanies home-based rehabilitation while providing additional motivation through social connections.

By implementing these recommendations, future VR rehabilitation systems could build on this study's promising findings, creating even more effective, engaging, and accessible tools for home-based management of CKP. This approach has significant potential to transform rehabilitation practices by addressing ongoing challenges related to patient engagement and exercise adherence.

Chapter 7: Conclusion

This research followed the development phase of the MRC framework for complex interventions by systematically evaluating an early-stage prototype of a VR-based physiotherapy toolkit. This toolkit is designed to support therapeutic exercises for individuals with CKP at home. As outlined in the research approach, the development phase incorporated most of the six core MRC elements, with context explored through a comprehensive literature review that identified gaps in current evidence concerning VR-based physiotherapy interventions for individuals with CKP. The findings, analysed through the TAM Model, reveal positive results in terms of perceived usefulness and perceived ease of use. These results suggest that VR technology presents a promising solution to significant challenges faced in traditional rehabilitation programs, particularly in enhancing patient engagement and adherence.

The VR rehabilitation system effectively implemented essential therapeutic principles while transforming exercise into an engaging experience. Biomechanical analysis confirmed that participants maintained proper movement quality as they progressed through increasingly complex challenges. The system successfully facilitated appropriate movement patterns and muscle activation strategies across five different exercise scenarios, demonstrating its potential for delivering targeted therapeutic benefits.

User experience data indicated high levels of engagement and enjoyment, with participants appreciating the game-like qualities that shifted their focus from pain concerns to the enjoyment of movement. This transformation in the rehabilitation experience is particularly beneficial for individuals with kinesiophobia and mild to moderate depressive symptoms, who often face difficulties with traditional exercise programmes.

The balance between physical challenges and cognitive engagement proved to be particularly valuable. It created an environment where participants could learn and refine their movement strategies while staying motivated. This dual-task approach may better prepare patients for real-world activities that require similar multitasking skills.

This research demonstrates that specifically designed VR rehabilitation can effectively deliver progressive therapeutic exercises while maintaining movement quality and significantly enhancing the user experience. The VR approach shows promise in addressing the well-documented challenges of adherence in home-based rehabilitation programmes by creating an intrinsically motivating exercise experience.

References

Aartolahti, E. et al. 2022. Effectiveness of gamification in knee replacement rehabilitation: protocol for a randomized controlled trial with a qualitative approach. *JMIR Research Protocols* 11(11), e38434.

Abdelazim, F., Elshazly, A., Gopal, N. S. and Elnegamy, T. E. 2016. Comparative study on virtual reality training (VRT) over sensory motor training (SMT) in unilateral chronic osteoarthritis—a randomized control trial. *International Journal of Medical Research & Health Sciences* 5, pp. 7–16.

Adomavičienė, A., Daunoravičienė, K., Kubilius, R., Varžaitytė, L. and Raistenskis, J. 2019. Influence of new technologies on post-stroke rehabilitation: a comparison of Armeo Spring to the Kinect system. *Medicina* 55(4), 98.

Ageberg, E. and Roos, E.M. 2015. Neuromuscular exercise as treatment of degenerative knee disease. *Exercise and Sport Sciences Reviews* 43(1), pp. 14–22.

Ahmad, M.A., Singh, D.K.A., Mohd Nordin, N.A., Hooi Nee, K. and Ibrahim, N. 2019. Virtual reality games as an adjunct in improving upper limb function and general health among stroke survivors. *International Journal of Environmental Research and Public Health* 16(24), 5144.

Aitken, D., Buchbinder, R., Jones, G. and Winzenberg, T. 2010. Interventions to improve adherence to exercise for chronic musculoskeletal pain in adults. *The Cochrane Database of Systematic Reviews* 2010(1), CD005956. doi: 10.1002/14651858.CD005956.PUB2.

Alexandre, R. and Postolache, O. 2018. Wearable and IoT technologies application for physical rehabilitation. In *2018 International symposium in sensing and instrumentation in IoT era (ISSI)*. IEEE, pp. 1–6.

Ali, S. A., Walsh, K. E. and Kloseck, M. 2018. Patient perspectives on improving osteoarthritis management in urban and rural communities. *Journal of Pain Research* 11, pp. 417–425. doi: 10.2147/JPR.S150578.

Altman, R. et al. 1986. Development of criteria for the classification and reporting of osteoarthritis classification of osteoarthritis of the knee. *Arthritis and Rheumatology* 29(8), pp. 1039–1049. doi: 10.1002/art.1780290816.

An, J., Kim, J., Lai, E. C. and Lee, B. C. 2020. Effects of a smartphone-based wearable telerehabilitation system for in-home dynamic weight-shifting balance exercises by Individuals with Parkinson's Disease. *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS*, *2020-July*, pp. 5678–5681. doi: 10.1109/EMBC44109.2020.9175967.

Angst, F., Aeschlimann, A. and Stucki, G. 2001. Smallest detectable and minimal clinically important differences of rehabilitation intervention with their implications for required sample sizes using WOMAC and SF-36 quality of life measurement instruments in patients with osteoarthritis of the lower extremities. *Arthritis Care & Research* 45(4), pp. 384–391.

Andriacchi, T. P., Favre, J., Erhart-Hledik, J. C. and Chu, C. R. 2015. A systems view of risk factors for knee osteoarthritis reveals insights into the pathogenesis of the disease. *Annals of Biomedical Engineering* 43, pp. 376–387.

Archer, K. R., Phelps, K. D., Seebach, C. L., Song, Y., Riley, L. H. and Wegener, S. T. 2012. Comparative study of short forms of the Tampa Scale for Kinesiophobia: fear of movement in a surgical spine population. *Archives of Physical Medicine and Rehabilitation* 93(8), pp. 1460–1462. doi: 10.1016/J.APMR.2012.03.024.

Arden, N. K. et al. 2021. Non-surgical management of knee osteoarthritis: comparison of ESCEO and OARSI 2019 guidelines. *Nature Reviews Rheumatology* 17(1), pp. 59–66. doi: 10.1038/s41584-020-00523-9.

Aromataris, E. and Munn, Z. 2020. *JBI Manual for Evidence Synthesis*. JBI. doi: 10.46658/JBIMES-20-01.

Artz, N., Elvers, K. T., Lowe, C. M., Sackley, C., Jepson, P. and Beswick, A. D. 2015. Effectiveness of physiotherapy exercise following total knee replacement: systematic review and meta-analysis. *BMC Musculoskeletal Disorders* 16, pp. 1–21.

Bagenal, J. 2022. The delivery plan for tackling the COVID-19 backlog of elective care falls short. *British Medical Journal* 377, o995.

Bailenson, J. 2018. *Experience on demand: what virtual reality is, how it works, and what it can do*. New York: WW Norton & Company.

Baliki, M. N. and Apkarian, A. V. 2015. Nociception, pain, negative moods, and behavior selection. *Neuron 87*(3), pp. 474–491.

Bangor, A., Kortum, P.T. and Miller, J.T. 2008. An empirical evaluation of the system usability scale. *International Journal of Human–Computer Interaction* 24(6), pp. 574–594.

Bannuru, R. R. et al. 2019. OARSI guidelines for the non-surgical management of knee, hip, and polyarticular osteoarthritis. *Osteoarthritis and Cartilage* 27(11), pp. 1578–1589. doi: 10.1016/j.joca.2019.06.011.

Barber, T., and Jahanbani. S. 2024. Physiotherapy and knee osteoarthritis. *British Columbia Medical Journal* 66(5), pp. 165–170. https://bcmj.org/articles/physiotherapy-and-knee-osteoarthritis.

Barnum, C. M. 2021. *Usability testing essentials*. Burlington, MA: Morgan Kaufmann. doi: 10.1016/b978-0-12-816942-1.00006-x.

Bartels, E. M., Juhl, C. B., Christensen, R., Hagen, K. B., Danneskiold-Samsøe, B., Dagfinrud, H. and Lund, H. 2016. Aquatic exercise for the treatment of knee and hip osteoarthritis. *Cochrane Database of Systematic Reviews*, *3*.

Bartholdy, C., Juhl, C., Christensen, R., Lund, H., Zhang, W. and Henriksen, M. (n.d.). The role of muscle strengthening in exercise therapy for knee osteoarthritis: A systematic review and meta-regression analysis of randomized trials. *Seminars in Arthritis and Rheumatism* 47(1), pp. 9–21. doi: 10.1016/j.semarthrit.2017.03.007.

Beckwée, D., Vaes, P., Cnudde, M., Swinnen, E. and Bautmans, I. 2012. Osteoarthritis of the knee: why does exercise work? A qualitative study of the literature. *Ageing Research Reviews* 12(1), pp. 226–236. doi: 10.1016/J.ARR.2012.09.005.

Bellamy, N. 1989. Pain assessment in osteoarthritis: experience with the WOMAC osteoarthritis index. *Seminars in Arthritis and Rheumatism* 18(4), pp. 14–17.

Bennell, K.L. et al. 2010. Efficacy of a multimodal physiotherapy treatment programme for hip osteoarthritis: a randomised placebo-controlled trial protocol. *BMC Musculoskeletal Disorders*, 11 pp.1-13.

Bennell, K. L. et al. 2016. Physical therapist–delivered pain coping skills training and exercise for knee osteoarthritis: randomized controlled trial. *Arthritis Care & Research* 68(5), pp. 590–602.

Bennell, K. L., Dobson, F. and Hinman, R. S. 2014. Exercise in osteoarthritis: moving from prescription to adherence. *Best Practice & Research: Clinical Rheumatology* 28(1), pp. 93–117. doi; 10.1016/J.BERH.2014.01.009.Bennell, K. L. and Hinman, R. S. 2011. A review of the clinical evidence for exercise in osteoarthritis of the hip and knee. *Journal of Science and Medicine in Sport 14*(1), pp. 4–9.

Bennell, K. L., Hunt, M. A., Wrigley, T. V., Lim, B. W. and Hinman, R. S. 2008a. Role of muscle in the genesis and management of knee osteoarthritis. *Rheumatic Diseases Clinics of North America* 34(3), pp. 731–754. doi: 10.1016/J.RDC.2008.05.005.

Bennell, K. L., Wrigley, T. V, Hunt, M. A., Lim, B.-W. and Hinman, R. S. 2013. Update on the role of muscle in the genesis and management of knee osteoarthritis. *Rheumatic Disease Clinics* 39(1), pp. 145–176.

Bettger, J. P. et al. 2020. Effects of virtual exercise rehabilitation in-home therapy compared with traditional care after total knee arthroplasty: VERITAS, a randomized controlled trial. *Journal of Bone and Joint Surgery* 102(2), pp. 101–109. doi: 10.2106/JBJS.19.00695.

Blasco, J., Igual-Camacho, C., Blasco, M., Antón-Antón, V., Ortiz-Llueca, I. and Roig-Casasús, S. 2021. The efficacy of virtual reality tools for total knee replacement rehabilitation: A systematic review. *Physiotherapy Theory and Practice* 37(6), pp. 682–692). doi: 10.1080/09593985.2019.1641865.

Błażkiewicz, M. and Wit, A. 2012. Comparison of sensitivity coefficients for joint angle trajectory between normal and pathological gait. *Acta Bioengineering and Biomechanics* 14(1), pp. 83–91.

Bohannon, R.W. and Glenney, S.S. 2014. Minimal clinically important difference for change in comfortable gait speed of adults with pathology: a systematic review. *Journal of Evaluation in Clinical Practice* 20(4), pp. 295–300.

Bohannon, R.W. and Crouch, R., 2019. 1-minute sit-to-stand test: systematic review of procedures, performance, and clinometric properties. *Journal of cardiopulmonary rehabilitation and prevention*, *39*(1), pp.2-8.

Bonnechère, B., Jansen, B., Omelina, L. and Jan, S. V. S. 2016. The use of commercial video games in rehabilitation: a systematic review. *International Journal of Rehabilitation Research* 39(4), pp. 277–290.

Bouchouras, G., Patsika, G., Hatzitaki, V. and Kellis, E. 2015. Kinematics and knee muscle activation during sit-to-stand movement in women with knee osteoarthritis. Clinical Biomechanics 30(6), pp. 599–607.

Bracchiglione, J., Meza, N., Bangdiwala, S.I., Niño de Guzmán, E., Urrútia, G., Bonfill, X. and Madrid, E. 2022. Graphical representation of overlap for overviews: GROOVE tool. *Research Synthesis Methods* 13(3), pp. 381–388.

Brady, T.J. 2011. Measures of self-efficacy: Arthritis self-efficacy scale (ASES), arthritis self-efficacy scale-8 item (ASES-8), children's arthritis self-efficacy scale (CASE), chronic disease self-efficacy scale (CDSES), parent's arthritis self-efficacy scale (PASE), and rheumatoid arthritis self-efficacy scale (RASE). *Arthritis Care & Research* 63(S11), pp. S473–S485.

Brennan, L., Zubiete, E. D. and Caulfield, B. 2020. Feedback design in targeted exercise digital biofeedback systems for home rehabilitation: a scoping review. *Sensors (Switzerland)* 20(1). doi: 10.3390/s20010181.

Brenneman, E. C., Kuntz, A. B., Wiebenga, E. G. and Maly, M. R. 2016. Does pain relate with activation of quadriceps and hamstrings muscles during strengthening exercise in people with knee osteoarthritis? *SpringerPlus* 5(1). doi: 10.1186/s40064-016-2048-1.

Brett, J., Staniszewska, S., Mockford, C., Herron-Marx, S., Hughes, J., Tysall, C. and Suleman, R. 2014. Mapping the impact of patient and public involvement on health and social care research: a systematic review. *Health Expectations* 17(5), pp. 637–650. doi: 10.1111/j.1369-7625.2012.00795. x.

Brett, J. et al. 2017. Reaching consensus on reporting patient and public involvement (PPI) in research: methods and lessons learned from the development of reporting guidelines. *BMJ Open* 7(10). doi: 10.1136/bmjopen-2017-016948.

Brooke, J. 1996. *SUS: a quick and dirty usability scale*. In Jordan, P. Thomas, B., Weerdmeester, B. and McClelland, A. eds. *Usability evaluation in industry.* London: Taylor and Francis.

Brosseau, L. et al. 2017. The Ottawa panel clinical practice guidelines for the management of knee osteoarthritis. Part two: strengthening exercise programmes. *Clinical Rehabilitation* 31(5), pp. 596–611. doi: 10.1177/0269215517691084.

Button, K.S., Ioannidis, J.P., Mokrysz, C., Nosek, B.A., Flint, J., Robinson, E.S. and Munafò, M.R. 2013. Power failure: why small sample size undermines the reliability of neuroscience. *Nature Reviews Neuroscience* 14(5), pp. 365–376.

Byra, J. and Czernicki, K. 2020. The effectiveness of virtual reality rehabilitation in patients with knee and hip osteoarthritis. *Journal of Clinical Medicine* 9(8), 1–18. doi: 10.3390/jcm9082639.

Calatayud, J., Casaña, J., Ezzatvar, Y., Jakobsen, M. D., Sundstrup, E. and Andersen, L. L. 2017. High-intensity preoperative training improves physical and functional recovery in the early post-operative periods after total knee arthroplasty: a randomized controlled trial. *Knee Surgery, Sports Traumatology, Arthroscopy* 25, pp. 2864–2872.

Campbell, R., Evans, M., Tucker, M., Quilty, B., Dieppe, P. and Donovan, J. L. 2001. Why don't patients do their exercises? Understanding non-compliance with physiotherapy in patients with osteoarthritis of the knee. *Journal of Epidemiology and Community Health* 55(2), pp. 132–138. doi: 10.1136/JECH.55.2.132.

Capecci, M. et al. 2018. An instrumental approach for monitoring physical exercises in a visual markerless scenario: a proof of concept. *Journal of Biomechanics* 69, pp. 70–80. doi: 10.1016/j.jbiomech.2018.01.008.

Carr, A. J., Robertsson, O., Graves, S., Price, A. J., Arden, N. K., Judge, A. and Beard, D. J. 2012. Knee replacement. *The Lancet* 379(9823), pp. 1331–1340.

Casuso-Holgado, M. J., Martín-Valero, R., Carazo, A. F., Medrano-Sánchez, E. M., Cortés-Vega, M. D. and Montero-Bancalero, F. J. 2018. Effectiveness of virtual reality training for balance and gait rehabilitation in people with multiple sclerosis: a systematic review and meta-analysis. *Clinical Rehabilitation* 32(9), pp. 1220–1234.

Ceballos-Laita, L., Lahuerta-Martín, S., Carrasco-Uribarren, A., Cabanillas-Barea, S., Hernández-Lázaro, H., Pérez-Guillén, S. and Jiménez-del-Barrio, S. 2023. Strength training vs. aerobic training for managing pain and physical function in patients with knee osteoarthritis: a systematic review and meta-analysis. *Healthcare* 12(1), 33.

Chau, B., Humbert, S. and Shou, A. 2021. Systemic literature review of the use of virtual reality for rehabilitation in Parkinson disease. *Federal Practitioner* 38(Suppl 1), S20.

Chen, T., Chen, J. and Or, C. K. 2024. Heuristic evaluation and end-user testing of a machine learning-based lower-limb exercise training system for management of knee pain in individuals aged 55 years or over. *International Journal of Industrial Ergonomics* 102. doi: 10.1016/j.ergon.2024.103607.

Chen, T., Or, C. K. and Chen, J. 2021. Effects of technology-supported exercise programmes on the knee pain, physical function, and quality of life of individuals with knee osteoarthritis and/or chronic knee pain: a systematic review and meta-analysis of randomized controlled trials. *Journal of the American Medical Informatics Association* 28(2), pp. 414–423. doi: 10.1093/jamia/ocaa282.

Cohen, J. 2013. *Statistical power analysis for the behavioral sciences*. Abingdon: Routledge.

Colberg, S. R. et al. 2016. Physical activity/exercise and diabetes: a position statement of the American Diabetes Association. *Diabetes Care* 39(11), 2065.

Collado-Mateo, D. et al. 2021. Key factors associated with adherence to physical exercise in patients with chronic diseases and older adults: an umbrella review.

International Journal of Environmental Research and Public Health 18(4), pp. 1–24. doi: 10.3390/ijerph18042023.

Collins, N. J., Bisset, L. M., Crossley, K. M. and Vicenzino, B. 2012. Efficacy of nonsurgical interventions for anterior knee pain: systematic review and meta-analysis of randomized trials. *Sports Medicine* 42, pp. 31–49.

Conner-Spady, B.L., Marshall, D.A., Bohm, E., Dunbar, M.J., Loucks, L., Khudairy, A.A. and Noseworthy, T.W. 2015. Reliability and validity of the EQ-5D-5L compared to the EQ-5D-3L in patients with osteoarthritis referred for hip and knee replacement., *Quality of Life Research* 24, pp. 1775–1784.

Corbetta, D., Imeri, F. and Gatti, R. 2015. Rehabilitation that incorporates virtual reality is more effective than standard rehabilitation for improving walking speed, balance, and mobility after stroke: a systematic review. *Journal of Physiotherapy* 61(3), pp. 117–124.

Costantini, L. et al. 2021. Screening for depression in primary care with Patient Health Questionnaire-9 (PHQ-9): A systematic review. *Journal of Affective Disorders* 279, pp. 473–483. doi: 10.1016/j.jad.2020.09.131.

Creswell, J. W. 2009. *Research design: Qualitative, quantitative, and mixed methods approach*. Thousand Oaks: Sage.

Crossley, K. M., van Middelkoop, M., Callaghan, M. J., Collins, N. J., Rathleff, M. S. and Barton, C. J. 2016. 2016 Patellofemoral pain consensus statement from the 4th International Patellofemoral Pain Research Retreat, Manchester. Part 2: recommended physical interventions (exercise, taping, bracing, foot orthoses and combined interventions). *British Journal of Sports Medicine* 50(14), pp. 844–852.

Daly, R. M., Dalla Via, J., Duckham, R. L., Fraser, S. F. and Helge, E. W. 2019. Exercise for the prevention of osteoporosis in postmenopausal women: an evidence-based guide to the optimal prescription. *Brazilian Journal of Physical Therapy* 23(2), pp. 170–180.

Dantas, L.O., de Fátima Salvini, T., and McAlindon, T.E. 2021. Knee osteoarthritis: key treatments and implications for physical therapy. *Brazilian Journal of Physical Therapy* 25(2), pp. 135–146.

Davis, F. D. 1987. *User acceptance of information systems: the technology acceptance model (TAM)*. University of Michigan working paper. Available at: https://quod.lib.umich.edu/b/busadwp/images/b/1/4/b1409190.0001.001.pdf.

Davis, F. D. 2014. *A technology acceptance model for empirically testing new end-user information systems*. PhD thesis, Massachusetts Institute of Technology. Available at: https://www.researchgate.net/publication/35465050.

Delsys Europe. (no date) *Systems*. Available at: https://delsyseurope.com/systems/ (Accessed: 04 December 2023).

de Rooij, M. et al. 2017. Efficacy of tailored exercise therapy on physical functioning in patients with knee osteoarthritis and comorbidity: a randomized controlled trial. *Arthritis Care & Research* 69(6), pp. 807–816.

de Santana, G. N., Dibai-Filho, A. V., da Silva Júnior, J. E. F., da Silva, A. C. B., de Jesus, S. F. C., dos Santos, P. G. and Fidelis-de-Paula-Gomes, C. A. 2022. Association between adherence to a home exercise programme and central sensitization, pain intensity, and functionality in individuals with knee osteoarthritis. *BMC Musculoskeletal Disorders* 23(1). doi: 10.1186/s12891-022-05959-6.

Dell'Isola, A., Allan, R., Smith, S. L., Marreiros, S. S. P. and Steultjens, M. 2016. Identification of clinical phenotypes in knee osteoarthritis: a systematic review of the literature. *BMC Musculoskeletal Disorders* 17, pp. 1–12.

Demir, S. 2022. Comparison of normality tests in terms of sample sizes under different skewness and Kurtosis coefficients. *International Journal of Assessment Tools in Education* 9(2), pp. 397–409.

Devlin, N.J., Shah, K.K., Feng, Y., Mulhern, B. and Van Hout, B. 2018. Valuing health-related quality of life: an EQ-5 D-5 L value set for England. *Health Economics* 27(1), pp. 7–22.

Dobson, F. et al. 2016. Barriers and facilitators to exercise participation in people with hip and/or knee osteoarthritis: synthesis of the literature using behavior change theory. *American Journal of Physical Medicine & Rehabilitation* 95(5), pp. 372–389. doi: 10.1097/PHM.0000000000000448.

Dockx, K. et al. 2016. Virtual reality for rehabilitation in Parkinson's disease. *Cochrane Database of Systematic Reviews* 12.

Dolezal, B. A., Neufeld, E. V, Boland, D. M., Martin, J. L. and Cooper, C. B. 2017. Interrelationship between sleep and exercise: a systematic review. *Advances in Preventive Medicine* 2017(1), 1364387.

Domínguez-Téllez, P., Moral-Muñoz, J.A., Salazar, A., Casado-Fernández, E. and Lucena-Antón, D. 2020. Game-based virtual reality interventions to improve upper limb motor function and quality of life after stroke: systematic review and meta-analysis. *Games for Health Journal* 9(1), pp.1–10.

Doury-Panchout, F., Metivier, J. C. and Fouquet, B. 2014. Kinesiophobia negatively influences recovery of joint function following total knee arthroplasty. *European Journal of Physical and Rehabilitation Medicine* 51(2), pp. 155–161.

Dupuis, F., Cherif, A., Batcho, C., Massé-Alarie, H. and Roy, J. S. 2023. The Tampa Scale of Kinesiophobia: a systematic review of its psychometric properties in people with musculoskeletal pain. *The Clinical Journal of Pain* 39(5), pp. 236–247. doi: 10.1097/AJP.0000000000001104.

Ebben, W.P., Simenz, C. and Jensen, R.L. 2008. Evaluation of plyometric intensity using electromyography. *The Journal of Strength & Conditioning Research* 22(3), pp. 861–868.

Ebrahimi, N., Rojhani-Shirazi, Z., Yoosefinejad, A. K. and Nami, M. 2021. The effects of virtual reality training on clinical indices and brain mapping of women with patellofemoral pain: a randomized clinical trial. *BMC Musculoskeletal Disorders 22*(1). doi: 10.1186/s12891-021-04785-6.

Edwards, A. W. F. 2005. RA Fischer, statistical methods for research workers (1925). In Grattan-Guinness, I. ed. *Landmark writings in western mathematics 1640-1940.* Amsterdam: Elsevier, pp. 856–870.

Ehioghae, M. et al. 2024. Effectiveness of virtual reality–based rehabilitation interventions in improving postoperative outcomes for orthopedic surgery patients. *Current Pain and Headache Reports* 28(1), pp. 37–45. doi: 10.1007/s11916-023-01192-5.

Eichler, S. et al. 2019. The effectiveness of telerehabilitation as a supplement to rehabilitation in patients after total knee or hip replacement: randomized controlled trial. *JMIR Rehabilitation and Assistive Technologies* 6(2), e14236.

Elaraby, A.E.R., Shahien, M., Jahan, A.M., Etoom, M. and Bekhet, A.H. 2023. The efficacy of virtual reality training in the rehabilitation of orthopedic ankle injuries: a systematic review and meta-analysis. *Advances in Rehabilitation Science and Practice* 12, 11795727231151636.

Escamilla, R. F. et al. 2009. Patellofemoral joint force and stress during the wall squat and one-leg squat. *Medicine and Science in Sports and Exercise* 41(4), pp. 879–888. doi: 10.1249/MSS.0B013E31818E7EAD.

Faul, F., Erdfelder, E., Lang, A. G. and Buchner, A. 2007. G*Power 3: a flexible statistical power analysis programme for the social, behavioral, and biomedical sciences. *Behavior Research Methods* 39(2), pp. 175–191. doi: 10.3758/BF03193146.

Fejer, R. and Ruhe, A, 2012. What is the prevalence of musculoskeletal problems in the elderly population in developed countries? A systematic critical literature review. *Chiropractic & Manual Therapies* 20, pp. 1–52.

Felson, D. T. 2009. Developments in the clinical understanding of osteoarthritis. *Arthritis Research and Therapy* 11(1), 203. doi: 10.1186/ar2531

Felson, D. T. 2013. Osteoarthritis as a disease of mechanics. *Osteoarthritis and Cartilage* 21(1), pp. 10–15.

Felson, D. T. et al. 2011. American College of Rheumatology/European League Against Rheumatism provisional definition of remission in rheumatoid arthritis for clinical trials. *Annals of the Rheumatic Diseases* 70(3), pp. 404–413. doi: 10.1136/ard.2011.149765.

Fernandes, C. S., Magalhães, B., Gomes, J. A. and Santos, C. 2022. Exergames to improve rehabilitation after anterior cruciate ligament injury: systematic review and GRADE evidence synthesis. *International Journal of Orthopaedic and Trauma Nursing* 44, 100917. doi: 10.1016/j.ijotn.2021.100917.

Fernandes, L. et al. 2013. EULAR recommendations for the non-pharmacological core management of hip and knee osteoarthritis. *Annals of the Rheumatic Diseases* 72(7), pp. 1125–1135. doi: 10.1136/ANNRHEUMDIS-2012-202745.

Field, A. 2024. *Discovering statistics using IBM SPSS statistics*. Thousand Oaks: Sage.

Fitzgerald, D., Foody, J., Kelly, D., Ward, T., Markham, C., McDonald, J. and Caulfield, B. 2007. Development of a wearable motion capture suit and virtual reality biofeedback system for the instruction and analysis of sports rehabilitation exercises. *Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, pp. 4870–4874. doi: 10.1109/IEMBS.2007.4353431.

Fragala, M. S., Cadore, E. L., Dorgo, S., Izquierdo, M., Kraemer, W. J., Peterson, M. D. and Ryan, E. D. 2019. Resistance training for older adults: position statement from the national strength and conditioning association. *The Journal of Strength & Conditioning Research* 33(8), 2019-2052. doi: 10.1519/JSC.0000000000003230.

Fransen, M., McConnell, S., Harmer, A. R., Van der Esch, M., Simic, M. and Bennell, K. L. 2015. Exercise for osteoarthritis of the knee. *Cochrane Database of Systematic Reviews* 2015(1). doi: 10.1002/14651858.CD004376.pub3.

French, D. J., France, C. R., Vigneau, F., French, J. A. and Evans, R. T. 2007. Fear of movement/(re)injury in chronic pain: a psychometric assessment of the original English version of the Tampa Scale for Kinesiophobia (TSK). *Pain* 127(1–2), pp. 42–51. doi: 10.1016/J.PAIN.2006.07.016.

Freund, T., Gensichen, J., Goetz, K., Szecsenyi, J. and Mahler, C. 2013. Evaluating self-efficacy for managing chronic disease: psychometric properties of the six-item Self-Efficacy Scale in Germany. *Journal of Evaluation in Clinical Practice* 19(1), pp. 39–43.

Fu, S. et al. 2021. Postural balance in individuals with knee osteoarthritis during stand-to-sit task. *Frontiers in Human Neuroscience* 15, 760960. doi: 10.3389/fnhum.2021.760960.

Garber, C. E. et al. 2011. Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: guidance for prescribing exercise. *Medicine & Science in Sports & Exercise* 43(7), pp, 1334–1359.

Garcia-Palacios, A. et al. 2015. Integrating virtual reality with activity management for the treatment of fibromyalgia: acceptability and preliminary efficacy. *Clinical Journal of Pain* 31(6), pp. 564-572. doi: 10.1097/AJP.0000000000000196.

Gazendam, A., Zhu, M., Chang, Y., Phillips, S. and Bhandari, M. 2022. Virtual reality rehabilitation following total knee arthroplasty: a systematic review and meta-analysis of randomized controlled trials. *Knee Surgery, Sports Traumatology, Arthroscopy* 30(8), pp. 2548-2555. doi: 10.1007/s00167-022-06910-x.

Geneen, L. J., Moore, R. A., Clarke, C., Martin, D., Colvin, L. A. and Smith, B. H. 2017. Physical activity and exercise for chronic pain in adults: an overview of Cochrane

Reviews. *Cochrane Database of Systematic Reviews* 2017(4). doi: 10.1002/14651858.CD011279.pub3.

Ghazwan, A., Wilson, C., Holt, C.A., and Whatling, G.M. 2022. Knee osteoarthritis alters peri-articular knee muscle strategies during gait. *PLOS One* 17(1), e0262798.

Gianola, S. et al. 2020. Effects of early virtual reality-based rehabilitation in patients with total knee arthroplasty: a randomized controlled trial. *Medicine (United States)* 99(7), e19136. doi: 10.1097/MD.0000000000019136.

Giggins, O. M., Persson, U. M. and Caulfield, B. 2013. Biofeedback in rehabilitation. *Journal of NeuroEngineering and Rehabilitation* 10(1), 60. doi: 10.1186/1743-0003-10-60.

Goh, S.-L. et al. 2019. Efficacy and potential determinants of exercise therapy in knee and hip osteoarthritis: a systematic review and meta-analysis. *Annals of Physical and Rehabilitation Medicine* 62(5), pp. 356–365.

Gold, J. I., Belmont, K. A. and Thomas, D. A. 2007. The neurobiology of virtual reality pain attenuation. *CyberPsychology & Behavior* 10(4), pp. 536–544.

Greenhalgh, T., Hinton, L., Finlay, T., Macfarlane, A., Fahy, N., Clyde, B. and Chant, A. 2019. Frameworks for supporting patient and public involvement in research: Systematic review and co-design pilot. *Health Expectations* 22(4), pp. 785–801. doi: 10.1111/hex.12888.

Group, T.E., 1990. EuroQol-a new facility for the measurement of health-related quality of life. *Health policy*, *16*(3), pp.199-208.

Gumaa, M. and Rehan Youssef, A. 2019. Is virtual reality effective in orthopedic rehabilitation? A systematic review and meta-analysis. *Physical Therapy* 99(10), pp. 1304–1325. doi: 10.1093/ptj/pzz093.

Guo, L., Li, S., Xie, S., Bian, L. and Shaharudin, S. 2024. The impact of digital healthcare systems on pain and body function in patients with knee joint pain: a systematic review and meta-analysis. *Scientific Reports* 14(1), 3310. doi: 10.1038/s41598-024-53853-z.

Hall, M. et al. 2021. Comparative effectiveness of exercise programmes for psychological well-being in knee osteoarthritis: a systematic review and network meta-analysis. *Seminars in Arthritis and Rheumatism* 51(5), pp. 1023–1032.

Hamilton, D. F., Akhtar, S., Griffiths, B., Prior, Y. and Jones, R. K. 2023. The use of technology to support lifestyle interventions in knee osteoarthritis: a scoping review. *Osteoarthritis and Cartilage Open* 5(2). doi: 10.1016/j.ocarto.2023.100344.

Hatfield, G. L., Morrison, A., Wenman, M., Hammond, C. A. and Hunt, M. A. 2016. Clinical tests of standing balance in the knee osteoarthritis population: systematic review and meta-analysis. *Physical Therapy 96*(3), pp. 324–337. doi: 10.2522/PTJ.20150025.

Heidari, B. 2011. Knee osteoarthritis prevalence, risk factors, pathogenesis, and features: Part I. *Caspian Journal of Internal Medicine* 2(2), 205.

Heiden, T. L., Lloyd, D. G. and Ackland, T. R. 2009. Knee joint kinematics, kinetics, and muscle co-contraction in knee osteoarthritis patient gait. *Clinical Biomechanics* 24(10), pp. 833–841.

Hensor, E. M. A., Dube, B., Kingsbury, S. R., Tennant, A. and Conaghan, P. G. 2014. Toward a clinical definition of early osteoarthritis: onset of patient-reported knee pain begins on stairs. Data from the Osteoarthritis Initiative. *Arthritis Care & Research* 67(1), 40. doi: 10.1002/ACR.22418.

Herdman, M. et al. 2011. Development and preliminary testing of the new five-level version of EQ-5D (EQ-5D-5L). *Quality of Life Research* 20(10), pp. 1727–1736. doi: 10.1007/s11136-011-9903-x.

Heuts, P.H., Vlaeyen, J.W., Roelofs, J., De Bie, R.A., Aretz, K., Van Weel, C., and Van Schayck, O.C. 2004. Pain-related fear and daily functioning in patients with osteoarthritis. *Pain* 110(1-2), pp. 228–235.

Hochberg, M.C. et al. 2012. American College of Rheumatology 2012 recommendations for the use of nonpharmacologic and pharmacologic therapies in osteoarthritis of the hand, hip, and knee. *Arthritis Care & Research* 64(4), pp. 465–474.

Hodges, P. W. and Tucker, K. 2011. Moving differently in pain: a new theory to explain the adaptation to pain. *Pain* 152(3), pp. S90–S98.

Høeg, E. R. et al. 2021. System immersion in virtual reality-based rehabilitation of motor function in older adults: a systematic review and meta-analysis. *Frontiers in Virtual Reality* 2. doi: 10.3389/frvir.2021.647993.

Hoffman, H. G. et al. 2011. Virtual reality as an adjunctive non-pharmacologic analgesic for acute burn pain during medical procedures. *Annals of Behavioral Medicine* 41(2), pp. 183–191.

Holden, M. A. et al. 2023. Recommendations for the delivery of therapeutic exercise for people with knee and/or hip osteoarthritis. An international consensus study from the OARSI Rehabilitation Discussion Group. *Osteoarthritis and Cartilage* 31(3), pp. 386–396. doi: 10.1016/j.joca.2022.10.009.

Holden, M. A., Nicholls, E. E., Young, J., Hay, E. M. and Foster, N. E. 2012. Role of exercise for knee pain: what do older adults in the community think? *Arthritis Care & Research* 64(10), pp. 1554–1564. doi: 10.1002/ACR.21700.

Holden, R. J. and Karsh, B. T. 2010. The technology acceptance model: its past and its future in health care. *Journal of Biomedical Informatics* 43(1), pp. 159–172. doi: 10.1016/j.jbi.2009.07.002.

Howard, M. C. 2017. A meta-analysis and systematic literature review of virtual reality rehabilitation programmes. *Computers in Human Behavior* 70, pp. 317–327. doi: 10.1016/j.chb.2017.01.013.

Hribernik, M., Umek, A., Tomažic, S. and Kos, A. 2022. Review of real-time biomechanical feedback systems in sport and rehabilitation. *Sensors* 22(8). doi: 10.3390/s22083006.

Hsu, W.C., Wang, T.M., Liu, M.W., Chang, C.F., Chen, H.L., and Lu, T.W. 2010. Control of body's center of mass motion during level walking and obstacle-crossing in older patients with knee osteoarthritis. *Journal of Mechanics* 26(2), pp. 229-237.

Hunt, M. A., Simic, M., Hinman, R. S., Bennell, K. L. and Wrigley, T. V. 2011. Feasibility of a gait retraining strategy for reducing knee joint loading: increased trunk lean guided by real-time biofeedback. *Journal of Biomechanics* 44(5), pp. 943–947.

Hunter, D. J. and Bierma-Zeinstra, S. 2019. Osteoarthritis. *The Lancet* 393(10182), pp. 1745–1759.

Hurley, M. et al. 2018. Exercise interventions and patient beliefs for people with hip, knee or hip and knee osteoarthritis: a mixed methods review. *The Cochrane Database of Systematic Reviews* 4(4). doi: 10.1002/14651858.CD010842.PUB2.

Hyodo, K., Masuda, T., Aizawa, J., Jinno, T. and Morita, S. 2017. Hip, knee, and ankle kinematics during activities of daily living: a cross-sectional study. *Brazilian Journal of Physical Therapy* 21(3), pp, 159–166. doi: 10.1016/j.bjpt.2017.03.012.

Ingham, S. L., Zhang, W., Doherty, S. A., McWilliams, D. F., Muir, K. R. and Doherty, M. 2011. Incident knee pain in the Nottingham community: a 12-year retrospective cohort study. *Osteoarthritis and Cartilage* 19(7), pp. 847–852. doi: 10.1016/J.JOCA.2011.03.012.

Jachak, S. and Phansopkar, P. 2022. Effect of oculus guided physical therapy in adjunct to conventional therapy in knee osteoarthritis patients. *Journal of Medical, Pharmaceutical and Allied Sciences* 11(4), pp. 5184–5189. doi: 10.55522/jmpas.V11I4.1315.

Jevsevar, D.S. 2013. Treatment of osteoarthritis of the knee: evidence-based guideline. *Journal of the American Academy of Orthopaedic Surgeons* 21(9), pp. 571–576.

Jin, C., Feng, Y., Ni, Y. and Shan, Z. 2018. Virtual reality intervention in postoperative rehabilitation after total knee arthroplasty: a prospective and randomized controlled clinical trial. *International Journal of Clinical and Experimental Medicine* 11(6), pp. 6119–6124.

Jinnouchi, H. et al. 2023. Brief self-exercise education for adults with chronic knee pain: a randomized controlled trial. *Modern Rheumatology* 33(2), pp. 408–415. doi: 10.1093/mr/roac009.

Jones, S. E., Campbell, P. K., Kimp, A. J., Bennell, K., Foster, N. E., Russell, T. and Hinman, R. S. 2021. Evaluation of a novel e-learning programme for physiotherapists to manage knee osteoarthritis via telehealth: qualitative study nested in the PEAK (physiotherapy exercise and physical activity for knee osteoarthritis) randomized controlled trial. *Journal of Medical Internet Research* 23(4). doi:10.2196/25872.

Jones, T., Moore, T. and Choo, J. 2016. The impact of virtual reality on chronic pain. *PLoS ONE* 11(12). doi: 10.1371/journal.pone.0167523.

Jorge, R. T. B., Souza, M. C. de, Chiari, A., Jones, A., Fernandes, A. da R. C., Júnior, I. L. and Natour, J. 2015. Progressive resistance exercise in women with osteoarthritis of the knee: a randomized controlled trial. *Clinical Rehabilitation* 29(3), pp. 234–243.

Juhl, C., Christensen, R., Roos, E. M., Zhang, W. and Lund, H. 2014. Impact of exercise type and dose on pain and disability in knee osteoarthritis: a systematic review and meta-regression analysis of randomized controlled trials. *Arthritis and Rheumatology* 66(3), pp. 622–636. doi: 10.1002/art.38290.

Karatsidis, A., Jung, M., Schepers, H.M., Bellusci, G., de Zee, M., Veltink, P.H. and Andersen, M.S. 2019. Musculoskeletal model-based inverse dynamic analysis under ambulatory conditions using inertial motion capture. *Medical Engineering & Physics* 65, pp. 68–77.

Kardong-Edgren, S.S., Farra, S.L., Alinier, G. and Young, H.M. 2019. A call to unify definitions of virtual reality. *Clinical Simulation in Nursing* 31, pp. 28–34.

Karimi, M. and Brazier, J. 2016. Health, health-related quality of life, and quality of life: what is the difference? *Pharmacoeconomics* 34, pp. 645–649.

Katz, J. and Seltzer, Z. 2009. Transition from acute to chronic postsurgical pain: risk factors and protective factors. *Expert Review of Neurotherapeutics* 9(5), pp. 723–744.

Kaya Utlu, D. 2023. Description, types, and prescription of the exercise. In Kaya Utlu, D. ed. *Functional Exercise Anatomy and Physiology for Physiotherapists*. Cham: Springer, pp. 3–18. doi: 10.1007/978-3-031-27184-7_1.

Kelley, G. A., Kelley, K. S. and Callahan, L. F. 2018. Community-deliverable exercise and anxiety in adults with arthritis and other rheumatic diseases: a systematic review with meta-analysis of randomised controlled trials. *BMJ Open* 8(2), e019138.

Kerari, A., Bahari, G., Alharbi, K. and Alenazi, L. 2024. The effectiveness of the chronic disease self-management programme in improving patients' self-efficacy and health-related behaviors: a quasi-experimental study. *Healthcare* 12(7), 778.

Khabsa, M., Elmagarmid, A., Ilyas, I., Hammady, H. and Ouzzani, M. 2015. Learning to identify relevant studies for systematic reviews using random forest and external information. *Machine Learning* 102, pp. 465–482. doi: 10.1007/s10994-015-5535-7.

King, W. R. and He, J. 2006. A meta-analysis of the technology acceptance model. *Information and Management* 43(6), pp. 740–755. doi: 10.1016/j.im.2006.05.003.

Knoop, J. et al. 2013. Knee joint stabilization therapy in patients with osteoarthritis of the knee: a randomized, controlled trial. *Osteoarthritis and Cartilage* 21(8), pp. 1025–1034.

Knoop, J. et al. 2014. Knee joint stabilization therapy in patients with osteoarthritis of the knee and knee instability: subgroup analyses in a randomized, controlled trial. *Journal of Rehabilitation Medicine* 46(7), pp. 703–707.

Knudson, D. 2009. Significant and meaningful effects in sports biomechanics research. *Sports Biomechanics* 8(1), pp. 96–104.

Koh, L. H., Hagger, M. S., Goh, V. H. H., Hart, W. G. and Gucciardi, D. F. 2017. Effects of a brief action and coping planning intervention on completion of preventive exercises prescribed by a physiotherapist among people with knee pain. *Journal of Science and Medicine in Sport* 20(8), pp. 723–728. doi: 10.1016/j.jsams.2017.02.008.

Koho, P., Aho, S., Watson, P. and Hurri, H. 2001. Assessment of chronic pain behaviour: reliability of the method and its relationship with perceived disability, physical impairment, and function. *Journal of Rehabilitation Medicine* 33(3), pp. 128–132.

Kolasinski, S. L. et al. 2020. 2019 American College of Rheumatology/Arthritis Foundation Guideline for the Management of Osteoarthritis of the Hand, Hip, and Knee. *Arthritis Care and Research* 72(2), pp. 149–162. doi: 10.1002/acr.24131.

Kortlever, J. T. P., Tripathi, S., Ring, D., McDonald, J., Smoot, B. and Laverty, D. 202). Tampa Scale for Kinesiophobia short form and lower extremity specific limitations. *Archives of Bone and Joint Surgery* 8(5), 581. doi: 10.22038/ABJS.2020.40004.2073

Krause, D. A., Elliott, J. J., Fraboni, D. F., McWilliams, T. J., Rebhan, R. L. and Hollman, J. H. 2018. Electromyography of the hip and thigh muscles during two variations of the lunge exercise: a cross-sectional study. *International Journal of Sports Physical Therapy* 13(2), 137.

Krepkovich, E. et al. 2022. Feasibility of a novel video game-based electromyography biofeedback system in patients with knee osteoarthritis. *Journal of Sport Rehabilitation* 31(7), pp. 937–942. doi: 10.1123/jsr.2021-0397.

Krippendorff, K. 2018. *Content analysis: an introduction to its methodology*. Thousand Oaks: Sage.

Kroenke, K., Spitzer, R. L. and Williams, J. B. W. 2001. The PHQ-9: validity of a brief depression severity measure. *Journal of General Internal Medicine* 16(9), pp. 606–613. doi: 10.1046/J.1525-1497.2001.016009606.X.

Lányi, C. S. 2014. *The thousand faces of virtual reality*. Croatia: InTech Open.

Larsson, C., Hansson, E. E., Sundquist, K. and Jakobsson, U. 2014. Psychometric properties of the Tampa Scale of Kinesiophobia (TSK-11) among older people with chronic pain. *Physiotherapy Theory and Practice* 30(6), pp. 421–428. doi: 10.3109/09593985.2013.877546.

Laver, K. E., Lange, B., George, S., Deutsch, J. E., Saposnik, G. and Crotty, M. 2017. Virtual reality for stroke rehabilitation. *Cochrane Database of Systematic Reviews*, 11.

Lee, I.-M., Shiroma, E. J., Lobelo, F., Puska, P., Blair, S. N. and Katzmarzyk, P. T. 2012. Effect of physical inactivity on major non-communicable diseases worldwide: an analysis of burden of disease and life expectancy. *The Lancet* 380(9838), pp. 219–229.

Lee, P.A., Wu, K.H., Lu, H.Y., Su, K.W., Wang, T.M., Liu, H.C. and Lu, T.W. 2021. Compromised balance control in older people with bilateral medial knee osteoarthritis during level walking. *Scientific Reports* 11(1), pp. 37–42.

Levac, D. E. and Galvin, J. 2013. When is virtual reality "therapy"? *Archives of Physical Medicine and Rehabilitation* 94(4), pp. 795–798.

Levin, M. F., Weiss, P. L. and Keshner, E. A. 2015. Emergence of virtual reality as a tool for upper limb rehabilitation: incorporation of motor control and motor learning principles. *Physical Therapy* 95(3), pp. 415–425.

Lewis, J.R. and Sauro, J. 2009. The factor structure of the system usability scale. *Proceedings of Human Centered Design: First International Conference, HCD 2009, Held as Part of HCI International 2009, San Diego, CA, USA, July 19-24, 2009, 1 (pp. 94-103).* Heidelberg: Springer Berlin.

Lewthwaite, R. and Wulf, G. 2017. Optimizing motivation and attention for motor performance and learning. *Current Opinion in Psychology* 16, pp. 38–42.

Ley, C. and Putz, P. 2024. Efficacy of interventions and techniques on adherence to physiotherapy in adults: an overview of systematic reviews and panoramic meta-analysis. *Systematic Reviews* 13(1). doi: 10.1186/s13643-024-02538-9.

Li, A., Montaño, Z., Chen, V. J. and Gold, J. I. 2011. Virtual reality and pain management: current trends and future directions. *Pain Management* 1(2), pp. 147–157.

Lin, P., Yu, L. F., Kuo, S. F., Wang, X. M., Lu, L. H. and Lin, C. H. 2022. Effects of computer-aided rowing exercise systems on improving muscle strength and function in older adults with mild knee osteoarthritis: a randomized controlled clinical trial. *BMC Geriatrics* 22(1). doi: 10.1186/s12877-022-03498-2.

Lin, Y. T., Lee, W. C. and Hsieh, R. L. 2020. Active video games for knee osteoarthritis improve mobility but not WOMAC score: a randomized controlled trial. *Annals of Physical and Rehabilitation Medicine* 63(6), pp. 458–465. doi: 10.1016/j.rehab.2019.11.008.

Lo, H. et al. 2024. Immersive and nonimmersive virtual reality–assisted active training in chronic musculoskeletal pain: systematic review and meta-analysis. *Journal of Medical Internet Research* 26, e48787. doi: 10.2196/48787.

Lohse, K. R., Hilderman, C. G. E., Cheung, K. L., Tatla, S. and Van der Loos, H. F. M. 2014. Virtual reality therapy for adults post-stroke: a systematic review and meta-analysis exploring virtual environments and commercial games in therapy. *PloS One* 9(3), e93318.

Lombard, M., Snyder-Duch, J. and Bracken, C. C. 2002. Content analysis in mass communication: assessment and reporting of intercoder reliability. *Human Communication Research* 28(4), pp. 587–604.

Lorig, K. R., Sobel, D. S., Ritter, P. L., Laurent, D. and Hobbs, M. 2001. Effect of a self-management programme on patients with chronic disease. *Effective Clinical Practice* 4(6), pp. 256–262.

Löwe, B., Unützer, J., Callahan, C.M., Perkins, A.J. and Kroenke, K, 2004. Monitoring depression treatment outcomes with the patient health questionnaire-9. *Medical Care* 42(12), pp. 1194–1201.

Lucena-Anton, D., Fernandez-Lopez, J.C., Pacheco-Serrano, A.I., Garcia-Munoz, C. and Moral-Munoz, J.A. 2022. Virtual and augmented reality versus traditional methods for teaching physiotherapy: A systematic review. *European Journal of Investigation in Health, Psychology and Education* 12(12), pp. 1780–1792.

Lundberg, M., Grimby-Ekman, A., Verbunt, J. and Simmonds, M.J. 2011. Pain-related fear: a critical review of the related measures. *Pain Research and Treatment* 2011(1), 494196.

Mallari, B., Spaeth, E. K., Goh, H. and Boyd, B. S. 2019. Virtual reality as an analgesic for acute and chronic pain in adults: a systematic review and meta-analysis. *Journal of Pain Research* 12, pp. 2053–2085. doi: 10.2147/JPR.S200498.

Malloy, K. M. and Milling, L. S. 2010. The effectiveness of virtual reality distraction for pain reduction: a systematic review. *Clinical Psychology Review* 30(8), pp. 1011–1018.

Mandal, S. 2013. Brief introduction of virtual reality & its challenges. *International Journal of Scientific & Engineering Research* 4(4), pp. 304–309.

Manlapaz, D.G., Sole, G., Jayakaran, P. and Chapple, C.M. 2022. Exergaming to improve balance and decrease the risk of falling in adults with knee osteoarthritis: a mixed-methods feasibility study. *Physiotherapy Theory and Practice* 38(13), pp. 2428–2440.

Marcori, A.J., Monteiro, P.H., Oliveira, J.A., Doumas, M. and Teixeira, L.A. 2022. Single leg balance training: a systematic review. *Perceptual and Motor Skills* 129(2), pp. 232–252.

Marks, R. 2012. Self-efficacy and its application in the treatment of knee osteoarthritis: a critical review. *Rheumatology Reports* 4(1), e10.

Marshall, A. N., Hertel, J., Hart, J. M., Russell, S. and Saliba, S. A. 2020. Visual biofeedback and changes in lower extremity kinematics in individuals with medial knee displacement. *Journal of Athletic Training* 55(3), pp. 255–264. doi: 10.4085/1062-6050-383-18.

Martinez-Hernandez, U. and Dehghani-Sanij, A. A. 2019. Probabilistic identification of sit-to-stand and stand-to-sit with a wearable sensor. *Pattern Recognition Letters* 118, pp. 32–41. doi: 10.1016/j.patrec.2018.03.020.

Matheve, T., Bogaerts, K. and Timmermans, A. 2020. Virtual reality distraction induces hypoalgesia in patients with chronic low back pain: a randomized controlled trial. *Journal of NeuroEngineering and Rehabilitation* 17(1), pp. 1–12. doi: 10.1186/S12984-020-00688-0/TABLES/2.

Matheve, T., Brumagne, S. and Timmermans, A. A. A. 2017. The effectiveness of technology-supported exercise therapy for low back pain: a systematic review. *American Journal of Physical Medicine & Rehabilitation* 96(5), pp. 347–356.

McAlindon, T. E. et al. 2014. OARSI guidelines for the non-surgical management of knee osteoarthritis. *Osteoarthritis and Cartilage* 22(3), pp. 363–388. doi: 10.1016/J.JOCA.2014.01.003.

McAllister, L. S. and Palombaro, K. M. 2020. Modified 30-second sit-to-stand test: reliability and validity in older adults unable to complete traditional sit-to-stand testing. *Journal of Geriatric Physical Therapy* 43(3), pp. 153–158. doi: 10.1519/JPT.0000000000000227.

McConnell, S., Kolopack, P. and Davis, A.M. 2001. The Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC): a review of its utility and measurement properties. *Arthritis Care & Research* 45(5), pp. 453–461.

Meldrum, D. et al. 2015. Effectiveness of conventional versus virtual reality–based balance exercises in vestibular rehabilitation for unilateral peripheral vestibular loss: results of a randomized controlled trial. *Archives of Physical Medicine and Rehabilitation* 96(7), 1319–1328.

Melzack, R. and Katz, J. 2013. Pain. *WIREs Cognitive Science* 4(1), pp. 1–15.

Merletti, R. and Muceli, S. 2019. Tutorial. Surface EMG detection in space and time: Best practices. *Journal of Electromyography and Kinesiology* 49, p.102363.

Messier, S. P. et al. 2013. Effects of intensive diet and exercise on knee joint loads, inflammation, and clinical outcomes among overweight and obese adults with knee osteoarthritis: the IDEA randomized clinical trial. *Journal of the American Medical Association* 310(12), pp. 1263–1273.

Mete, E. and Sari, Z. 2022. The efficacy of exergaming in patients with knee osteoarthritis: a randomized controlled clinical trial. *Physiotherapy Research International* 27(3). doi: 10.1002/pri.1952.

microsoft.com. 2022. *Azure Kinect DK documentation | Microsoft Learn*. https://learn.microsoft.com/en-us/azure/kinect-dk/.

Miguel-Rubio, A.D., Rubio, M.D., Salazar, A., Moral-Munoz, J.A., Requena, F., Camacho, R. and Lucena-Anton, D. 2020. Is virtual reality effective for balance recovery in patients with spinal cord injury? A systematic review and meta-analysis. *Journal of Clinical Medicine* 9(9), 2861.

Miller, R. P., Kori, S. H. and Todd, D. D. 1991. The Tampa scale: a measure of kinesiophobia. *The Clinical Journal of Pain* 7(1), 51. doi: 10.1097/00002508-199103000-00053.

Mills, K., Hettinga, B. A., Pohl, M. B. and Ferber, R. 2013. Between-limb kinematic asymmetry during gait in unilateral and bilateral mild to moderate knee osteoarthritis. *Archives of Physical Medicine and Rehabilitation* 94(11), pp. 2241–2247.

Minshull, C. and Gleeson, N. 2017. Considerations of the principles of resistance training in exercise studies for the management of knee osteoarthritis: a systematic review. *Archives of Physical Medicine and Rehabilitation* 9(9), pp. 1842–1851. doi: 10.1016/j.apmr.2017.02.026.

Mirelman, A., Patritti, B. L., Bonato, P. and Deutsch, J. E. 2010. Effects of virtual reality training on gait biomechanics of individuals post-stroke. *Gait and Posture* 31(4), pp. 433–437. doi: 10.1016/j.gaitpost.2010.01.016.

Molina, K.I., Ricci, N.A., de Moraes, S.A., and Perracini, M.R. 2014. Virtual reality using games for improving physical functioning in older adults: a systematic review. *Journal of Neuroengineering and Rehabilitation* 11, pp. 1–20.Moseley, G. L. and Butler, D. S. 2015. Fifteen years of explaining pain: the past, present, and future. *The Journal of Pain* 16(9), pp. 807–813.

Musahl, V. and Karlsson, J. 2019. Anterior cruciate ligament tear. *New England Journal of Medicine* 380(24), pp. 2341–2348.

Myer, G. D. et al. 2014. The back squat: a proposed assessment of functional deficits and technical factors that limit performance. *Strength & Conditioning Journal* 36(6), pp. 4–27.

Myers, J., Kokkinos, P. and Nyelin, E. 2019. Physical activity, cardiorespiratory fitness, and the metabolic syndrome. *Nutrients* 11(7), 1652.

National Institute for Care and Health Excellence. 2014. Osteoarthritis: care and management. *NICE Guidelines*. Available at: https://www.nice.org.uk/guidance/cg177.

National Institute for Care and Health Excellence. (2020). *Recommendations | Osteoarthritis: care and management.* NICE. https://www.nice.org.uk/guidance/cg177/chapter/1-recommendations.

Neogi, T. 2013. The epidemiology and impact of pain in osteoarthritis. *Osteoarthritis and Cartilage* 21(9), pp. 1145–1153. doi: 10.1016/J.JOCA.2013.03.018.

Neumann, D. A. 2024. *Neumann's kinesiology of the musculoskeletal system*. London: Elsevier Health Sciences.

Nicholas, M.K. et al. 2013. Self-management intervention for chronic pain in older adults: a randomised controlled trial. *Pain* 154(6) pp. 824–835.

Nicolson, P. J. A., Bennell, K. L., Dobson, F. L., Van Ginckel, A., Holden, M. A. and Hinman, R. S. 2017. Interventions to increase adherence to therapeutic exercise in older adults with low back pain and/or hip/knee osteoarthritis: a systematic review and meta-analysis. *British Journal of Sports Medicine* 51(10), pp. 791–799.

Nolan, C.M., Longworth, L., Lord, J., Canavan, J.L., Jones, S.E., Kon, S.S. and Man, W.D. 2016. The EQ-5D-5L health status questionnaire in COPD: validity, responsiveness, and minimum important difference. *Thorax* 71(6), pp. 493–500.

Noordzij, M., Tripepi, G., Dekker, F.W., Zoccali, C., Tanck, M.W. and Jager, K.J. 2010. Sample size calculations: basic principles and common pitfalls. *Nephrology Dialysis Transplantation* 25(5), pp.1388–1393.

Ocloo, J., Garfield, S., Franklin, B. D. and Dawson, S. 2021. Exploring the theory, barriers, and enablers for patient and public involvement across health, social care, and patient safety: a systematic review of reviews. *Health Research Policy and Systems* 19(1). doi: 10.1186/s12961-020-00644-3.

Okubo, Y., Schoene, D. and Lord, S.R. 2017. Step training improves reaction time, gait and balance and reduces falls in older people: a systematic review and meta-analysis. *British Journal of Sports Medicine* 51(7), pp. 586–593.

O'Reilly, S. C., Muir, K. R., Doherty, M., O'Reilly, S. C. and Muir, K. R. 1996. Screening for pain in knee osteoarthritis: which question? *Annals of Rheumatic Disease* 55, pp. 931–933. doi: 10.1136/ard.55.12.931.

Ouzzani, M., Hammady, H., Fedorowicz, Z. and Elmagarmid, A. 2016. Rayyan—a web and mobile app for systematic reviews. *Systematic Reviews* 5, pp. 1–10.

Overstreet, D. S. et al. 2023. A brief overview: sex differences in prevalent chronic musculoskeletal conditions. *International Journal of Environmental Research and Public Health* 20(5). doi: 10.3390/ijerph20054521.

Page, M. J. et al. 2016. Epidemiology and reporting characteristics of systematic reviews of biomedical research: a cross-sectional study. *PLoS Medicine* 13(5), e1002028.

Paillard, T. 2017. Relationship between muscle function, muscle typology and postural performance according to different postural conditions in young and older adults. *Frontiers in Physiology* 8, 585.

Pal, C. P., Singh, P., Chaturvedi, S., Pruthi, K. K. and Vij, A. 2016. Epidemiology of knee osteoarthritis in India and related factors. *Indian Journal of Orthopaedics 50*(5), 518. doi: 10.4103/0019-5413.189608.

Palazzo, C., Nguyen, C., Lefevre-Colau, M. M., Rannou, F. and Poiraudeau, S. 2016. Risk factors and burden of osteoarthritis. *Annals of Physical and Rehabilitation Medicine* 59(3), pp. 134–138. doi: 10.1016/J.REHAB.2016.01.006.

Pan, J., Huang, W., Huang, Z., Luan, J., Zhang, X. and Liao, B. 2023. Biomechanical analysis of lower limbs during stand-to-sit tasks in patients with early-stage knee osteoarthritis. *Frontiers in Bioengineering and Biotechnology* 11. doi: 10.3389/fbioe.2023.1330082.

Parmanto, B., Lewis, A.N., Graham, K.M. and Bertolet, M.H. 2016. Development of the telehealth usability questionnaire (TUQ). *International Journal of Telerehabilitation* 8(1), 3.

Patel, A.V. et al. 2019. American College of Sports Medicine roundtable report on physical activity, sedentary behavior, and cancer prevention and control. *Medicine and Science in Sports and Exercise* 51(11), 2391.

Patton, M. Q. 2014. *Qualitative research & evaluation methods: integrating theory and practice*. Thousand Oaks: Sage.

Pedersen, B.K. and Saltin, B., 2015. Exercise as medicine–evidence for prescribing exercise as therapy in 26 different chronic diseases. *Scandinavian journal of medicine & science in sports*, *25*, pp.1-72.

Pickford, C.G. et al. 2019. Quantifying sit-to-stand and stand-to-sit transitions in free-living environments using the activPAL thigh-worn activity monitor. *Gait & Posture* 73, pp. 140–146.

Pieper, D., Buechter, R.B., Li, L., Prediger, B. and Eikermann, M. 2015. Systematic review found AMSTAR, but not R(evised)-AMSTAR, to have good measurement properties. *Journal of Clinical Epidemiology* 68(5), pp. 574–583.

Piercy, K. L. et al. 2018. The physical activity guidelines for Americans. *Journal of the American Medical Association* 320(19), pp. 2020–2028. doi: 10.1001/JAMA.2018.14854.

Piqueras, M. et al. 2013. Effectiveness of an interactive virtual telerehabilitation system in patients after total knee arthroplasty: a randomized controlled trial. *Journal of Rehabilitation Medicine* 45(4), pp. 392–396. doi: 10.2340/16501977-1119.

Pirayeh, N., Kazemi, K., Rahimi, F., Mostafaee, N. and Shaterzadeh-Yazdi, M. J. 2022. The effect of balance training on functional outcomes in patients with knee osteoarthritis: a systematic review. *Medical Journal of the Islamic Republic of Iran*, 36(1), pp. 1–15. doi: 10.47176/mjiri.36.107.

Pollock, M., Fernandes, R. M., Becker, L. A., Pieper, D. and Hartling, L. 2020. Overviews of reviews. In *Cochrane Handbook for Systematic Reviews of Interventions Version 6*. Available at: https://training.cochrane.org/handbook.

Popay, J., Roberts, H., Sowden, A., Petticrew, M., Arai, L., Rodgers, M., Britten, N., Roen, K. and Duffy, S., 2006. Guidance on the conduct of narrative synthesis in systematic reviews. *A product from the ESRC methods programme Version*, *1*(1), p.b92.

Powers, C. M., Ho, K.-Y., Chen, Y.-J., Souza, R. B. and Farrokhi, S. 2014. Patellofemoral joint stress during weight-bearing and non—weight-bearing quadriceps exercises. *Journal of Orthopaedic & Sports Physical Therapy* 44(5), pp. 320–327.

Price, A., Clarke, M., Staniszewska, S., Chu, L., Tembo, D., Kirkpatrick, M. and Nelken, Y. 2022. Patient and public involvement in research: a journey to co-production. *Patient Education and Counseling* 105(4), pp. 1041–1047. doi: 10.1016/j.pec.2021.07.021.

Pruna, E., Pilatásig, M., Angueta, H., Hernandez, C., Escobar, I., Galarza, E. D. and Jacho, N. 2017. 3D virtual system trough 3 space mocap sensors for lower limb rehabilitation. In: De Paolis, L., Bourdot, P. and Mongelli, A. eds. *Augmented reality, virtual reality, and computer graphics. Lecture notes in computer science, vol 10325*. Cham: Springer. doi: 10.1007/978-3-319-60928-7_10.

Pua, Y.-H., Ong, P.-H., Clark, R. A., Matcher, D. B. and Lim, E. C.-W. 2017. Falls efficacy, postural balance, and risk for falls in older adults with falls-related emergency department visits: prospective cohort study. *BMC Geriatrics* 17, pp. 1–7.

Quicke, J. G., Foster, N. E., Thomas, M. J. and Holden, M. A. 2015. Is long-term physical activity safe for older adults with knee pain? A systematic review. *Osteoarthritis and Cartilage* 23(9), pp. 1445–1456.

Raja, S.N. et al. 2020. The revised International Association for the Study of Pain definition of pain: concepts, challenges, and compromises. *Pain* 161(9), pp. 1976–1982.

Rathleff, M.S., Rathleff, C.R., Olesen, J.L., Rasmussen, S., and Roos, E.M. 2016. Is knee pain during adolescence a self-limiting condition? Prognosis of patellofemoral pain and other types of knee pain. The American Journal of Sports Medicine 44(5), pp. 1165–1171.

Richards, R., van den Noort, J. C., van der Esch, M., Booij, M. J. and Harlaar, J. 2018. Gait retraining using real-time feedback in patients with medial knee osteoarthritis: feasibility and effects of a six-week gait training programme. *Knee* 25(5), pp. 814–824. doi: 10.1016/j.knee.2018.05.014.

Riddle, D.L., Wade, J.B., and Jiranek, W.A. 2010. Major depression, generalized anxiety disorder, and panic disorder in patients scheduled for knee arthroplasty. *The Journal of Arthroplasty* 25(4), pp. 581–588.

Ritter, P. L. and Lorig, K. 2014. The English and Spanish Self-Efficacy to Manage Chronic Disease Scale measures were validated using multiple studies. *Journal of Clinical Epidemiology* 67(11), pp. 1265–1273. doi: 10.1016/j.jclinepi.2014.06.009.

Rixe, J.A., Glick, J.E., Brady, J. and Olympia, R.P. 2013. A review of the management of patellofemoral pain syndrome. *The Physician and Sportsmedicine* 41(3), pp. 19–28.

Rizzo, A. S. and Shilling, R. 2017. Clinical virtual reality tools to advance the prevention, assessment, and treatment of PTSD. *European Journal of Psychotraumatology* 8(supp. 5), 1414560.

Robert-Lachaine, X., Mecheri, H., Larue, C. and Plamondon, A. 2017. Validation of inertial measurement units with an optoelectronic system for whole-body motion analysis. *Medical & Biological Engineering & Computing* 55, pp. 609–619.

Roelofs, J. et al. 2011. Norming of the Tampa Scale for Kinesiophobia across pain diagnoses and various countries. *Pain* 152(5), pp. 1090–1095. doi: 10.1016/J.PAIN.2011.01.028.

Roetenberg, D., Luinge, H. and Slycke, P. 2009. Xsens MVN: full 6DOF human motion tracking using miniature inertial sensors. *Xsens Motion Technologies BV* February, pp. 1–7.

Rogante, M., Grigioni, M., Cordella, D. and Giacomozzi, C. 2010. Ten years of telerehabilitation: a literature overview of technologies and clinical applications. *NeuroRehabilitation* 27(4), pp. 287–304. doi: 10.3233/NRE-2010-0612.

Rutkowski, S., Kiper, P., Cacciante, L., Mazurek, J. and Turolla, A. 2020. Use of virtual reality-based training in different fields of rehabilitation: a systematic review and meta-analysis. *Journal of Rehabilitation Medicine* 52(11), pp. 1–16.

Sabashi, K. et al. 2022. Changes in postural control strategy during quiet standing in individuals with knee osteoarthritis. *Journal of Back and Musculoskeletal Rehabilitation* 35(3), pp. 565–572.

Sammito, S. et al. 2021. Risk factors for musculoskeletal injuries in the military: a qualitative systematic review of the literature from the past two decades and a new prioritizing injury model. *Military Medical Research* 8(1), pp. 1–40. doi: 10.1186/S40779-021-00357-W/FIGURES/2.

Saposnik, G. et al. 2016. Efficacy and safety of non-immersive virtual reality exercising in stroke rehabilitation (EVREST): a randomised, multicentre, single-blind, controlled trial. *The Lancet Neurology* 15(10), pp. 1019–1027.

Sarantakos, S. 2017. *Social research*. London: Bloomsbury Publishing.

Sauro, J. 2011. *A practical guide to the system usability scale: Background, benchmarks & best practices*. Measuring Usability LLC.

Schepers, M., Giuberti, M. and Bellusci, G. 2018. Xsens MVN: consistent tracking of human motion using inertial sensing. *Xsens Technol* 1(8), pp. 1–8.

Schmitt, L. C. and Rudolph, K. S. 2008. Muscle stabilization strategies in people with medial knee osteoarthritis: the effect of instability. *Journal of Orthopaedic Research* 26(9), pp. 1180–1185. doi: 10.1002/jor.20619.

Scopaz, K. A., Piva, S. R., Wisniewski, S. and Fitzgerald, G. K. 2009. Relationships of fear, anxiety, and depression with physical function in patients with knee osteoarthritis. *Archives of Physical Medicine and Rehabilitation* 90(11), pp. 1866–1873.

Segal, N.A., Boyer, E.R., Wallace, R., Torner, J.C. and Yack, H.J. 2013. Association between chair stand strategy and mobility limitations in older adults with symptomatic knee osteoarthritis. *Archives of Physical Medicine and Rehabilitation* 94(2), pp. 375–383.

Sekhon, M., Cartwright, M. and Francis, J. J. 2017. Acceptability of healthcare interventions: an overview of reviews and development of a theoretical framework. *BMC Health Services Research* 17(1). doi: 10.1186/s12913-017-2031-8.

Semanik, P.A., Chang, R.W., and Dunlop, D.D. 2012. Aerobic activity in prevention and symptom control of osteoarthritis. *PM & R* 4(5), pp. S37–S44.

Shah, N.V., Gold, R., Dar, Q.A., Diebo, B.G., Paulino, C.B. and Naziri, Q. 2021. Smart technology and orthopaedic surgery: current concepts regarding the impact of smartphones and wearable technology on our patients and practice. *Current Reviews in Musculoskeletal Medicine* 14(6), pp.1-14.

Shea, B.J. et al. 2017. AMSTAR 2: a critical appraisal tool for systematic reviews that include randomised or non-randomised studies of healthcare interventions, or both. *British Medical Journal* 358, j4008.

Sherman, W. R. and Craig, A. B. 2003. *Understanding virtual reality*. San Francisco, CA: Morgan Kauffman.

Sherrington, C. and Tiedemann, A. 2015. Physiotherapy in the prevention of falls in older people. Journal of Physiotherapy 61(2), pp. 54–60.

Shi, Y. and Wu, W. 2023. Multimodal non-invasive non-pharmacological therapies for chronic pain: mechanisms and progress. *BMC Medicine* 21(1). doi: 10.1186/s12916-023-03076-2.

Simic, M., Hinman, R. S., Wrigley, T. V, Bennell, K. L. and Hunt, M. A. 2011. Gait modification strategies for altering medial knee joint load: a systematic review. *Arthritis Care & Research* 63(3), pp. 405–426.

Simons, L.E. et al. 2022. Virtual reality–augmented physiotherapy for chronic pain in youth: protocol for a randomized controlled trial enhanced with a single-case experimental design. *JMIR Research Protocols* 11(12), e40705.

Skjæret, N., Nawaz, A., Morat, T., Schoene, D., Helbostad, J.L. and Vereijken, B. 2016. Exercise and rehabilitation delivered through exergames in older adults: an integrative review of technologies, safety, and efficacy. *International Journal of Medical Informatics* 85(1), pp. 1–16.

Skivington, K. et al. 2021. A new framework for developing and evaluating complex interventions: update of Medical Research Council guidance. *British Medical Journal* 374. doi: 10.1136/BMJ.N2061.

Skou, S. T., Rasmussen, S., Laursen, M. B., Rathleff, M. S., Arendt-Nielsen, L., Simonsen, O. and Roos, E. M. 2015. The efficacy of 12 weeks non-surgical treatment for patients not eligible for total knee replacement: a randomized controlled trial with 1-year follow-up. *Osteoarthritis and Cartilage* 23(9), pp. 1465–1475. doi: 10.1016/j.joca.2015.04.021.

Sluka, K.A. 2016. *Mechanisms and management of pain for the physical therapist*. Lippincott Williams & Wilkins.

Smith, B. E. et al. 2018. Incidence and prevalence of patellofemoral pain: a systematic review and meta-analysis. *PLoS ONE* 13(1). doi: 10.1371/journal.pone.0190892.

Somaiya, K.J., Samal, S. and Boob, M.A. 2024. Physiotherapeutic intervention techniques for knee osteoarthritis: a systematic review. *Cureus* 16(3).

Somers, T.J. 2009. Pain catastrophizing and pain-related fear in osteoarthritis patients: relationships to pain and disability. *Journal of Pain and Symptom Management* 37(5), pp. 863–872.

Staartjes, V. E. and Schröder, M. L. 2018. The five-repetition sit-to-stand test: evaluation of a simple and objective tool for the assessment of degenerative pathologies of the lumbar spine. *Journal of Neurosurgery: Spine* 29(4), pp. 380–387. doi: 10.3171/2018.2.SPINE171416.

Stallard, N. and Rees, K. 2014. Using the NIHR research design service. *Paediatrics and Child Health* 24(12), pp. 572–573. doi: 10.1016/j.paed.2014.07.003.

Steinmetz, J.D. et al. 2023. Global, regional, and national burden of osteoarthritis, 1990–2020 and projections to 2050: a systematic analysis for the Global Burden of Disease Study 2021. *The Lancet Rheumatology* 5(9), pp. e508–e522.

Sterne, J.A. et al. 2016. ROBINS-I: a tool for assessing risk of bias in non-randomised studies of interventions. *British Medical Journal* 355.

Stubbs, B., Aluko, Y., Myint, P. K. and Smith, T. O. 2016. Prevalence of depressive symptoms and anxiety in osteoarthritis: a systematic review and meta-analysis. *Age and Ageing* 45(2), pp. 228–235.

Swift, D. L., McGee, J. E., Earnest, C. P., Carlisle, E., Nygard, M. and Johannsen, N. M. 2018. The effects of exercise and physical activity on weight loss and maintenance. *Progress in Cardiovascular Diseases* 61(2), pp. 206–213.

Swinkels-Meewisse, E.J.C.M., Swinkels, R.A.H.M., Verbeek, A.L.M., Vlaeyen, J.W.S. and Oostendorp, R.A.B. 2003. Psychometric properties of the Tampa Scale for Kinesiophobia and the Fear-Avoidance Beliefs questionnaire in acute low back pain. *Manual Therapy* 8(1), pp. 29–36.

Taherdoost, H. 2018. A review of technology acceptance and adoption models and theories. *Procedia Manufacturing* 22, pp. 960–967. doi: 10.1016/j.promfg.2018.03.137.

Tanaka, R., Ozawa, J., Kito, N. and Moriyama, H. 2013. Efficacy of strengthening or aerobic exercise on pain relief in people with knee osteoarthritis: a systematic review and meta-analysis of randomized controlled trials. *Clinical Rehabilitation* 27(12), pp. 1059–1071.

Templeton, K. J. 2020. Sex and gender issues in pain management. *Journal of Bone and Joint Surgery* 102(1 Suppl), pp. 32–35. doi: 10.2106/JBJS.20.00237.

Terbizan, D. J., Dolezal, B. A. and Albano, C. 2002. Validity of seven commercially available heart rate monitors. *Measurement in Physical Education and Exercise Science* 6(4), pp. 243–247. doi: 10.1207/S15327841MPEE0604_3.

The Health Foundation. 2023. *A once-in-a-generation opportunity to tackle the NHS's workforce crisis*. Retrieved from https://www.health.org.uk/news-and-comment/blogs/a-once-in-a-generation-opportunity-to-tackle-the-nhs-s-workforce-crisis.

Thumboo, J., Chew, L.H. and Soh, C.H. 2001. Validation of the Western Ontario and Mcmaster University osteoarthritis index in Asians with osteoarthritis in Singapore. *Osteoarthritis and Cartilage* 9(5), pp. 440–446.

Treede, R. D. et al. 2019. Chronic pain as a symptom or a disease: the IASP classification of chronic pain for the International Classification of Diseases (ICD-11). *Pain 160*(1), pp. 19–27. doi: 10.1097/J.PAIN.0000000000001384.

Trost, Z., France, C., Anam, M. and Shum, C. 2021. Virtual reality approaches to pain: toward a state of the science. *Pain* 162(2), pp. 325–331. doi: 10.1097/j.pain.0000000000002060.

Trost, Z., Zielke, M., Guck, A., Nowlin, L., Zakhidov, D., France, C. R. and Keefe, F. 2015. The promise and challenge of virtual gaming technologies for chronic pain: the case of graded exposure for low back pain. *Pain Management* 5(3), pp. 197–206.

Tschon, M., Contartese, D., Pagani, S., Borsari, V. and Fini, M. 2021. Gender and sex are key determinants in osteoarthritis not only confounding variables. A systematic review of clinical data. *Journal of Clinical Medicine* 10(14), 3178. doi: 10.3390/jcm10143178.

Tuck, N. et al. 2022. Active virtual reality for chronic primary pain: mixed methods randomized pilot study. *JMIR Formative Research* 6(7), e38366.

Tullis, T.S. and Stetson, J.N. 2004. A comparison of questionnaires for assessing website usability. *Usability Professional Association Conference* 1, pp. 1-12.

Turner, M., Kitchenham, B., Brereton, P., Charters, S. and Budgen, D. 2010. Does the technology acceptance model predict actual use? A systematic literature review. *Information and Software Technology* 52(5), pp. 463–479. doi: 10.1016/j.infsof.2009.11.005.

Uritani, D., Kasza, J., Campbell, P. K., Metcalf, B. and Egerton, T. 2020. The association between psychological characteristics and physical activity levels in people with knee osteoarthritis: a cross-sectional analysis. *BMC Musculoskeletal Disorders 21*(1). doi: 10.1186/s12891-020-03305-2.

Van Hout, B. et al. 2012. Interim scoring for the EQ-5D-5L: mapping the EQ-5D-5L to EQ-5D-3L value sets. *Value in Health* 15(5), pp. 708–715.

Vehovar, V., Toepoel, V. and Steinmetz, S. 2016. Non-probability sampling. In Wolfe, C., Joye, D., Smith, T. and Fu, Y-C. eds. *The SAGE Handbook of Survey Methodology.* Thousand Oaks: Sage, pp. 327–343.

Venkatesh, V. and Bala, H. 2008. Technology acceptance model 3 and a research agenda on interventions. *Decision Sciences* 39(2), pp. 273–315. doi: 10.1111/j.1540-5915.2008.00192.x.

Venkatesh, V. and Davis, F. D. 2000. Theoretical extension of the technology acceptance model: four longitudinal field studies. *Management Science* 46(2), pp. 186–204. doi: 10.1287/mnsc.46.2.186.11926.

Venkatesh, V., Morris, M. G., Davis, G. B. and Davis, F. D. 2003. User acceptance of information technology: toward a unified view. *MIS Quarterly* 27(3), pp. 425–478.

Verlaan, L. et al. 2018. Biomechanical alterations during sit-to-stand transfer are caused by a synergy between knee osteoarthritis and obesity. *BioMed Research International 2018*. doi: 10.1155/2018/3519498.

Versus Arthritis. 2022. *The state of musculoskeletal health 2022*. Retrieved from https://versusarthritis.org/about-arthritis/data-and-statistics/the-state-of-musculoskeletal-health/

Versus Arthritis. 2024. *Versus Arthritis osteoarthritis information booklet*. Available at: https://www.versusarthritis.org/media/22908/osteoarthritis-information-booklet.pdf

Vierck, C. J., Whitsel, B. L., Favorov, O. V, Brown, A. W. and Tommerdahl, M. 2013. Role of primary somatosensory cortex in the coding of pain. *Pain* 154(3), pp. 334–344.

Villadsen, A., Overgaard, S., Holsgaard-Larsen, A., Christensen, R. and Roos, E. M. 2014. Immediate efficacy of neuromuscular exercise in patients with severe osteoarthritis of the hip or knee: a secondary analysis from a randomized controlled trial. *The Journal of Rheumatology* 41(7), pp. 1385–1394.

Vincent, K. R., Conrad, B. P., Fregly, B. J. and Vincent, H. K. 2012. The pathophysiology of osteoarthritis: a mechanical perspective on the knee joint. *PM&R*, 4(5), pp. S3–S9.

Vlaeyen, J.W., Kole-Snijders, A.M., Boeren, R.G. and van Eek, H. 1995. Fear of movement/(re) injury in chronic low back pain and its relation to behavioral performance. *Pain* 62(3), pp. 363–372.

Vlaeyen, J. W. S. and Linton, S. J. 2000. Fear-avoidance and its consequences in chronic musculoskeletal pain: a state of the art. *Pain* 85(3), pp. 317–332.

Wade, D. T., Smeets, R. J. E. M. and Verbunt, J. A. 2010. Research in rehabilitation medicine: methodological challenges. *Journal of Clinical Epidemiology* 63(7), pp. 699–704.

Wallis, J. A., Webster, K. E., Levinger, P. and Taylor, N. F. 2013. What proportion of people with hip and knee osteoarthritis meet physical activity guidelines? A systematic review and meta-analysis. *Osteoarthritis and Cartilage* 21(11), pp. 1648–1659. doi: 10.1016/J.JOCA.2013.08.003.

Wang, B., Shen, M., Wang, Y., He, Z., Chi, S. and Yang, Z. 2019. Effect of virtual reality on balance and gait ability in patients with Parkinson's disease: a systematic review and meta-analysis. *Clinical Rehabilitation* 33(7), pp. 1130–1138.

Wang, Q., Kurillo, G., Ofli, F. and Bajcsy, R. 2015. Evaluation of pose tracking accuracy in the first and second generations of Microsoft Kinect. *Proceedings – 2015 IEEE International Conference on Healthcare Informatics, ICHI 2015*, pp. 380–389. doi: 10.1109/ICHI.2015.54.

Wang, X. et al. 2019. Technology-assisted rehabilitation following total knee or hip replacement for people with osteoarthritis: a systematic review and meta-analysis. *BMC Musculoskeletal Disorders 20*(1), 506. doi: 10.1186/s12891-019-2900-x.

Wasenmüller, O. and Stricker, D. 2017. Comparison of kinect v1 and v2 depth images in terms of accuracy and precision. *In Computer Vision–ACCV 2016 Workshops: ACCV 2016 International Workshops, Taipei, Taiwan, November 20-24, 2016, Revised Selected Papers, Part II.* Springer International Publishing, pp. 34-45.

Wiederhold, B. K., Gao, K., Sulea, C. and Wiederhold, M. D. 2014. Virtual reality as a distraction technique in chronic pain patients. *Cyberpsychology, Behavior, and Social Networking* 17(6), pp. 346–352.

Wilson, P. et al. 2015. ReseArch with Patient and Public invOlvement: a RealisT evaluation – the RAPPORT study. *Health Services and Delivery Research* 3(38), pp. 1–176. doi: 10.3310/hsdr03380.

Winter, D. A. 2009. *Biomechanics and motor control of human movement*. Hoboken, NJ: John Wiley & Sons.

Wood, D., Metcalfe, A., Dodge, J. and Templeton-Ward, O. 2016. Are squats and lunges safe in the rehabilitation of patients with patellofemoral pain? *Orthopaedic Journal of Sports Medicine 4*(2_suppl), 2325967116S0002. doi: 10.1177/2325967116s00020.

Wood, G., Neilson, J., Cottrell, E., and Hoole, S.P., 2023. Osteoarthritis in people over 16: diagnosis and management—updated summary of NICE guidance*. British Medical Journal* 380.

Woolf, C. J. 2011. Central sensitization: implications for the diagnosis and treatment of pain. *Pain 152*(3), pp. S2–S15.

Wu, L. R., Parkerson, G. R. and Doraiswamy, P. M. 2002. Health perception, pain, and disability as correlates of anxiety and depression symptoms in primary care patients. *The Journal of the American Board of Family Practice* 15(3), pp. 183–190.

Xsens Technologies B.V. 2021. *MVN user manual [online]. Version 2020.2*. Available at: https://www.xsens.com/hubfs/Downloads/usermanual/MVN_User_Manual.pdf [Accessed: 10 December 2023].

Yasen, S. K. 2023. Common knee injuries, diagnosis, and management. *Surgery (Oxford)* 41(4), pp. 215–555.

Young, J. J., Pedersen, J. R. and Bricca, A. 2023. Exercise therapy for knee and hip osteoarthritis: is there an ideal prescription? *Current Treatment Options in Rheumatology* 9(3), pp. 82–98. doi: 10.1007/s40674-023-00205-z.

Yu, M., Corletto, J. and Barkley, L. C. 2021. *Exercise Prescription*. www.acsm-csmr.org.

Zeng, C.-Y., Zhang, Z.-R., Tang, Z.-M. and Hua, F.-Z. 2021. Benefits and mechanisms of exercise training for knee osteoarthritis. *Frontiers in Physiology 12*, 794062.

Zhu, S., Qu, W. and He, C. 2024. Evaluation and management of knee osteoarthritis. *Journal of Evidence-Based Medicine* 17(3), pp. 675–687.

Zimmerli, L., Jacky, M., Lünenburger, L., Riener, R. and Bolliger, M. 2013. Increasing patient engagement during virtual reality-based motor rehabilitation. *Archives of Physical Medicine and Rehabilitation* 94(9), pp. 1737–1746.

Appendices

Appendix 1

Study 1: Effects of technology-supported exercise programmes on the knee pain, physical function, and quality of life of individuals with knee osteoarthritis and/or chronic knee pain: A systematic review and meta-analysis of randomised controlled trials

Study name	Effects of technology-supported exercise programmes on the knee pain, physical function, and quality of life of individuals with knee osteoarthritis and/or chronic knee pain
Study details	Chen T, Or CK, Chen J. Effects of technology-supported exercise programmes on the knee pain, physical function, and quality of life of individuals with knee osteoarthritis and/or chronic knee pain: A systematic review and meta-analysis of randomized controlled trials. J Am Med Inform Assoc. 2021;28(2):414-423. doi:10.1093/jamia/ocaa282
Author/year	Tianrong Chen, Calvin Kalun Or, and Jiayin Chen/ 24 January 2022
Objectives	examine the effects of technology-supported exercise programmes on the knee pain, physical function, and quality of life of individuals with knee osteoarthritis and/or chronic knee pain by a systematic review and meta-analysis of randomized controlled trials.
Participants (characteristics, total number)	adults (18 years of age or older), included individuals who had a diagnosis of knee OA or had chronic knee pain for at least 1 month in the last 12 months prior to the studies (Total number range from 34-282)
Setting/context	Remote/home setting
Description of interventions/phenomenon of interest	All the RCTs implemented the technology-supported exercise programmes for a short period (4 weeks to 6 months). - conventional care, such as face-to-face physical therapy or educational materials - Five types of technology were used to deliver exercise programmes such as telephone,

	web-based exercise video, web and mobile app, Interactive exercise games supported by computer and virtual reality.
Search details	The search used both Medical Subject Headings and free-text words related to knee OA, knee pain, exercise therapy, sup- porting technology, the outcomes of interest to this review, as well as the Cochrane Highly Sensitive Search Strategy to identify RCTs. Duplicate citations were removed using EndNote and by manual screening. Screen the titles and abstracts, then reviewed the full texts of potentially relevant citations to determine whether they should be included in the analysis. Finally, the reference lists were manually searched to identify any studies that had been missed and warranted inclusion.
Sources searched	MEDLINE via Ovid (from 1946 to present) resulted in 304, EMBASE via Ovid (from 1974 to present) resulted in 1.167, CINAHL Plus via EBSCOhost (from 1937 to present) resulted in 265, and the Cochrane Library (no date restriction) resulted in 980 citations.
Range (years) of included studies	Before 2010/ 1 study 2010–2014/ 2 studies 2015–2019/ 9 studies
Number of studies included	12
Types of studies included	RCTs
Country of origin of included studies	North America Asia Oceania Africa
Appraisal	The methodological quality, Quality graded as high, moderate, or low for studied outcomes. For each of the outcomes, the quality of evidence was downgraded by 1 level from high quality for each serious problem found in the domains of risk of bias, inconsistency, indirectness, imprecision, and publication bias
Appraisal instruments used	The GRADE (Grading of Recommendations Assessment, Development and Evaluation) approach

	The methodological quality of each included RCT was assessed independently by T.C. and J.C. using the Cochrane risk-of-bias tool.
Appraisal rating	The quality of evidence across all the RCTs for quality of life was high, while that for knee pain and physical function was moderate due to substantial heterogeneity. details of the random-sequence generation were not reported in 2 (16.7%) RCTs & lack of clarity regarding adequate allocation concealment was in 5 (41.7%) RCTs were identified as having selection bias, performance bias was detected owing to lack of or the partial blinding of participants and healthcare providers was identified in 11 (91.7%) RCTs, and it was unclear whether the outcome assessors were blinded in 8 (66.7%) RCTs, Attrition bias was detected in 1 (8.3%) RCT, with dropout rate > 50%.
Analysis	• The meta-analysis results measured by the standardized mean difference (SMD) for the following outcome Knee pain → -0.29 (-0.48 to -0.10) Physical function → 0.22 (0 to 0.43) Quality of life → 0.25 (0.04 to 0.46) • The I2 statistic was used to measure heterogeneity Knee pain → 62 % substantial heterogeneity Physical function → 73% substantial heterogeneity Quality of life → 45% low to moderate heterogeneity • Egger's regression test was used to assess the possibility of publication bias *t* value Knee pain → 1.20 Physical function → 0.33 Quality of life → 0.72 • Subgroup analysis for the outcomes by technology type

	There was no significant improvement in physical function when assessing the individual technology type, and no significant subgroup difference was detected (P= 0.69) • Subgroup analysis of the outcomes by programme feature Programmes that involved the feature of video-based exercise demonstration were associated with a significantly greater improvement in physical function, compared with those that did not involve this feature (subgroup difference: P= 0.02). Programmes that involved the features of video-based exercise demonstration and sensor-based motion and physical activity tracking, they did not show a significant improvement in quality of life, and similar changes were identified between subgroups.
Method of analysis	Random effect Meta-analysis
Outcome/s assessed	Knee pain, physical function, and quality of life.
Results/findings	The short-term effects of technology-supported exercise programmes on knee pain, physical function, and quality of life among individuals with knee OA and/or chronic knee pain were associated with significant and clinically important improvements in knee pain and quality of life but not with physical function.
Significance/direction	A significant reduction in knee pain was observed (SMD = −0.29; 95% confidence interval [CI], −0.48 to −0.10; P = .003); Based on the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) pain subscale. The observed SMD of –0.29 can be translated to a WOMAC pain change of –1.31 points on the 0-20 scale, which can be considered clinically important. For quality of life, a statistically significant improvement was detected (SMD = 0.25; 95% CI, 0.04 to 0.46; P = .02), and the observed SMD represented an improvement of 4.80

	points on the most frequently reported 100-point Knee Injury and Osteoarthritis Outcome Score quality-of-life subscale. No find evidence for a significant improvement in physical function was found (SMD = 0.22; 95% CI, 0 to 0.43; P = .053). Subgroup analysis for the outcomes by technology type: o For knee pain, the use of web (SMD = −0.48; 95% CI, −0.90 to −0.05; *P* = .03) or mobile app (SMD = −0.45; 95% CI, −0.88 to −0.02; *P* = .04) was associated with a significant reduction in knee pain, which equated to a decrease of more than 2 points on the 20-point WOMAC pain subscale, but for the use of telephone it wasn't; the subgroup difference was not significant (*P* = .27). o The use of Web to deliver the programmes was associated with improved quality of life (SMD = 0.59; 95% CI, 0.11 to 1.07; P = .02), which equated to an improvement of 11.33 points on the 100-point Knee Injury and Osteoarthritis Outcome Score quality-of-life subscale, whereas the use of telephone, mobile app, or computer was not; the subgroup difference was not significant (P = .32) No significant improvement in physical function was observed, when assessing the individual technology type, and no significant subgroup difference was detected (P = .69).

Heterogeneity	For knee pain and physical function substantial heterogeneity was reported ($I^2 > 50\%$).

Study 2: Is Virtual Reality Effective in Orthopaedic Rehabilitation? A Systematic Review and Meta-Analysis

Study name	Is Virtual Reality Effective in Orthopaedic Rehabilitation?
Study details	A Systematic Review and Meta-Analysis
Author/year	Mohammed Gumaa and Aliaa Rehan Youssef/ October 2019
Objectives	To systematically review and critically appraise controlled clinical trials that have investigated VR's effectiveness in orthopaedic rehabilitation.
Participants (characteristics, total number)	19 articles were included in the quality assessment categorized into general, region-specific (upper, and lower limb) disorders. In lower limb disorders, 5 articles were included with 2 articles only on Knee OA, 119 participants in total.
Setting/context	Clinical setting
Description of interventions/phenomenon of interest	Articles were included if they were controlled clinical trials conducted involving adult individuals with orthopaedic disorders who were treated with VR as either a standalone or adjunct therapy for more than 1 treatment session.
Search details	The following keywords and Boolean operators: (virtual OR virtual reality OR virtual environment OR computer-based OR computer-interface OR cyberspace OR artificial intelligence OR computer simulat∗ OR simulator OR Exergam∗ OR active video gam∗ OR interactive gam∗ OR game OR gaming OR X-box OR Kinect OR Nintendo OR Wii) AND (orthopedic∗ OR orthopaedic∗ OR musculoskeletal) AND (physical therapy OR physiotherapy OR exercise OR therapeutic∗ OR treatment OR training OR intervention OR rehabilitation) NOT (stroke OR cerebral palsy OR cancer OR tumor OR carcinoma OR oncology OR

	neurologic* OR dentistry OR obesity OR children OR pediatric). The search was carried out from database inception until September 6, 2018. The bibliographic references of included articles were searched manually for additional relevant studies. Finally, all eligible studies were entered in Scopus and the Web of Science to identify all the articles that had cited them (snowballing).
Sources searched	PubMed, CINAHL, Embase, PEDro, REHABDATA, and Sage Publications
Range (years) of included studies	2007/2017
Number of studies included	Nineteen articles – 2 articles on Knee OA
Types of studies included	controlled clinical trials
Country of origin of included studies	Taiwan, Republic of China And Republic of Korea
Appraisal	The methodological quality
Appraisal instruments used	the Evaluation Guidelines for Rating the Quality of an Intervention Study scoring system.
Appraisal rating	The Final score of the quality assessment in Lin et.al. (2007) study is thirty. The Final score of the quality assessment in Kim et.al. (2017) is twenty-two.
Analysis	The Review Manager (RevMan) software
Method of analysis	A random-effects model
Outcome/s assessed	ROM, pain, strength, function, balance, and gait
Results/findings	It has been concluded that VR is comparable with other exercises and can be used alternatively for OA treatment.
Significance/direction	For knee OA, evidence from two studies of low to moderate quality revealed VR comparability with physical exercises and superiority to no treatment control. More high-quality studies are thus needed to confirm VR effectiveness in the management of OA of different severities and in different joints.

Heterogeneity	N/A

Study 3: Virtual reality rehabilitation following total knee arthroplasty: a systematic review and meta-analysis of randomised controlled trials.

Study name	Virtual reality rehabilitation following total knee arthroplasty
Study details	A Systematic Review and Meta-Analysis
Author/year	Aaron Gazendam, Meng Zhu, Yaping Chang, Steve Phillips, Mohit Bhandari/ February 2022
Objectives	To analyse pain scores, functional outcomes and cost analyses from randomized controlled trials utilizing VR- based rehabilitation in patients following TKA
Participants (characteristics, total number)	9 RCTs with 835 patients randomized to VR-based telerehabilitation vs. traditional rehabilitation. All patients underwent primary TKA. The median sample size was 50 (range 26–306). The median age of included patients was 68.5 (IQR; 66.9–72.7) years. Of the 835 patients, 299 (36%) were male. Follow-up ranged from 10 days postoperatively to 6 months postoperatively
Setting/context	Burlington, ON, Canada
Description of interventions/phenomenon of interest	Eligible studies were RCTs investigating a rehabilitation programme involving a VR tool; defined as hardware/software devices creating a simulated environment for adult patients who have undergone TKA to interact with.
Search details	Both index terms and free-text terms regarding “virtual reality” and “TKA” were searched, and the results were filtered for RCTs. In addition, the reference lists of related systematic reviews were cross-referenced to identify eligible studies.
Sources searched	Ovid MEDLINE, Ovid EMBASE, and Cochrane Controlled Register of Trials (CENTRAL) were searched for potentially eligible studies
Range (years) of included studies	from inception to October 25, 2021
Number of studies included	9 RCTs
Types of studies included	RCT
Country of origin of included studies	Not mentioned

Appraisal	Risk of bias, quality of evidence and quantitative synthesis
Appraisal instruments used	the Cochrane risk of bias two tool and the GRADE (Grading of Recommendations, Assessment, Development and Evaluations) approach and using Review Manager (RevMan).
Appraisal rating	• The highest risk of bias was performance bias arising from inadequate blinding of participants and personnel. • GRADE rating ○ VAS (≤2 weeks – 3months after TKA)- Very Low quality DSI- Moderate for 12 weeks after, low for 6 months after TKA and very low for ≤6 weeks after TKA
Analysis	A meta-analysis
Method of analysis	A random-effects model was performed and generated forest plots.
Outcome/s assessed	VAS for pain scores, functional outcomes (WOMAC, KOOS), and cost analyses

Results/findings	• For VAS
	  ○ In studies evaluating pain scores within 2 weeks following surgery (n = 282), no differences in pain scores were identified between sample and control group. Similarly, in studies evaluating pain scores > 3 months from surgery (n = 133), no differences in pain scores were found between groups.
	• For DSI
	  ○ Four studies (n = 457) evaluated DSI within the 6-week postoperative period - no significant differences were demonstrated
	VR-based rehabilitation made statistically significant improvements in DSI at 12 weeks (n = 353) postoperatively [mean difference (MD) − 3.32, 95% confidence interval (CI) − 5.20 to − 1.45] and 6 months (n = 66)

	postoperatively [MD − 4.75, 95% CI − 6.69 to − 2.81], compared to traditional rehabilitation
Significance/direction	The quality of evidence was moderate to very low, indicating that current evidence is inadequate to allow a clear conclusion. Small sample size in the meta-analysis is one of the main concerns. The review is limited by the available of high-quality evidence and variability in the rehabilitation protocols. Future research is required to confirm the results of the current study and to evaluate the optimal VR-rehabilitation protocol
Heterogeneity	None

Study 4: Exergames to improve Rehabilitation after Anterior Cruciate Ligament Injury

Study name	Exergames to improve Rehabilitation after Anterior Cruciate Ligament Injury
Study details	https://doi.org/10.1016/j.ijotn.2021.100917 Exergames to improve Rehabilitation after Anterior Cruciate Ligament Injury: Systematic review and GRADE evidence synthesis. Carla Sílvia Fernandes, PhD, Bruno Magalha˜es, Jos´e Augusto Gomes, C´elia Santos.
Author/year	Carla Sílvia Fernandes, PhD Bruno Magalha˜esb, Jos´e Augusto Gomesd, C´elia Santos/ November 2021
Objectives	To assess the effectiveness of exergames compared to standard rehabilitation care after reconstruction of the anterior cruciate ligament.
Participants (characteristics, total number)	In total, 128 people participated in all the studies and were mostly men (n = 96) from younger age groups.
Setting/context	Not mentioned
Description of interventions/phenomenon of interest	the intervention programmes used were primarily the Nintendo Wii
Search details	Regarding population, all publications in which the diagnosis was ACL rupture and in which injuries were surgically reconstructed, were included. Regarding intervention, all publications that described and evaluated an exergame to

	support patients at any stage of the rehabilitation process were included. The following outcomes were included in the analysis: rehabilitation outcomes, pain, strength, balance, coordination, and knee proprioception. Only publications reporting RCTs were considered.
Sources searched	MEDLINE, CINAHL, SPORTDiscus, SCOPUS, SciELO, Cochrane Central Register of Controlled Trials and PEDro.
Range (years) of included studies	All studies up to May 2021.
Number of studies included	Five articles
Types of studies included	Only RCTs with a diagnosis of ACL rupture, surgically reconstructed, and an intervention with exergames carried out, using of two groups, comparing exergame with usual functional rehabilitation care.
Country of origin of included studies	Portugal
Appraisal	The quality of evidence and the strength of the recommendations
Appraisal instruments used	The Rating, Development, and Evaluation of the Rating of Recommendations (GRADE)
Appraisal rating	The overall quality of the evidence of efficacy was assessed mostly as moderate.
Analysis	Meta-analysis
Method of analysis	The Review Manager software RevMan
Outcome/s assessed	Rehabilitation outcomes, pain, strength, balance, coordination, and knee proprioception
Results/findings	The results showed that after the intervention a non-significant standardised mean difference was found regarding the deficit of concentric and eccentric coordination deviation, anterior excursion, functional score (LEFS), centre of severity (GOG), balance score, International Knee Documentation (IKDC) score, Lysholm activity scale score, and knee flexion excursion. At the end of the 8-week follow-up with exergames, there was a significant standardised mean difference in relation to the flexion angle difference for 30, 60, and 90◦
Significance/direction	- Regarding the effectiveness of exergames for rehabilitation after ACL reconstruction, the pooled effect estimate for proprioception

	deviation was − 1.73 (95% CI -4.75 to 1.28, $p < 0.0004$). - there was no difference between the exergame intervention and the control group for pain and strength, with the GRADE of evidence categorized as moderate and low quality, respectively. However, strength recovery is an important parameter in functional outcomes. - there was no difference between the exergame intervention and the control group for the deficit of concentric and eccentric coordination deviation, anterior excursion, functional score (LEFS), center of gravity (GOG)) and balance score.
Heterogeneity	Had existed in pain, proprioception deviation, errors of difference between joint angles, strength, deficit of concentric and eccentric co- ordination deviation, anterior excursion, functional score (LEFS), centre of gravity (GOG), balance score, International Knee Documentation (IKDC), Lysholm activity scale score, and knee flexion excursion in degrees. • Pain (using VAS): $Chi^2 = 0.10$, $I^2 = 0\%$ • Proprioception deviation: $Chi^2 = 19.86$, $I^2 = 95\%$ • Strength: $Chi^2 = 0.34$, $I^2 = 0\%$

Study 5: The efficacy of virtual reality tools for total knee replacement rehabilitation: A systematic review

Study name	The efficacy of virtual reality tools for total knee replacement rehabilitation
Study details	PHYSIOTHERAPY THEORY AND PRACTICE 2021, VOL. 37, NO. 6, 682–692 https://doi.org/10.1080/09593985.2019.1641865
Author/year	José M. Blasco, Celedonia Igual-Camacho, María C. Blasco, Virgilia Antón-Antón, Álvaro Ortiz-Llueca, and Sergio Roig-Casasús 2019
Objectives	To assess the effects of training with virtual reality tools (VRT) during rehabilitation of patients after total knee replacement (TKR)
Participants (characteristics, total number)	A total of 312 participants were included Eligibility criteria included:

	1) trials in which participants with severe knee osteoarthritis underwent TKR surgery. 2) trials were allocated into (at least) one group that took part in a rehabilitation programme using a virtual reality tool. 3) trials in which results of rehabilitation were assessed.
Setting/context	At home/clinic (supervised)
Description of interventions/phenomenon of interest	Most experimental interventions augmented control group therapy with the use of VRT, augmented control therapy training with lower extremity exercises and compared experimental intervention against conventional outpatient physical therapy.
Search details	A preliminary search included the terms “total knee replacement,” “total. knee arthroplasty,” “virtual,” and “rehabilitation”
Sources searched	Medline, Web of Science, Physiotherapy Evidence Database Research, Scopus, Embase, and Cochrane Library.
Range (years) of included studies	Inception- January 2018
Number of studies included	Six studies
Types of studies included	5 RCTs and one case-control
Country of origin of included studies	None
Appraisal	Quality assessment and risk of bias
Appraisal instruments used	The PEDro scale, The Cochrane collaboration tool
Appraisal rating	The quality of the randomized trials according to the PEDro scale suggested studies used in the evaluation had fair quality (3/5) and high quality (2/5). Internal validity assessed with the Cochrane tool indicated that randomized clinical trials had a high or unclear risk of selection (4/5), performance (5/5), detection (1/5), and attrition bias (1/5)
Analysis	None
Method of analysis	None
Outcome/s assessed	Self-reported functionality, functional performance, and function, as well as pain and balance.
Results/findings	The main finding was that both physical therapies augmented with VRT and alternative VRT training had no advantage over conventional rehabilitation. Overall, therapy with and without VRT were similarly effective in

	improving functional outcomes and resolving pain.
Significance/direction	Overall, VRT did not result in significant improvement in self- reported functionality and functional performance, while results for knee function were inconclusive. Only there was a significant balance improvement when using the dynamometric platform to enhance balance.
Heterogeneity	Exists in the design of individual studies, and the range of different outcomes measured in existing trials that precluded quantitative meta-analysis.

Study 6: Technology-assisted rehabilitation following total knee or hip replacement for people with osteoarthritis: a systematic review and meta-analysis.

Study name	Technology-assisted rehabilitation following total knee or hip replacement for people with osteoarthritis
Study details	BMC Musculoskelet Disord 20, 506 (2019). https://doi.org/10.1186/s12891-019-2900-x
Author/year	Wang, X., Hunter, D.J., Vesentini, G. *et al.*/ 2019
Objectives	To evaluate the effectiveness and safety of technology-assisted rehabilitation following total hip/knee replacement.
Participants (characteristics, total number)	Game-based therapy using video games, VR or bio-feedback technologies was investigated in 5 trials (N= 232, mean age = 64 years old) of post-TKR rehabilitation
Setting/context	via telephone counselling/coaching (6 trials, N = 1070) or videoconferencing (5 trials, N = 526).
Description of interventions/phenomenon of interest	Technology-based intervention, in isolation or in combination with other interventions, compared with usual care and no treatment. Technology-based inter- ventions were defined as any type of health-related services such as education, monitoring or treatment delivering via telecommunication technologies, internet, software, or VR devices.
Search details	Search strategy contained both controlled vocabulary and free text terms.

	Initial search yielded 8603 articles, after screening thirty-four full text articles that met criteria were screened for eligibility and of these 21 articles were included in the review.
Sources searched	Six electronic databases were searched without language or time restrictions for relevant studies: MEDLINE, EMBASE, Cochrane Library, CINAHL, SPORTDiscus, Physiotherapy Evidence Database (PEDro)
Range (years) of included studies	from inception to November 7th, 2018
Number of studies included	Twenty-one studies in total, 17 studies of which are in post-TKR rehabilitation.
Types of studies included	RCTs
Country of origin of included studies	China, Australia, Canada, South Korea, Denmark, Spain, United States, Germany.
Appraisal	The methodological quality and quality of evidence
Appraisal instruments used	The PEDro scale, GRADE (the Grading of Recommendations, Assessment, Development and Evaluation approach)
Appraisal rating	The average methodological quality of included studies was 5.8 (range: 2 to 8) on the PEDro scale. A total of 7 studies (N = 1494, mean age = 65.8 years old) were considered of high methodological quality (PEDro score ≥ 7). The most common methodological limitation was lack of blinding of the assessor observed in 10 of the 21 included trials (N = 1364); or therapist (16 trials, N = 1817) The quality of evidence was initially considered as high and downgraded based on five criteria: high risk of bias (e.g. > 25% of participants for studies with a PEDro score of ≤6), inconsistency of results (I2 > 50%), indirectness (comparison of different populations and interventions), imprecision (e.g. sample size <400, 95% CI overlaps no effect) and publication bias (visual inspection of funnel plots and Egger’s regression test).
Analysis	Meta-analysis
Method of analysis	Review Manager

Outcome/s assessed	The primary outcomes were pain and function. The secondary outcomes were quality of life, adherence, user experience and safety.
Results/findings	Compared to usual care, technology-based intervention was more effective in reducing pain (mean difference (MD): − 0.25; 95% confidence interval (CI): − 0.48, − 0.02; moderate evidence) and improving function measured with the timed up-and-go test (MD: -7.03; 95% CI: − 11.18, − 2.88) in people undergoing TKR. No between-group differences were observed in rates of hospital readmissions or treatment-related adverse events (AEs) in those studies
Significance/direction	There is moderate-quality of evidence showed technology-assisted rehabilitation, in particular, telerehabilitation, results in a statistically significant improvement in pain; and low-quality of evidence for the improvement in functional mobility in people undergoing TKR. The effects were however too small to be clinically significant.
Heterogeneity	None

Study 7: The Effectiveness of Virtual Reality Rehabilitation in Patients with Knee and Hip Osteoarthritis

Study name	The Effectiveness of Virtual Reality Rehabilitation in Patients with Knee and Hip Osteoarthritis
Study details	J. Clin. Med. 2020, 9, 2639; doi:10.3390/jcm9082639
Author/year	Joanna Byra and Krzysztof Czernicki /2020
Objectives	Investigating whether virtual reality rehabilitation significantly improves the physical function of elderly patients suffering from knee or hip osteoarthritis, including patients after arthroplasty. An additional purpose of this review was to assess the impact of this type of intervention on patients' quality of life, adherence, acceptance, and its usefulness in the process of rehabilitation.

Participants (characteristics, total number)	In the total 10 RCTs, there were 492 subjects with a mean age of 60.6 years. Nine of the trials included information regarding sex, and thus the percentage of male participants was 41.6%. The included information regarding sex, and thus the percentage of male participants was 41.6%. The studies focused on the rehabilitation of the following orthopaedic conditions: seven total knee-focused on rehabilitation of the following orthopaedic conditions: seven total knee arthroplasties. (TKA), two knee osteoarthritis (KOA), and one total hip arthroplasty (THA).
Setting/context	Hospital or clinic assisted by a therapist or researcher and home rehabilitation.
Description of interventions/phenomenon of interest	the Virtual Reality Rehabilitation System (VRRS, Khymeia, Italy) the Hot Plus system (Supreme Investment Co., Taipei, Taiwan) the Light Race game virtual reality (Mide Technology Inc., Cangzhou, China) an interactive cognitive game, Kawashima's Brain Training: How Old Is Your Brain? (Nintendo; Kyoto, Japan) The Nintendo Wii Fit Plus game associated with Wii Balance Board (Nintendo of America, Inc., Redmond, WA, USA)
Search details	The primary search keywords were "hip replacement OR knee replacement OR osteoarthritis AND virtual reality AND rehabilitation" and their synonyms. For PubMed, we used the following search strategy: "(((((((hip osteoarthritis) OR knee osteoarthritis) OR knee replacement) OR hip replacement) OR hip arthroplasty) OR knee arthroplasty)) AND (((((exergame*) OR video game) OR virtual reality) OR augmented reality)) AND ((((((rehabilitation) OR physical therapy) OR physiotherapy) OR activity) OR exercise)) [All Fields]"
Sources searched	PubMed, Medline, Web of Science, Scopus and PEDro

Range (years) of included studies	Last 10 years (January 2010–April 2020)
Number of studies included	Ten studies
Types of studies included	RCTs
Country of origin of included studies	Italy, Taiwan, China, South Korea, Germany, Saudi Arabia, USA, Canada
Appraisal	The methodological quality
Appraisal instruments used	The PEDro scale
Appraisal rating	The methodological quality of the analysed research rated on the PEDro scale ranged from moderate quality four points to high quality 8 points with a mean score of 5.9 points (moderate quality). Four studies were high quality above 7 points on the PEDro scale
Analysis	None
Method of analysis	None
Outcome/s assessed	Physical function, balance, gait, range of motion, muscle strength, pain, proprioception
Results/findings	There are no conclusive reports that interventions based on VR are more effective than standard physical therapy.
Significance/direction	The effectiveness of VR-based rehabilitation is unclear, although interventions based on VR are promising in view of pain management, postural and proprioception training. However, this evidence is not sufficient to create clinical guidelines, and further high-quality studies are needed.
Heterogeneity	None

Study 8: Virtual reality-based rehabilitation in patients following total knee arthroplasty: a systematic review and meta-analysis of randomised controlled trials.

Study name	Virtual reality-based rehabilitation in patients following total knee arthroplasty: a systematic review and meta-analysis of randomized controlled trials
Study details	DOI: 10.1097/CM9.0000000000001847
Author/year	Peng et al. (2021)
Objectives	Investigates VR-based rehabilitation's effectiveness on TKA outcomes

Participants (characteristics, total number)	adult patients who had undergone TKA surgery N= 805 patients The demographic data of the participants was not provided
Setting/context	Not mentioned however two of the included studies conducted at inpatient physiotherapy
Description of interventions/phenomenon of interest	VR-based rehabilitation this includes: 15 minutes of Nintendo Wii Fit Interactive virtual telerehabilitation kit for 1 hour a day real-time visual feedback via a Kinect sensor. virtual exercise rehabilitation assistant system (VERA) VR glasses (Hyundai Chemistry, South Korea) and a smart phone-based balance game
Search details	(total knee arthroplasty OR total knee replacement) AND (VR OR VR exposure therapy OR game(s) OR computer game(s) OR videogame(s) OR video game(s) OR active game(s) OR serious game(s) OR exergam OR interactive OR immersive OR Wii OR Kinect OR Xbox OR PlayStation).
Sources searched	Physiotherapy Evidence Database (PEDro), PubMed/Medline, Cumulative Index to Nursing and Allied Health Literature, Web of Science, the Cochrane Central Register of Controlled Trials, PsycINFO, Embase, Scopus, China National Knowledge Infrastructure, and Wanfang. Reference list of resulted studies was also searched.
Range (years) of included studies	From inception to May 22, 2021
Number of studies included	8

Types of studies included	RCT
Country of origin of included studies	one in Canada one in Spain two in China one in Germany one in Italy one in the USA one in Korea
Appraisal	The methodological quality
Appraisal instruments used	The PEDro scale
Appraisal rating	Good (range 6–8)
Analysis	Cochrane Collaboration Review Manager software (RevManVersion 5.3, Oxford, UK)
Method of analysis	meta-analysis
Outcome/s assessed	Pain (visual analog scale (VAS), numerical pain rating scale (NPRS)) Function (Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC). Hospital for Special Surgery Knee Score (HSS) Balance Berg Balance Scale (BBS) QOL Short Form Health Survey-36 (SF-36) EuroQol Five-Dimensional Questionnaire (EQ-5D) ROM Active ROM Postural control Timed Up and Go (TUG)
Results/findings	VR-based rehabilitation improved pain (low-quality evidence), and function (high-quality evidence), but not postural control (low-quality evidence).
Significance/direction	Pain

	VR-based rehabilitation improve pain within 1 month but did not within 2 and 3 months. Function VR-based rehabilitation significantly improved WOMAC scores within 1 month but did not within 3 months Balance No solid conclusion can made. QOL no significant difference ROM no significant difference Postural control no significant difference
Heterogeneity	Pain Significant heterogeneity (I 2 = 63%) Function (WAMAC) No significant heterogeneity (I 2 = 0%) (HSS) not applicable Balance not applicable QOL not applicable ROM not applicable Postural control high heterogeneity (I 2 = 70%,)

Appendix 2

AMSTAR 2: a critical appraisal tool for systematic reviews that include randomised or non-randomised studies of healthcare interventions, or both

1. Did the research questions and inclusion criteria for the review include the components of PICO?

For Yes:	Optional (recommended)	
☐ Population ☐ Intervention ☐ Comparator group ☐ Outcome	☐ Timeframe for follow-up	☐ Yes ☐ No

2. Did the report of the review contain an explicit statement that the review methods were established prior to the conduct of the review and did the report justify any significant deviations from the protocol?

For Partial Yes:	For Yes:	
The authors state that they had a written protocol or guide that included ALL the following: ☐ review question(s) ☐ a search strategy ☐ inclusion/exclusion criteria ☐ a risk of bias assessment	As for partial yes, plus the protocol should be registered and should also have specified: ☐ a meta-analysis/synthesis plan, if appropriate, *and* ☐ a plan for investigating causes of heterogeneity ☐ justification for any deviations from the protocol	☐ Yes ☐ Partial Yes ☐ No

3. Did the review authors explain their selection of the study designs for inclusion in the review?

For Yes, the review should satisfy ONE of the following:	
☐ *Explanation for* including only RCTs ☐ OR *Explanation for* including only NRSI ☐ OR *Explanation for* including both RCTs and NRSI	☐ Yes ☐ No

4. Did the review authors use a comprehensive literature search strategy?

For Partial Yes (all the following):	For Yes, should also have (all the following):	
☐ searched at least 2 databases (relevant to research question) ☐ provided key word and/or search strategy ☐ justified publication restrictions (e.g. language)	☐ searched the reference lists / bibliographies of included studies ☐ searched trial/study registries ☐ included/consulted content experts in the field ☐ where relevant, searched for grey literature ☐ conducted search within 24 months of completion of the review	☐ Yes ☐ Partial Yes ☐ No

5. Did the review authors perform study selection in duplicate?

For Yes, either ONE of the following:	
☐ at least two reviewers independently agreed on selection of eligible studies and achieved consensus on which studies to include ☐ OR two reviewers selected a sample of eligible studies <u>and</u> achieved good agreement (at least 80 percent), with the remainder selected by one reviewer.	☐ Yes ☐ No

AMSTAR 2: a critical appraisal tool for systematic reviews that include randomised or non-randomised studies of healthcare interventions, or both

6. Did the review authors perform data extraction in duplicate?

For Yes, either ONE of the following:

- ☐ at least two reviewers achieved consensus on which data to extract from included studies
- ☐ OR two reviewers extracted data from a sample of eligible studies and achieved good agreement (at least 80 percent), with the remainder extracted by one reviewer.

☐ Yes
☐ No

7. Did the review authors provide a list of excluded studies and justify the exclusions?

For Partial Yes:	For Yes, must also have:	
☐ provided a list of all potentially relevant studies that were read in full-text form but excluded from the review	☐ Justified the exclusion from the review of each potentially relevant study	☐ Yes ☐ Partial Yes ☐ No

8. Did the review authors describe the included studies in adequate detail?

For Partial Yes (ALL the following):	For Yes, should also have ALL the following:	
☐ described populations ☐ described interventions ☐ described comparators ☐ described outcomes ☐ described research designs	☐ described population in detail ☐ described intervention in detail (including doses where relevant) ☐ described comparator in detail (including doses where relevant) ☐ described study's setting ☐ timeframe for follow-up	☐ Yes ☐ Partial Yes ☐ No

9. Did the review authors use a satisfactory technique for assessing the risk of bias (RoB) in individual studies that were included in the review?

RCTs For Partial Yes, must have assessed RoB from ☐ unconcealed allocation, *and* ☐ lack of blinding of patients and assessors when assessing outcomes (unnecessary for objective outcomes such as all-cause mortality)	For Yes, must also have assessed RoB from: ☐ allocation sequence that was not truly random, *and* ☐ selection of the reported result from among multiple measurements or analyses of a specified outcome	☐ Yes ☐ Partial Yes ☐ No ☐ Includes only NRSI
NRSI For Partial Yes, must have assessed RoB: ☐ from confounding, *and* ☐ from selection bias	For Yes, must also have assessed RoB: ☐ methods used to ascertain exposures and outcomes, *and* ☐ selection of the reported result from among multiple measurements or analyses of a specified outcome	☐ Yes ☐ Partial Yes ☐ No ☐ Includes only RCTs

10. Did the review authors report on the sources of funding for the studies included in the review?

For Yes

- ☐ Must have reported on the sources of funding for individual studies included in the review. Note: Reporting that the reviewers looked for this information but it was not reported by study authors also qualifies

☐ Yes
☐ No

11. If meta-analysis was performed did the review authors use appropriate methods for statistical combination of results?

RCTs For Yes: ☐ The authors justified combining the data in a meta-analysis ☐ AND they used an appropriate weighted technique to combine study results and adjusted for heterogeneity if present. ☐ AND investigated the causes of any heterogeneity	☐ Yes ☐ No ☐ No meta-analysis conducted
For NRSI For Yes: ☐ The authors justified combining the data in a meta-analysis ☐ AND they used an appropriate weighted technique to combine study results, adjusting for heterogeneity if present ☐ AND they statistically combined effect estimates from NRSI that were adjusted for confounding, rather than combining raw data, or justified combining raw data when adjusted effect estimates were not available ☐ AND they reported separate summary estimates for RCTs and NRSI separately when both were included in the review	☐ Yes ☐ No ☐ No meta-analysis conducted

12. If meta-analysis was performed, did the review authors assess the potential impact of RoB in individual studies on the results of the meta-analysis or other evidence synthesis?

For Yes: ☐ included only low risk of bias RCTs ☐ OR, if the pooled estimate was based on RCTs and/or NRSI at variable RoB, the authors performed analyses to investigate possible impact of RoB on summary estimates of effect.	☐ Yes ☐ No ☐ No meta-analysis conducted

13. Did the review authors account for RoB in individual studies when interpreting/ discussing the results of the review?

For Yes: ☐ included only low risk of bias RCTs ☐ OR, if RCTs with moderate or high RoB, or NRSI were included the review provided a discussion of the likely impact of RoB on the results	☐ Yes ☐ No

14. Did the review authors provide a satisfactory explanation for, and discussion of, any heterogeneity observed in the results of the review?

For Yes: ☐ There was no significant heterogeneity in the results ☐ OR if heterogeneity was present the authors performed an investigation of sources of any heterogeneity in the results and discussed the impact of this on the results of the review	☐ Yes ☐ No

15. If they performed quantitative synthesis did the review authors carry out an adequate investigation of publication bias (small study bias) and discuss its likely impact on the results of the review?

For Yes: ☐ performed graphical or statistical tests for publication bias and discussed the likelihood and magnitude of impact of publication bias	☐ Yes ☐ No ☐ No meta-analysis conducted

16. Did the review authors report any potential sources of conflict of interest, including any funding they received for conducting the review?	
For Yes: ☐ The authors reported no competing interests OR ☐ The authors described their funding sources and how they managed potential conflicts of interest	☐ Yes ☐ No

To cite this tool: Shea BJ, Reeves BC, Wells G, Thuku M, Hamel C, Moran J, Moher D, Tugwell P, Welch V, Kristjansson E, Henry DA. AMSTAR 2: a critical appraisal tool for systematic reviews that include randomised or non-randomised studies of healthcare interventions, or both. BMJ. 2017 Sep 21;358:j4008.

Appendix 3

VIRTUAL REALITY: PHONE SCREENING FORM

Date of Phone Screening: ____/____/____ **Screened by:**_______________

Name:____ **Age:**

Sex: Male / Female

Daytime phone:________________________________(home / work / mobile)

Alternative phone:______________________________(home / work / mobile)

Email:_______________________________@____________________

How did you find out about study?____

Selection Criteria circle Yes or No (Bold = pass)

Are you aged over 18?	Yes No
Are you able to attend one assessment appointment at the School of Healthcare in Cardiff University? *(Assessment will last approx. 60 minutes)*	Yes No

Knee Symptoms and general health

	Left Knee	Right Knee
Do you have pain in both knees or one knee? (if bilateral circle Right & Left)	Left	Right
If pain in both knees, which is the most painful knee at the moment? *(This will be the Study Knee)*	Left	Right
How long have you suffered from knee pain? *Is this greater than 3 months?*	Yes No	Yes No
How often have you had knee pain in the last month?		
• *Is this most days (5-7 days/week or 20-30 days/month)?*	Yes No	Yes No

Have you had any knee surgery including arthroscopes in the past 6 months? *Details:*	Yes No	Yes No

Other than your knee, have you experienced any other arthritis, joint or muscle pain, such as in your foot, ankle, hip or back, within the past 6 months?	Yes No
☐ Right foot ☐ Right ankle ☐ Right Hip ☐ Back ☐ Left foot ☐ Left ankle ☐ Left Hip ☐ Other:	
If Yes, did you seek treatment from a health professional or did the pain limit your ability to perform daily activities such as walking for more than a week? *Details:*	Yes No
Do you have any other health problems that affect your walking, apart from your knee pain? *Details:*	Yes No
Do you have any inflammatory arthritic conditions (eg, rheumatoid arthritis, fibromyalgia) or osteonecrosis, Paget's disease or haemophilia?	Yes No
Do you have any neurological conditions such as a history of stroke, Multiple sclerosis (MS), polio, a neuropathy, peripheral nerve disease or Parkinson's disease? *Any mention of numbness in the feet may indicate peripheral nerve disease or diabetes. Should be excluded.* *Details:*	Yes No
Do you currently use a walking stick or gait aid to walk?	Yes No
Do you suffer from vertigo or suffer from dizziness?	Yes No

Is the subject appropriate for proceeding to an appointment for data collection?	**YES** NO
If YES, which knee is suitable? **RIGHT** **LEFT** **BOTH**	
If **NO** - although you are not eligible for the study at the moment, are you happy for us to contact you to see if you are eligible for this study at a later date? If yes, at what date should the follow-up phone call be after?	Yes No / /
If **NO** - although you are not eligible for the study, are you happy for us to contact you about other studies in the future that we think you may be suitable for?	Yes No

STAGE TWO confirm appointment and check pain score on the day before testing

☐ Check that mail has been received regarding appointment

☐ Confirm that they are still happy to participate

Participant will be coming in by:

☐ Car, and will use the carpark OR ☐ Public transport or other means

☐ Remind to bring in a pair of shorts

Appendix 4

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

CONSENT FORM

Title of research project:

Development of portable virtual reality physiotherapy games for knee rehabilitation

SREC reference and committee:

Name of Chief/Principal Investigator: Alhanouf Almutairi

	Please initial box
I confirm that I have read the information sheet dated 04/10/2023 version [4] for the above research project.	
I confirm that I have understood the information sheet dated 04/10/2023 version [4] for the above research project and that I have had the opportunity to ask questions that 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 consent to being audio recorded/ video recorded taken for the purposes of the research project and I understand how it will be used in the research.	
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, date of birth, contact information] 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 published in a journal to made 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 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)

THANK YOU FOR PARTICIPATING IN OUR RESEARCH

YOU WILL BE GIVEN A COPY OF THIS CONSENT FORM TO KEEP

Appendix 5

The Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC)

Name:_______________________________ Date:______________

Instructions: Please rate the activities in each category according to the following scale of difficulty: 0 = None, 1 = Slight, 2 = Moderate, 3 = Very, 4 = Extremely

Circle **one number** for each activity

Pain	1. Walking	0	1	2	3	4
	2. Stair Climbing	0	1	2	3	4
	3. Nocturnal	0	1	2	3	4
	4. Rest	0	1	2	3	4
	5. Weight bearing	0	1	2	3	4
Stiffness	1. Morning stiffness	0	1	2	3	4
	2. Stiffness occurring later in the day	0	1	2	3	4
Physical Function	1. Descending stairs	0	1	2	3	4
	2. Ascending stairs	0	1	2	3	4
	3. Rising from sitting	0	1	2	3	4
	4. Standing	0	1	2	3	4
	5. Bending to floor	0	1	2	3	4
	6. Walking on flat surface	0	1	2	3	4
	7. Getting in / out of car	0	1	2	3	4
	8. Going shopping	0	1	2	3	4
	9. Putting on socks	0	1	2	3	4
	10. Lying in bed	0	1	2	3	4
	11. Taking off socks	0	1	2	3	4
	12. Rising from bed	0	1	2	3	4
	13. Getting in/out of bath	0	1	2	3	4
	14. Sitting	0	1	2	3	4
	15. Getting on/off toilet	0	1	2	3	4
	16. Heavy domestic duties	0	1	2	3	4
	17. Light domestic duties	0	1	2	3	4

Total Score: ______ / 96 = _______%

Comments / Interpretation (to be completed by therapist only):

Appendix 6 (EQ-5D-5L)

Under each heading, please tick the ONE box that best describes your health TODAY.

MOBILITY

I have no problems in walking about ☐
I have slight problems in walking about ☐
I have moderate problems in walking about ☐
I have severe problems in walking about ☐
I am unable to walk about ☐

SELF-CARE

I have no problems washing or dressing myself ☐
I have slight problems washing or dressing myself ☐
I have moderate problems washing or dressing myself ☐
I have severe problems washing or dressing myself ☐
I am unable to wash or dress myself ☐

USUAL ACTIVITIES *(e.g. work, study, housework, family or leisure activities)*

I have no problems doing my usual activities ☐
I have slight problems doing my usual activities ☐
I have moderate problems doing my usual activities ☐
I have severe problems doing my usual activities ☐
I am unable to do my usual activities ☐

PAIN / DISCOMFORT

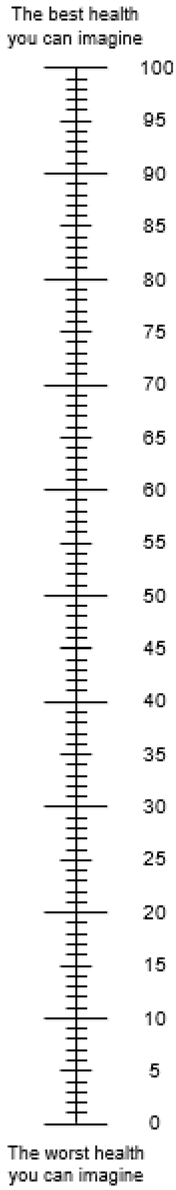
I have no pain or discomfort ☐
I have slight pain or discomfort ☐
I have moderate pain or discomfort ☐
I have severe pain or discomfort ☐
I have extreme pain or discomfort ☐

ANXIETY / DEPRESSION

I am not anxious or depressed ☐
I am slightly anxious or depressed ☐
I am moderately anxious or depressed ☐
I am severely anxious or depressed ☐
I am extremely anxious or depressed ☐

2

- We would like to know how good or bad your health is TODAY.
- This scale is numbered from 0 to 100.
- 100 means the <u>best</u> health you can imagine.
  0 means the <u>worst</u> health you can imagine.
- Please mark an X on the scale to indicate how your health is TODAY.
- Now, write the number you marked on the scale in the box below.



YOUR HEALTH TODAY =

SMRC
Self-Management Resource Center

Self-Efficacy for Managing Chronic Disease 6-item Scale

We would like to know how confident you are in doing certain activities. For each of the following questions, please choose the number that corresponds to your confidence that you can do the tasks regularly at the present time.

1. How confident do you feel that you can keep the fatigue caused by your disease from interfering with the things you want to do?
   not at all confident 1 2 3 4 5 6 7 8 9 10 totally confident
2. How confident do you feel that you can keep the physical discomfort or pain of your disease from interfering with the things you want to do?
   not at all confident 1 2 3 4 5 6 7 8 9 10 totally confident
3. How confident do you feel that you can keep the emotional distress caused by your disease from interfering with the things you want to do?
   not at all confident 1 2 3 4 5 6 7 8 9 10 totally confident
4. How confident do you feel that you can keep any other symptoms or health problems you have from interfering with the things you want to do?
   not at all confident 1 2 3 4 5 6 7 8 9 10 totally confident
5. How confident do you feel that you can the different tasks and activities needed to manage your health condition so as to reduce your need to see a doctor?
   not at all confident 1 2 3 4 5 6 7 8 9 10 totally confident
6. How confident do you feel that you can do things other than just taking medication to reduce how much your illness affects your everyday life?
   not at all confident 1 2 3 4 5 6 7 8 9 10 totally confident

Scoring

The score for each item is the number circled. If two consecutive numbers are circled, code the lower number (less self-efficacy). If the numbers are not consecutive, do not score the item. The score for the

1

Appendix 8

PATIENT HEALTH QUESTIONNAIRE-9 (PHQ-9)

Over the <u>last 2 weeks</u>, how often have you been bothered by any of the following problems? *(Use "✔" to indicate your answer)*	Not at all	Several days	More than half the days	Nearly every day
1. Little interest or pleasure in doing things	0	1	2	3
2. Feeling down, depressed, or hopeless	0	1	2	3
3. Trouble falling or staying asleep, or sleeping too much	0	1	2	3
4. Feeling tired or having little energy	0	1	2	3
5. Poor appetite or overeating	0	1	2	3
6. Feeling bad about yourself — or that you are a failure or have let yourself or your family down	0	1	2	3
7. Trouble concentrating on things, such as reading the newspaper or watching television	0	1	2	3
8. Moving or speaking so slowly that other people could have noticed? Or the opposite — being so fidgety or restless that you have been moving around a lot more than usual	0	1	2	3
9. Thoughts that you would be better off dead or of hurting yourself in some way	0	1	2	3

FOR OFFICE CODING __0__ + ______ + ______ + ______

=Total Score: ______

If you checked off <u>any</u> problems, how <u>difficult</u> have these problems made it for you to do your work, take care of things at home, or get along with other people?

Not difficult at all	Somewhat difficult	Very difficult	Extremely difficult
☐	☐	☐	☐

Developed by Drs. Robert L. Spitzer, Janet B.W. Williams, Kurt Kroenke and colleagues, with an educational grant from Pfizer Inc. No permission required to reproduce, translate, display or distribute.

NovoPsych

Tampa Scale of Kinesiophobia (TSK)

Instructions:

In these days of high-tech medicine, one of the most important sources of information about you is often missing from your medical records: your own feeling or intuitions about what is happening with your body. We hope that the following information will help to fill that gap.

Please answer the following questions according to your true feelings, not according to what others think you should believe. Score each statement from strongly disagree to strong agree by tapping the appropriate box.

		Strongly disagree	Somewhat disagree	Somewhat agree	Strongly agree
1	I'm afraid that I might injury myself if I exercise	1	2	3	4
2	If I were to try to overcome it, my pain would increase	1	2	3	4
3	My body is telling me I have something dangerously wrong	1	2	3	4
4	My pain would probably be relieved if I were to exercise	4	3	2	1
5	People aren't taking my medical condition seriously enough	1	2	3	4
6	My accident has put my body at risk for the rest of my life	1	2	3	4
7	Pain always means I have injured my body	1	2	3	4
8	Just because something aggravates my pain does not mean it is dangerous	4	3	2	1
9	I am afraid that I might injure myself accidentally	1	2	3	4
10	Simply being careful that I do not make any unnecessary movements is the safest thing I can do to prevent my pain from worsening	1	2	3	4
11	I wouldn't have this much pain if there weren't something potentially dangerous going on in my body	1	2	3	4
12	Although my condition is painful, I would be better off if I were physically active	4	3	2	1
13	Pain lets me know when to stop exercising so that I don't injure	1	2	3	4
14	It's really not safe for a person with a condition like mine to be physically active	1	2	3	4
15	I can't do all the things normal people do because it's too easy for me to get injured	1	2	3	4

NovoPsych

		Strongly disagree	Somewhat disagree	Somewhat agree	Strongly agree
16	Even though something is causing me a lot of pain, I don't think it's actually dangerous	4	3	2	1
17	No one should have to exercise when he/she is in pain	1	2	3	4

Developer Reference:

The original Tampa Scale of Kinesiophobia (TSK) was developed by R. Miller, S. Kopri, and D. Todd, in 1991. This represents a modified version.

Appendix 10

Open-ended Questions

1- Can you describe your experience using the VR-based physiotherapy exercise toolkit?

2- Can you write how the VR exercises affected your pain levels during and after participation?

3- What aspects of the VR toolkit did you find most engaging?

4- Were there specific VR exercises or scenarios you preferred over others? Why?

5- What features or aspects of the VR toolkit would you change or improve, if any?

6- Were there any aspects of the VR exercises that you found challenging or uncomfortable?

7- Do you have any recommendations for improving the VR exercises for people with knee pain in the future?

8- Is there anything else you would like to add about your experience with the VR toolkit?

Appendix 11

Coding Units

Unit of Analysis: Any word or phrase that describes the VR system.

Framework Development Process

Stage 1: Initial Code Development

Through line-by-line analysis of participant verbalisations, 24 specific codes emerged directly from the data through open coding procedures.

Stage 2: Category Formation

Related codes were grouped into seven meaningful categories based on conceptual similarities and thematic relationships.

Stage 3: Theme Identification

Categories were analysed to identify three overarching themes that captured broader patterns in participant experiences.

Coding Framework Structure

THEME 1: OVERALL SATISFACTION

Category: Positive Feedback

Definition: Participant expressions that reflect favourable, satisfactory, or beneficial experiences with the VR intervention.

Codes:

- **Engaged**
  - *Definition*: Expressions indicating active involvement, attention, and participation in VR activities
  - *Coding Rule*: Apply when participant describes being absorbed, focused, or actively participating

- **Enjoyment & Fun**
  - *Definition*: Expressions of pleasure, entertainment, amusement, or positive emotional responses
  - *Coding Rule*: Apply when participant uses words related to enjoyment, fun, pleasure, or positive emotions
- **Challenged**
  - *Definition*: Expressions indicating an appropriate level of difficulty that stimulates without overwhelming
  - *Coding Rule*: Apply when participant describes tasks as appropriately challenging or stimulating
- **Positive Impact**
  - *Definition*: Expressions reflecting perceived beneficial effects or improvements from the VR intervention
  - *Coding Rule*: Apply when participant describes improvements, benefits, or positive outcomes
- **Motivation & Encouragement**
  - *Definition*: Expressions of increased motivation, inspiration, or encouragement received
  - *Coding Rule*: Apply when participant describes feeling motivated or encouraged by the system or experience

Category: Negative Feedback

Definition: Participant expressions that reflect unfavourable, unsatisfactory, or problematic experiences with the VR intervention.

Codes:

- **Lack of Engagement**
  - *Definition*: Expressions reflecting diminished interest, attention, or involvement in activities
  - *Coding Rule*: Apply when participant describes disinterest, boredom, or lack of involvement
- **Boring or Repetitive Content**

    - *Definition*: Expressions indicating content perceived as monotonous, repetitive, or insufficiently varied
    - *Coding Rule*: Apply when participant specifically mentions boredom or repetition
- **Inadequate Feedback**
    - *Definition*: Expressions indicating insufficient or unclear system feedback
    - *Coding Rule*: Apply when participant requests more feedback or describes current feedback as insufficient
- **Complexity of Tasks**
    - *Definition*: Expressions indicating tasks are overly difficult, complicated, or confusing
    - *Coding Rule*: Apply when participant describes tasks as too difficult or complex
- **Frustration**
    - *Definition*: Expressions of annoyance, irritation, or dissatisfaction with system performance
    - *Coding Rule*: Apply when participant expresses frustration, annoyance, or irritation
- **Audio Discomfort**
    - *Definition*: Expressions of discomfort related to audio components of the VR system
    - *Coding Rule*: Apply when participant mentions audio-related discomfort or issues.
- **Preference for Simplicity**
    - *Definition*: Expressions favouring simpler task designs or interfaces
    - *Coding Rule*: Apply when participant explicitly requests or prefers simpler options
- **Lack of Realistic Reaction**
    - *Definition*: Expressions indicating system responses lack practicality or reality
    - *Coding Rule*: Apply when participant comments on unrealistic system responses

- **Interruption of Focus**
  - *Definition*: Expressions indicating concentration or focus were disrupted
  - *Coding Rule*: Apply when the participant describes a distraction or a focus interruption
- **Overload of Visual Information**
  - *Definition*: Expressions indicating an overwhelming amount of visual stimuli
  - *Coding Rule*: Apply when the participant describes too much visual information

THEME 2: TECHNICAL AND ACTIVITY-RELATED CHALLENGES

Category: Technical

Definition: Participant comments related to hardware, software, or system performance issues.

Codes:

- **Hardware Problems**
  - *Definition*: Issues related to physical equipment malfunction or performance
  - *Coding Rule*: Apply when participant mentions specific hardware issues or malfunctions
- **System Responsiveness**
  - *Definition*: Comments about system lag, delay, or response time
  - *Coding Rule*: Apply when participant mentions timing issues or system responsiveness
- **System Glitches**
  - *Definition*: Technical errors, bugs, or unexpected system behaviours
  - *Coding Rule*: Apply when participant describes unexpected or irregular system behaviour.

Category: Activity Experience

Definition: Participant reflections on the physical and cognitive aspects of VR activities.

Codes:

- **Body Perception**
    - *Definition*: Participant awareness and reflection on physical sensations and movement
    - *Coding Rule*: Apply when participant describes physical sensations, body awareness, or movement.
- **Reflection on Dual Tasks**
    - *Definition*: Experiences with complex activities requiring simultaneous cognitive and physical coordination
    - *Coding Rule*: Apply when participant describes experiences with multi-component or coordination tasks

THEME 3: USABILITY, CLARITY, AND SUGGESTIONS

Category: Ease of Use

Definition: Participant perceptions of system accessibility and user-friendliness.

Codes:

- **Easy**
    - *Definition*: Expressions indicating the system was user-friendly and accessible
    - *Coding Rule*: Apply when participant describes the system as easy, simple, or user-friendly
- **Hard**
    - *Definition*: Expressions indicating the system was hard to use.
    - *Coding Rule*: Apply when the participant describes difficulty using the system.

Category: Clarity of Instruction

Definition: Participant feedback regarding the comprehensibility and adequacy of the provided instructions.

Codes:

- **Needs more Clarification**
  - *Definition*: Requests for more precise instructions or additional guidance
  - *Coding Rule*: Apply when participant requests clarification or reports unclear instructions

Category: Suggestions

Definition: Participant recommendations for improving the VR toolkit.

Codes:

- **Ideas to Improve the System**
  - *Definition*: Participant recommendations for enhancing the VR toolkit.
  - *Coding Rule*: Apply when participant offers specific suggestions or improvement ideas.

Appendix 12

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

School of Healthcare Sciences
Ysgol y Gwyddorau Gofal Iechyd

Head of School and Dean /Pennaeth yr Ysgol Dros Dro a Deon Professor David Whitaker

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www.caerdydd.ac.uk

2 November 2023

Alhanouf Almutairi
Cardiff University
School of Healthcare Sciences

Dear Alhanouf

Research project title: Development of Portable Virtual Reality Physiotherapy Games for Knee Rehabilitation
SREC reference: REC894

The School Of Healthcare Sciences Research Ethics Committee reviewed the above application via its proportionate review process.

Ethical Opinion
The Committee gave:

> a favourable ethical opinion of the above application on the basis described in the application form, protocol and supporting documentation.

Additional approvals
This letter provides an ethical opinion only. You must not start your research project until all appropriate approvals are in place.

Amendments
Any substantial amendments to documents previously reviewed by the Committee must be submitted to the Committee 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 hcarethics@cardiff.ac.uk for its records.

Monitoring requirements
The Committee must be informed of any unexpected ethical issues or unexpected adverse events that arise during the research project e.g.

- End of project report ONLY;
- Annual reports;
- 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.

The Committee must be informed when your research project has ended. This notification should be made to hcareethics@cardiff.ac.uk within three months of research project completion.

Appendix 13

(The normality tests of Kinematic results)

1- The marching scenario kinematic results

Normality Test of kinematic results in sagittal and frontal plane:

Results of the normality tests indicated that all variables met the assumption of normality, except for **Left Hip Flexion_Extension and Left Knee Flexion_Extension**. However, visual inspection of the boxplot figure (1) suggested that the deviation was minor and primarily influenced by an outlier. Given the robustness of repeated measures ANOVA to minor violations of normality, this test was deemed appropriate for analysing the data.

Table 1 Normality Tests results for lower limb joints in sagittal and frontal plane in both sides.

Sagittal plane	**Shapiro-Wilk**		**Frontal plane**	**Shapiro-Wilk**	
	Statistic	**Sig.**		**Statistic**	**Sig.**
Right Hip Flexion_Extension	.925	.015	Right Hip Abduction_Adduction	.949	.088
Left Hip Flexion_Extension	.894	.002	Left Hip Abduction_Adduction	.964	.261
Right Knee Flexion_ Extension	.927	.018	Right Knee Abduction_Adduction	.951	.105
Left Knee Flexion_Extension	.908	.005	Left Knee Abduction_Adduction	.984	.858
Right Ankle Dorsiflexion_Plantarflexion	.973	.503	Right Ankle eversion -inversion	.967	.328
Left Ankle Dorsiflexion_Plantarflexion	.965	.288	Left Ankle eversion - inversion	.979	.689

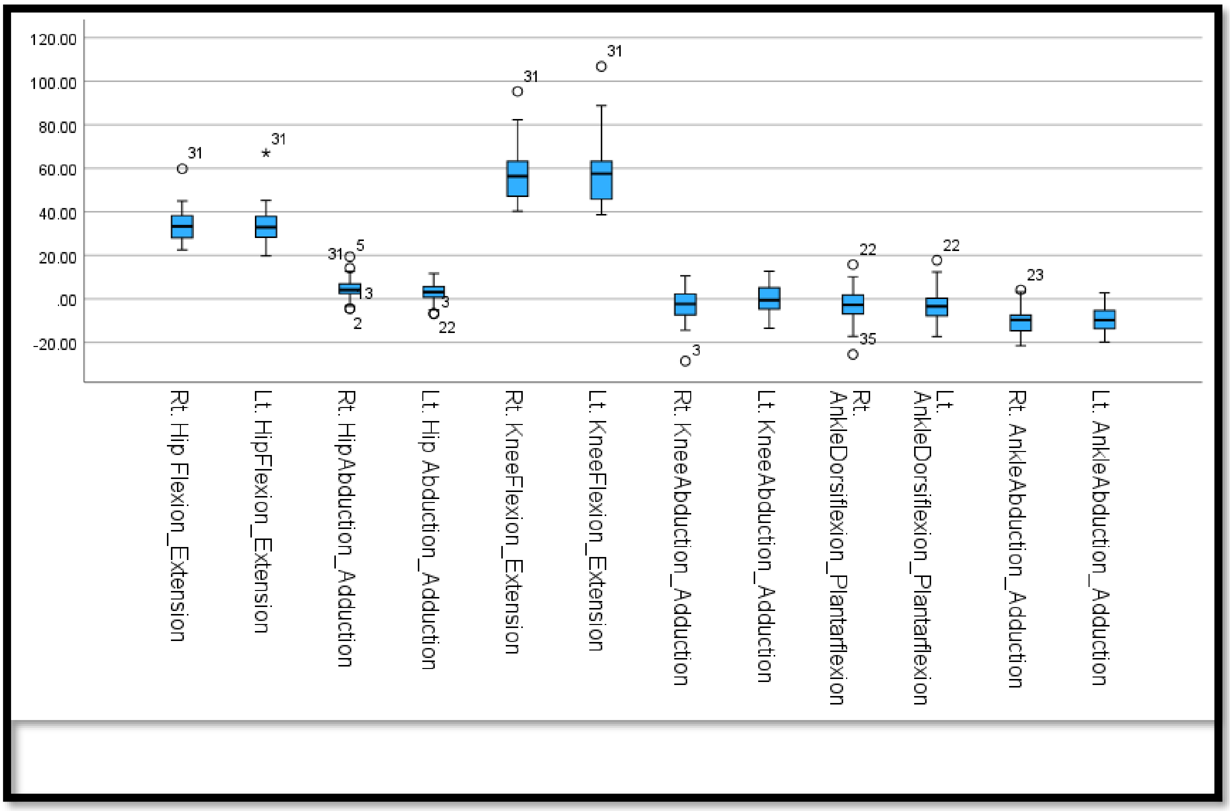

Figure 1 Boxplot of Normality test.

Normality Test of EMG amplitude across all four muscles:

The normality tests results indicated that most muscle data (RF, VM, MG, and BF) were not normally distributed ($p < .001$). This finding directed the selection of non-parametric tests for subsequent analysis. As the Marching scenario only had one level, then the Wilcoxon signed-rank test was employed to compare EMG activity between each muscle's left and right sides.

Table 2 Tests of Normality for EMG amplitude for lower limb muscles in both sides

	Shapiro-Wilk	
	df	Sig.
Left.RF	29	<.001
Left.VM	29	<.001
Left.MG	29	<.001
Left.BF	29	<.001
Right.RF	29	<.001
Right.VM	29	<.001
Right.MG	29	<.001

Right.BF	29	<.001

2- The High-stepping scenario kinematic results

Normality Test of ROM measures:

Sagittal plane:

Results of the normality test indicated that all variables met the assumption of normality. Results, presented in Table (3), indicated that most measures across levels (L1 and L2) did not deviate significantly from normality, with p > 0.05. However, one measure, **Right Ankle Dorsiflexion_Plantarflexion_L2** showed a significant result, suggesting a deviation from normality for this specific measure.

Visual inspection of the boxplot (Figure 2) provided further insights into the distribution of ROM measures. The data for most measures appeared approximately symmetrical with no extreme deviations or severe skewness. For **Right Ankle Dorsiflexion_Plantarflexion_L2**, the presence of a minor outlier was observed, which may have influenced the result of the normality test. However, the overall distribution for this measure does not appear substantially non-normal.

In conclusion, despite the significant result for one measure, the deviation from normality was minor and unlikely to affect the repeated measures ANOVA. Therefore, the analysis proceeded without transformations or alternative non-parametric tests. The robustness of ANOVA to minor normality violations, especially with the given sample size, supports the validity of the findings (Field A 2024).

Table 3 Tests of Normality for ROM measures in sagittal plane

Measures	**Shapiro-Wilk test**		**Measures**	**Shapiro-Wilk test**	
	Statistic	**Sig.**		**Statistic**	**Sig.**
Right Hip Flexion_Extension_L1	**.970**	**.472**	**Right Hip Flexion_Extension_L2**	**.945**	**.086**
Left Hip Flexion_Extension_L1	**.978**	**.705**	**Left Hip Flexion_Extension_L2**	**.964**	**.313**
Right Knee Flexion_Extension_L1	**.974**	**.584**	**Right Knee Flexion_Extension_L2**	**.987**	**.942**
Left Knee Flexion_Extension_L1	**.975**	**.601**	**Left Knee Flexion_Extension_L2**	**.987**	**.956**
Right Ankle Dorsiflexion_Plantarflexion_L1	**.979**	**.741**	**Right Ankle Dorsiflexion_Plantarflexion_L2**	**.932**	**.037**

Left Ankle Dorsiflexion_Plantarflexion_L1	.980	.759	**Left Ankle Dorsiflexion_Plantarflexion_L2**	.950	.121

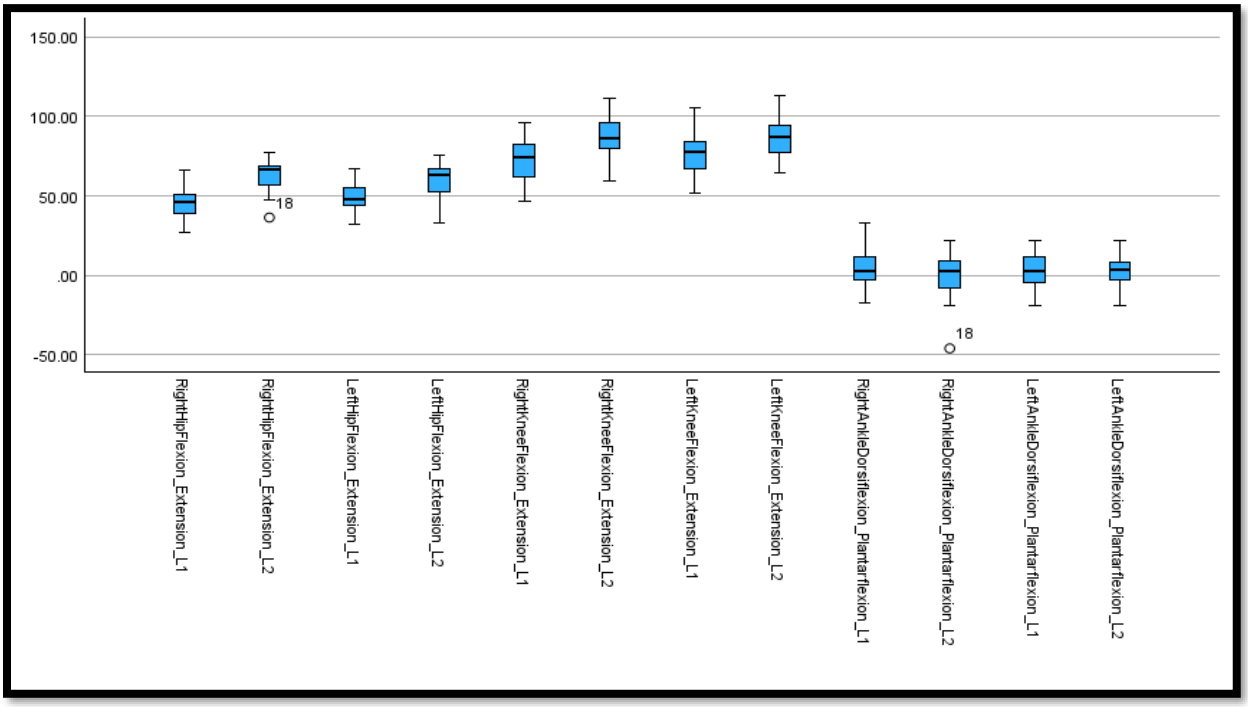

Figure 2 Boxplot of Normality test in sagittal plane.

Frontal plane:

The results of the normality of Range of Motion (ROM) measures in the frontal plane indicate that most measures did not significantly deviate from normality ($p > 0.05$), with a few exceptions (Table 4).

Table 4 Tests of Normality for ROM measures in Frontal plane.

Measures	Shapiro-Wilk test		Measures	Shapiro-Wilk test	
	Statistic	Sig.		Statistic	Sig.
Right Hip Abduction_Adduction_L1	.955	.169	Right Hip Abduction_Adduction_L2	.986	.941
Left Hip Abduction_Adduction_L1	.982	.828	Left Hip Abduction_Adduction_L2	.948	.104
Right Knee Abduction_Adduction_L1	.980	.767	Right Knee Abduction_Adduction_L2	.952	.141
Left Knee Abduction_Adduction_L1	.951	.130	Left Knee Abduction_Adduction_L2	.975	.598
Right Ankle Eversion inversion _L1	.966	.362	Right Ankle Eversion_inversion_L2	.958	.213
Left Ankle Eversion_inversion_L1	.915	.012	Left Ankle Eversion_inversion_L2	.835	<.001

The measures **Left Ankle Abduction_Adduction_L1 and Left Ankle Abduction_Adduction_L2** showed a significant deviation from normality. These significant results suggest that the distributions for these specific measures deviate from the assumption of normality. However, the remaining measures demonstrated non-significant results ($p > 0.05$), indicating that their distributions were approximately normal.

Visual inspection of the boxplot (Figure 3) provides additional context. While most distributions appear symmetric, a few measures, particularly **Left Ankle Abduction_Adduction_L1 and Left Ankle Abduction_Adduction_L2**, exhibit some outliers that may contribute to the observed deviations from normality. Despite these outliers, the overall distributions do not appear to be severely non-normal.

In summary, while a few measures demonstrated significant deviations from normality, the violations are minor and primarily influenced by outliers. Given the robustness of repeated measures ANOVA to such minor deviations, the analysis proceeded without requiring transformations or non-parametric methods.

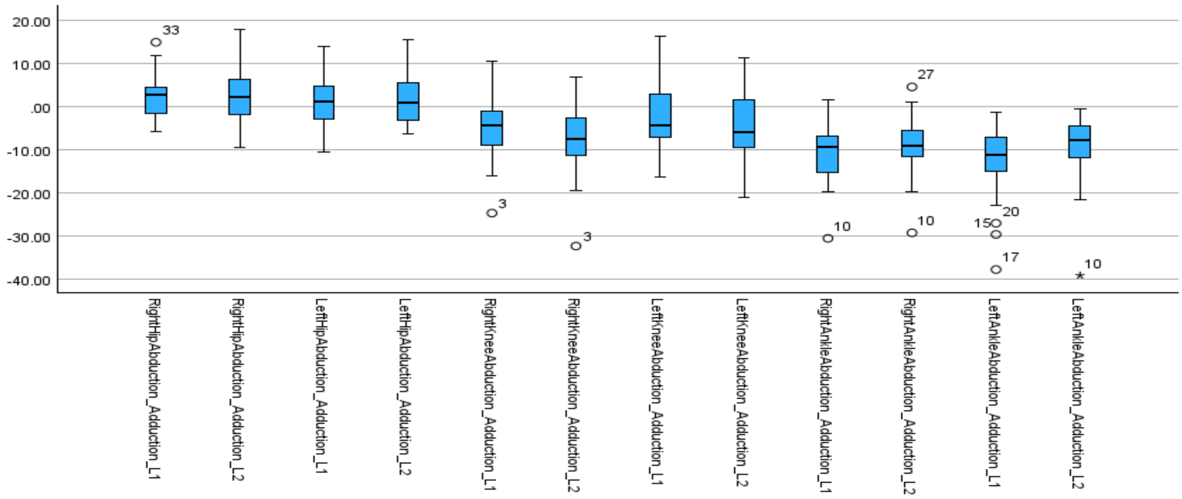

Figure 3 Boxplot of Normality tests in frontal plane.

Normality test for EMG amplitude:

The results of the Shapiro-Wilk test indicated that all EMG variables significantly deviated from normal distribution ($p < .001$) (Table 5).

Even the variables that appeared closer to a normal distribution, such as Right RF L2 ($p = .003$) and Right BF L1 and L2 ($p < .001$), still failed to meet the assumption of normality. Given these findings, non-parametric statistical methods would be more appropriate for analysing this EMG dataset.

Table 5 Normality test of EMG Amplitude

		Shapiro-Wilk test			
Measures	**Statistic**	**Sig.**	**Measures**	**Statistic**	**Sig.**
Left.RF_L1	.607	<.001	Right.RF_L1	.646	<.001
Left.RF_L2	.652	<.001	Right.RF_L2	.890	.003
Left.VM_L1	.204	<.001	Right.VM_L1	.218	<.001
Left.VM_L2	.224	<.001	Right.VM_L2	.300	<.001
Left.MG_L1	.312	<.001	Right.MG_L1	.320	<.001
Left.MG_L2	.318	<.001	Right.MG_L2	.256	<.001
Left.BF_L1	.493	<.001	Right.BF_L1	.852	<.001
Left.BF_L2	.509	<.001	Right.BF_L2	.846	<.001

3- The Weight shifting scenario.

Normality Testing:

Normality test of Total exertion of COM:

The normality test was conducted to assess whether the weight-shifting exertion data (TotExc) for both levels (L1 and L2) followed a normal distribution. The results showed significant deviations from normality for both levels (Table 6).

Table 6 Tests of Normality for the Total exertion of COM

Measures	Shapiro-Wilk	
	Statistic	Sig.
TotExc_L1	.155	<.001
TotExc_L2	.155	<.001

Due to significant deviations from normality as indicated by Shapiro-Wilk tests ($W = 0.155$, $p < .001$), differences in total exertion between weight-shifting exercise levels were analysed using the Wilcoxon signed-rank test, with significance set at $p < .05$.

Normality Test of EMG Amplitude:

The distribution of EMG data was examined using the Shapiro-Wilk tests. The results indicated that most muscle data (RF, VM, MG, and BF) were not normally distributed ($p < .001$). This finding directed the selection of non-parametric tests for subsequent analysis.

Table 7 Tests of Normality for the EMG amplitude

Measures	Shapiro-Wilk		Measures	Shapiro-Wilk	
	Statistic	Sig.		Statistic	Sig.
Lt. RF_L1	.322	<.001	Lt. RF_L2	.553	<.001
Lt.VM_L1	.200	<.001	Lt. VM_L2	.308	<.001
Lt.MG_L1	.394	<.001	Lt. MG_L2	.250	<.001
Lt.BF_L1	.856	<.001	Lt. BF_L2	.916	.012
Rt. RF_L1	.330	<.001	Rt. RF_L2	.444	<.001
Rt.VM_L1	.331	<.001	Rt.VM_L2	.511	<.001
Rt.MG_L1	.719	<.001	Rt.MG_L2	.917	.013
Rt.BF_L1	.839	<.001	Rt.BF_L2	.854	<.001

4- **The step forward scenario**

5.5.4.1 Normality Testing:

Normality test of ROM measures in sagittal plane:

As indicated by the Shapiro-Wilk tests, which showed that most of the measurements are not normally distributed ($p < 0.05$) (Table 8), non-parametric tests will be used to compare the Range of Motion (ROM) between sides, as well as between the different levels (L1 and L2). Although some ankle measurements exhibited a normal distribution, applying the same statistical approach across all measurements will ensure consistency in the analysis.

Table 8 Normality Test of ROM measures in sagittal plane

Measures	Shapiro-Wilk		Measures	Shapiro-Wilk	
	Statistic	Sig.		Statistic	Sig.
Right Hip Flexion_Extension_L1	.669	<.001	Right Hip Flexion_Extension_L2	.585	<.001
Left Hip Flexion_Extension_L1	.543	<.001	Left Hip Flexion_Extension_L2	.623	<.001
Right Knee Flexion_Extension_L1	.625	<.001	Right Knee Flexion_Extension_L2	.569	<.001
Left Knee Flexion_Extension_L1	.577	<.001	Left Knee Flexion_Extension_L2	.571	<.001
Right Ankle Dorsiflexion_Plantarflexion_L1	.966	.369	Right Ankle Dorsiflexion_Plantarflexion_L2	.959	.230
Left Ankle Dorsiflexion_Plantarflexion_L1	.912	.010	Left Ankle Dorsiflexion_Plantarflexion_L2	.970	.474

Normality Test of ROM measures in frontal plane:

The results showed that all variables were normally distributed ($p > 0.05$). This confirms that it is appropriate to use parametric statistical tests, such as repeated measures ANOVA, for subsequent analyses of these variables.

Table 9 Normality Test of ROM measures in frontal plane

Measures	Shapiro-Wilk		Measures	Shapiro-Wilk	
	Statistic	Sig.		Statistic	Sig.
Right Hip Abduction_Adduction_L1	.948	.108	Right Hip Abduction_Adduction_L2	.973	.559

Left Hip Abduction_Adduction_L1	.960	.250	Left Hip Abduction_Adduction_L2	.958	.218
Right Knee Abduction_Adduction_L1	.942	.070	Right Knee Abduction_Adduction_L2	.986	.927
Left Knee Abduction_Adduction_L1	.975	.624	Left Knee Abduction_Adduction_L2	.972	.526
Right Ankle Abduction_Adduction_L1	.944	.082	Right Ankle Abduction_Adduction_L2	.970	.453
Left Ankle Abduction_Adduction_L1	.986	.938	Left Ankle Abduction_Adduction_L2	.978	.720

Normality test for EMG amplitude:

The Shapiro-Wilk tests demonstrated significant deviations from normal distribution in the EMG data for all muscles tested under both conditions (L1 and L2), with p-values ranging from less than 0.001 to 0.002.

Given these findings, non-parametric tests will be used for analysis instead of parametric tests.

Table 10 Normality test for EMG amplitude

Measure	Shapiro-Wilk		Measure	Shapiro-Wilk	
	Statistic	Sig.		Statistic	Sig.
Left.RF_L1	.255	<.001	Left.RF_L2	.214	<.001
Left.VM_L1	.189	<.001	Left.VM_L2	.225	<.001
Left.MG_L1	.239	<.001	Left.MG_L2	.345	<.001
Left.BF_L1	.773	<.001	Left.BF_L2	.838	<.001
Right.RF_L1	.618	<.001	Right.RF_L2	.339	<.001
Right.VM_L1	.293	<.001	Right.VM_L2	.204	<.001
Right.MG_L1	.710	<.001	Right.MG_L2	.224	<.001
Right.BF_L1	.878	.002	Right.BF_L2	.817	<.001

5- The sit to stand scenario.

5.5.5.1 Normality testing:

Normality Test of symmetry index of ROM measures in sagittal plane:

The Shapiro-Wilk test results in table (11) show that the data's normality varies depending on the specific variable being examined.

The symmetry index (SI) Hip Flexion_Extension variables (L1, L2, and L3) have p-values greater than 0.05, indicating that they are normally distributed. Parametric statistical tests assuming normality can be used to analyse these variables further. In this case, repeated measures ANOVA will be used.

On the other hand, the SI Knee Flexion_Extension variables show mixed results. L1 and L3 have p-values greater than 0.05, suggesting normal distribution, while L2 has a p-value of 0.017, less than 0.05, indicating non-normal distribution. This suggests that non-parametric tests such as the Friedman test may be more appropriate for analysing the SI Knee Flexion_Extension variables, especially when considering L2.

Lastly, the SI Ankle Dorsiflexion_Plantarflexion variables (L1, L2, and L3) have p-values less than 0.001, much smaller than the typical alpha level of 0.05. This suggests that these variables are not normally distributed, and non-parametric tests should be used for their analysis such as the Friedman test.

Table 11 Normality test of SI of Average ROM in sagittal plane for lower limb joint

Measures	**Shapiro-Wilk**		**Measures**	**Shapiro-Wilk**		**Measures**	**Shapiro-Wilk**	
	Statistic	**Sig.**		**Statistic**	**Sig.**		**Statistic**	**Sig.**
SI Hip Flexion_Extension L1	.987	.956	SI Hip Flexion_Extension L2	.961	.274	SI Hip Flexion_Extension L3	.987	.948
SI Knee Flexion_Extension LI	.974	.606	SI Knee Flexion_Extension L2	.919	.017	SI Knee Flexion_Extension L3	.960	.257
SI Ankle Dorsiflexion_Plantarflexion L1	.394	<.001	SI Ankle Dorsiflexion_Plantarflexion L2	.598	<.001	SI Ankle Dorsiflexion_Plantarflexion L3	.348	<.001

Normality Test of symmetry index of ROM measures in Frontal plane:

The results of the normality tests are presented in Table 12. The Shapiro-Wilk test revealed that none of the variables followed a normal distribution, with p-values ranging from less than 0.001 to 0.003. These findings indicate that the data for each variable across all levels violated the normality assumption.

Table 12 Tests of Normality on frontal plane for lower limb joint

Measures	Shapiro-Wilk		
	Statistic	df	Sig.
SI Hip Abd_Add L1	.475	33	<.001
SI Hip Abd_Add L2	.441	33	<.001
SI Hip Abd_Add L3	.889	33	.003
SI Knee Abd_Add L1	.307	33	<.001
SI Knee Abd_Add L2	.687	33	<.001
SI Knee Abd_Add L3	.794	33	<.001
SI Ankle Abd_Add L1	.495	33	<.001
SI Ankle Abd_Add L2	.827	33	<.001
SI Ankle Abd_Add L3	.250	33	<.001

Tests of Normality for EMG amplitude:

The results of the Shapiro-Wilk tests show that the EMG data predominantly follows non-normal distributions (Table 13). This conclusion is supported by significance values ($p < .001$) for all variables.

Table 13 Tests of Normality

Measures	Shapiro-Wilk		Measures	Shapiro-Wilk		Measures	Shapiro-Wilk	
	Statistic	Sig.		Statistic	Sig.		Statistic	Sig.
Left.RF_L1	.888	.003	Left.RF_L2	.335	<.001	Left.RF_L3	.441	<.001
Left.VM_L1	.409	<.001	Left.VM_L2	.200	<.001	Left.VM_L3	.382	<.001

Left.MG_L1	.340	<.001	**Left.MG_L2**	.219	<.001	**Left.MG_L3**	.277	<.001
Left.BF_L1	.607	<.001	**Left.BF_L2**	.675	<.001	**Left.BF_L3**	.248	<.001
Right.RF_L1	.774	<.001	**Right.RF_L2**	.878	.002	**Right.RF_L3**	.710	<.001
Right.VM_L1	.397	<.001	**Right.VM_L2**	.679	<.001	**Right.VM_L3**	.780	<.001
Right.MG_L1	.305	<.001	**Right.MG_L2**	.408	<.001	**Right.MG_L3**	.602	<.001
Right.BF_L1	.408	<.001	**Right.BF_L2**	.446	<.001	**Right.BF_L3**	.383	<.001

[i] Range of motion

[ii] Western Ontario and McMaster Universities Osteoarthritis Index

[iii] Visual Analog Scale for Pain

[iv] Knee Injury and Osteoarthritis Outcome Score

[v] Hospital for Specific Surgery

[vi] Timed Up & Go Test

[vii] Berg Balance Scale