University of Minho
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Masters Dissertation
Master's in Informatics Engineering

Dissertation supervised by
Professor Cristina P. Santos

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Acknowledgements

Chegar até aqui foi uma jornada longa e cheia de desafios. Desde o momento em que entrei em Engenharia Informática até agora, foram cinco anos de trabalho árduo, empenho e sacrifício. Admito que, muitas vezes, senti-me como um peixe fora de água, especialmente no início, mas, ao longo do caminho, fui encontrando sempre as ferramentas necessárias para superar qualquer obstáculo e nunca deixei que a dúvida ditasse o meu percurso. Hoje, posso dizer que estou imensamente orgulhosa de mim mesma, das escolhas que fiz e que moldaram não só a pessoa que sou hoje, mas também a profissional que serei amanhã. Ainda assim, por mais que deva o maior dos agradecimentos a mim mesma, à minha resiliência e persistência, não posso deixar de expressar a minha gratidão a todas as pessoas que, de uma forma ou de outra, contribuíram para que este capítulo fosse concluído.

Em primeiro lugar, quero deixar um enorme agradecimento à minha orientadora, a Professora Cristina P. Santos, cujo apoio, disponibilidade e entusiasmo levaram à concretização desta dissertação e se traduziram em muitos momentos de reflexão, descoberta e crescimento. Quero também destacar um especial agradecimento à aluna de doutoramento Cristiana Pinheiro, que contribuiu incansavelmente para a conquista desta dissertação. Foi um privilégio trabalhar com uma profissional como tu, aprender com a tua dedicação, competência e paixão pelo que fazes. Obrigada por sempre reconheceres o meu esforço e qualidades, e por ajudares a elevar o meu trabalho a outro nível.

Um agradecimento querido à minha família, pai e mãe, a quem foram retiradas muitas horas da minha companhia, mas que, apesar das nossas divergências, sempre lutaram pelo melhor para mim. Nos momentos mais difíceis, eles estavam lá, a incentivar-me a continuar, mas também a confortar-me com a ideia de que, aconteça o que acontecer, tenho sempre uma casa à qual posso voltar. Obrigada por me proporcionarem a educação que vocês próprios não tiveram, por se sacrificarem dia e noite para que eu pudesse ter mais e melhores oportunidades, e por se gabarem de mim ao mundo, mesmo quando eu própria não sentia que merecia tamanho orgulho. Sou profundamente grata por ser vossa filha.

Ao meu namorado, o meu maior pilar ao longo deste percurso. Obrigada por não só celebrares as minhas vitórias e carregares as minhas derrotas como se fossem tuas, mas também por me apoiares em todas as minhas decisões e seres um motor de força que me faz acreditar que sou capaz de tudo. És uma fonte inesgotável de inspiração, e sinto-me incrivelmente sortuda por ter alguém como tu que me dá coragem para enfrentar qualquer desafio. Por último, aos meus amigos, obrigada por me levantarem sempre nas alturas mais derrotistas e contribuírem com as memórias mais felizes que jamais esquecerei.

Statement of Integrity

I hereby declare having conducted this academic work with integrity.

I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

Resumo

A doença de Parkinson (DP) tem um impacto significativo na saúde global, afetando mais de 7 a 10 milhões de pessoas em todo o mundo, com uma taxa de incidência maior entre aqueles com 60 anos ou mais. Esta condição neurodegenerativa resulta em deficiências motoras debilitantes, tornando desafiadoras as tarefas do quotidiano, como apertar uma camisa, transportar uma mala, comer ou destrancar uma porta. É importante destacar que a prevalência da DP duplicou nos últimos 25 anos, o que enfatiza a necessidade urgente de lidar com este problema. A combinação de realidade virtual (RV) e terapia do espelho (TE) tem-se mostrado promissora na reabilitação de outras condições neurológicas visto que oferece um ambiente imersivo e multisensorial para a recuperação motora, a coordenação dos membros e o envolvimento do paciente. No entanto, no contexto da DP, esta combinação tem recebido atenção limitada, sendo precisas mais contribuições para a contínua discussão sobre o assunto.

O objetivo desta dissertação é desenvolver e validar um ambiente baseado em RV para TE, adequado para ser utilizado tanto por indivíduos saudáveis como por pacientes com DP. Este projeto visa definir e conduzir um protocolo de três sessões que integra observação de ação (OA), imaginação motora (IM), e execução motora (EM) com *feedback* em tempo real. Ao fundir estas técnicas e usar sensores vestíveis, esta dissertação ambiciona fazer uma contribuição importante para a restauração das habilidades motoras e melhorar a qualidade de vida daqueles que precisam.

Uma validação preliminar com participantes saudáveis e um paciente com DP demonstrou que a OA e o *feedback* em tempo real, em geral, levaram a maiores melhorias no desempenho motor em comparação com a IM, cujos resultados foram inconclusivos e requerem mais investigação. O paciente com DP apresentou piores resultados após a intervenção, sugerindo que o *feedback* em tempo real necessita de ajustes mais personalizados para acomodar as capacidades motoras de cada indivíduo em trabalhos futuros. Os participantes saudáveis aproximaram-se mais dos dados de referência apenas com OA, enquanto a adição de IM teve um desempenho pior, e o *feedback* em tempo real produziu resultados intermédios nas atividades. Testes de usabilidade revelaram que o *feedback* em tempo real aumentou o envolvimento, melhorando a participação dos utilizadores. De forma geral, o sistema desenvolvido foi bem recebido, mostrando potencial para reabilitação motora, com vantagens em relação às terapias tradicionais.

Palavras-chave Biomecânica, Doença de Parkinson, Execução Motora, *Feedback* em Tempo Real, Imaginação Motora, Observação de Ação, Realidade Virtual, Terapia do Espelho

Abstract

Parkinson's disease (PD) exerts a significant global health impact, affecting over 7 to 10 million people worldwide, with a greater incidence rate among those aged 60 and older. This neurodegenerative condition results in debilitating motor deficiencies, rendering everyday tasks challenging, such as buttoning a shirt, carrying a bag, eating, or unlocking a door. Notably, the prevalence of PD has doubled in the last 25 years, emphasizing the urgent need to address this issue. The combination of virtual reality (VR) and mirror therapy (MT) has shown to be promising in the rehabilitation of other neurological conditions by offering an immersive, multi-sensory environment for motor recovery, limb coordination, and patient engagement. However, in the context of PD, this has received limited attention, requiring more insights to the ongoing discussion on the subject.

The main objective of this dissertation is to develop and validate a VR-based environment for mirror training, suitable for use by both healthy individuals and patients with PD. Additionally, it seeks to design and conduct a three-session protocol that integrates action observation (AO), motor imagery (MI) and motor execution (ME) with real-time feedback. By merging these techniques and employing wearable sensors, the dissertation aspires to make a meaningful contribution towards the restoration of motor abilities and, as a result, improve the quality of life for those afflicted.

A preliminary validation with healthy subjects and a PD patient demonstrated that AO and real-time feedback generally led to greater improvements in motor performance compared to MI, whose results were inconclusive and require further research. The PD patient experienced worsened post-intervention outcomes, suggesting that real-time feedback needs more personalized adjustments to accommodate individual motor abilities in future work. Healthy participants showed better alignment with reference data undergoing only AO, while the addition of MI underperformed, and real-time feedback produced intermediate results across activities. Usability tests revealed that real-time feedback increased engagement, enhancing user involvement. Overall, the developed system was well-received, showing potential for motor rehabilitation with advantages over traditional therapies.

Keywords Action Observation, Biomechanics, Mirror Therapy, Motor Execution, Motor Imagery, Parkinson's Disease, Real-time Feedback, Virtual Reality

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Acronyms

ABC Activities-Specific Balance Confidence.

AO Action observation.

AP Anteroposterior.

BBS Berg Balance Scale.

BDI Beck Depression Inventory.

BiRD Lab Biomedical Robotic Devices Laboratory.

BOLD Blood oxygen-level dependent.

CMEMS Center for MicroElectroMechanical Systems.

COM Center of mass.

DNI Dynamic Neurocognitive Imagery.

EEG Electroencephalography.

ERD Event-related desynchronization.

FoG Freezing of Gait.

H&Y Hoehn and Yahr.

HMD Head-mounted display.

IMI Intrinsic Motivation Inventory.

IPQ Igroup Presence Questionnaire.

KPI Key performance indicator.

KVIQ Kinesthetic and Visual Imagery Questionnaire.

ME Motor execution.

MI Motor imagery.

ML Mediolateral.

MMSE Mini-Mental State Examination.

MNS Mirror Neuron System.

MRI Magnetic resonance imaging.

MT Mirror therapy.

MVF Mirror Visual Feedback.

MWT Minute Walk Test.

NFOGQ New Freezing of Gait Questionnaire.

PD Parkinson's disease.

PDQ-39 Parkinson's Disease Questionnaire-39.

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

RCT Randomized controlled trial.

RPM Ready Player Me.

TUG Timed Up and Go.

UMinho University of Minho.

UPDRS Unified Parkinson's Disease Rating Scale.

VR Virtual reality.

VRE Virtual reality-based environment.

VRMT Virtual mirror training.

1 Introduction

In pursuit of a master's degree in Informatics Engineering, the document presented elaborates on the core considerations that will be conducted to complete a dissertation project, entitled "Combining a virtual reality-based environment with mirror training to improve motor function". This project is set to be accomplished in the Biomedical Robotic Devices Laboratory (BiRD Lab), which is an integral of the Center for MicroElectroMechanical Systems (CMEMS) at University of Minho (UMinho). Cristina Santos, an Assistant Professor at UMinho, specializing in Electronics and Robotics, and a distinguished researcher at CMEMS, serves as the head of BiRD Lab and will be in charge of supervising the dissertation. In addition to this management, Cristiana Pinheiro, a dedicated doctorate student in Biomedical Engineering at CMEMS, will provide valuable guidance and expertise. Support for involving a PD patient was also offered by Dr. Margarida Rodrigues, a neurologist at Campus Neurológico Sénior in Braga (CNS).

1.1 Motivation and Problem Statement

In the field of neurodegenerative disorders, Parkinson's disease (PD) emerges as a prominent public health issue, ranking second only to dementia in terms of prevalence [1]. With an estimated 7 to 10 million cases worldwide [2], and an anticipated 80% increase over the next two decades, PD predominantly affects older people, with a greater incidence rate among men over the age of 60. Given that this is a chronic and progressive ailment, it is characterized by a gradual loss of motor control over time, which leads to challenges with daily activities and mobility. As a result, this condition imposes a significant physical, psychological and economic burden, not only felt by those diagnosed and their families [1], but also by healthcare systems and societies as a whole. The financial implications of PD go beyond medical expenses to include caregiving costs, reduced work productivity, and increased healthcare consumption.

The consequences of this condition transcend its clinical symptoms, casting a financial shadow on a global scale. For instance, just in the United States, the annual monetary effects of PD reach a staggering $25 billion per year [3], which corresponds to approximately 10% of Portugal's Gross Domestic Product (GDP) in 2022. This includes the expenses associated with medical treatment, social security payments and lost income because of job incapacity. In this manner, the development of strategies to address neurodegenerative disorders like PD is crucial, not only for its impact on the quality of life of those afflicted, but also due to its macroeconomic implications on countries.

The name "paralysis agitans" was suggested in 1817 by the English physician James Parkinson to describe this issue. His work, *An Essay on the Shaking Palsy* [4], enumerated its movement-related characteristics, encompassing tremors, abnormal posture and gait, muscle rigidity and bradykinesia (slowness of physical movements). As PD progresses, its impact also extends to non-motor problems, such as apathy, sleep disturbances, and loss of independence in everyday tasks [5]. A study by Hely *et al.* [6] outlined that people with PD frequently report a range of complications, including falls (81%), daytime sleepiness (79%), depression (50%), dysphagia (50%), speech impediments (27%), and bone fractures (23%). These repercussions often culminate in hospitalizations [5].

Although PD remains impervious to a cure, many therapy techniques have evolved to reduce its symptoms and improve the quality of life of patients. Medication (e.g. levodopa) and surgical procedures (e.g. deep brain stimulation) are examples of this. Despite being combined to reduce the reliance on medication, these forms of treatment are not without drawbacks, since they are expensive and do not impede the ailment's progression. Levodopa, in particular, is prone to lose effectiveness over time, and may rise additional health concerns, such as dyskinesia and fluctuations in medication response [2]. In deep brain stimulation, surgical risks loom as alarming complications, including bleeding, stroke, infection, and damage to vital brain regions during the procedure. Post-surgery caution is required around certain electronic devices due to possible hardware malfunctions and the need for regular battery replacements.

Among a spectrum of innovative technologies, mirror therapy (MT) has gained recognition as a promising therapeutic solution for movement rehabilitation in PD due to its positive effects on motor function and ability to induce brain plasticity. Invented by Vilayanur S. Ramachandran in the 1990s, this technique was originally designed for the treatment of various neurological impairments [7, 8], particularly in post-stroke upper limb paresis [9]. By observing a traditional mirror to create the bidimensional illusion of two functional limbs, with the affected limb hidden behind it, MT deceives the brain with action observation (AO) and excites the sensorimotor regions, facilitating mobility recovery [10]. As patients watch activities being performed through video recordings, AO therapy capitalizes on the potential of visual learning [11, 12]. An essential role in shaping the success of such therapy is visual stimuli, which involves the complexity of observed actions and the perspective from which they are viewed (whether envisioning the action execution from a first-person point or from an external standpoint) [13]. On the other hand, motor imagery (MI) is a strategy that relies on mental rehearsal of activities without actually moving. When an individual vividly imagines himself doing tasks, particularly in the first person and in conjunction with its observation, the Mirror Neuron System (MNS) is activated. The MNS is a cluster of neurons in the parietofrontal and limbic systems, which enhances motor comprehension through the simulation of self-execution and observed actions. This capability enables the anticipation of action goals and sequences, thereby supporting motor planning [11, 12] and positively impacting bradykinesia, a common symptom in PD.

Scientific evidence shows that the combination of AO and MI may enhance corticospinal, (the system of nerves connecting the brain's motor cortex to the spinal cord) excitability in healthy participants [14, 15]. In people with PD, changes in corticospinal excitability not only help explain why they experience differences in how their muscles prepare for movement [16], but also expands its potential into dual-task gait and balance training. This integrated approach encourages distinct functional reorganization in brain areas associated with motor control and concentration. Consequently, those with postural instability and gait disorders benefit from longer and more significant effects on dual-task mobility and balance [17]. However, there is a noticeable lack of studies that explore the amalgamation of AO and MI in PD rehabilitation, requiring further research contributions to attain a more comprehensive conclusion.

Another pivotal advance in this domain is virtual reality (VR). Serving as the major driving force for the therapeutic intervention, it blurs the lines between reality and virtuality and intensifies body ownership [18]. The level of immersion determines the user's experience. In fully immersive VR, users wear a head-mounted display (HMD), being completely isolated from foreign stimuli. This has been demonstrated to fool the brain by closely mirroring real-world events, hence augmenting rehabilitation efficacy. It also shields patients from external distractions, allowing them to focus entirely on the exercises [19]. Nonetheless, the outcomes of VR interventions have exhibited irregularities for PD rehabilitation, ranging from significant improvements in some cases to no substantial difference compared to traditional therapy in others [20].

Virtual mirror training (VRMT) remains an insufficiently underexplored subject within the realm of the disease under study. Given the proven benefits of virtual mirror paradigms in addressing other neurological impairments, there is a strong rationale for investigating the potential application of VRMT in PD. As a medium for AO, MI and motor execution (ME), the immersive virtual reality-based environment (VRE) offers a tridimensional (3D) illusion of the limbs, creating a more realistic and interactive experience. In contrast to conventional MT, this technique has been found to stimulate cortical neuroplasticity to a greater extent [18, 21]. Furthermore, the real-time feedback mechanisms inherent to VR can encourage patients to synchronize their movements with the observed actions. As a result, it fosters their active participation in the learning process and promotes bilateral brain activation [22, 23].

1.2 Dissertation Goals and Research Questions

This dissertation is driven by the overarching goal of **developing and validating a VRE for mirror training**. This procedure integrates different MT tasks, such as AO, MI, and ME with real-time feedback, to specifically target the PD symptoms of bradykinesia, balance impairment, and tremors. In fact, one of the core objectives is to investigate strategies that have received limited attention in the existing literature. By bridging all these techniques within the context of PD and employing wearable sensors, the present document aspires to contribute additional insights to the ongoing discussion on the subject. Another goal is to explore the potential biomechanical adjustments in movement performance before and after the VRMT, anticipating positive changes in coordination and overall motor function. The following objectives and the respective deliverables were established:

- **Objective 1: Conduct a literature review on two topics.** One concerning the integration of MT in PD rehabilitation, specifically focusing on the combination of AO, MI and ME, and the other on the convergence of VR and MT in various neurological disorders. Two deliverables will be produced: (i) a report on the current state of MT for PD rehabilitation, and (ii) a report on the current state of VRMT applications in the literature. This is addressed in Chapter 2.

- **Objective 2: Identify the system requirements** to implement a VRMT solution for PD, taking into consideration the achievements and limitations found in the literature. Additionally, establish the solution proposal and the research outcomes to enable assessment in the motor function and well-being of patients under treatment. This includes the deliverable of a report outlining the solution proposal and the system requirements. This is addressed in Chapter 4.

- **Objective 3: Develop the VRMT framework** incorporating wearable and multi-sensory technology for AO, MI and real-time feedback. This implementation should deliver visual and audible cues tailored to the participant's motor execution. The deliverable encompasses the VRMT framework and an algorithm for real-time feedback. This is covered in Chapter 4, while the acquisition of reference learning data used for AO and feedback is discussed in Chapter 3.

- **Objective 4: Design and conduct a three-session experimental protocol**. In Session A, participants will undergo: (1) pre-VRMT; (2) AO within VR; (3) post-VRMT. In Session B, the same stages will be performed, but an additional stage of MI within VR will follow AO. Session C introduces AO, MI, and ME with real-time feedback. The deliverables include: (i) a report detailing the protocol planning, and (ii) a list of clinical outcomes and questionnaires. This is addressed in Chapter 5.

- **Objective 5: Acquire, analyze and discuss biomechanical data** from both healthy individuals and a PD subject to evaluate the VRMT effectiveness in achieving the desired outcomes, along with data from established questionnaires in the VR field assessing system usability. The deliverables include: (i) graphs comparing biomechanical data and questionnaire responses across sessions and before/after VRMT, and (ii) a report discussing the impact of the proposed VRMT technology on motor function. This is addressed in Chapter 6.

- **Objective 6: Document the implementation** of the combined VR and MT solution for PD rehabilitation. The deliverable is the completed dissertation document.

This dissertation endeavors to make a meaningful impact on the lives of individuals affected by this impairment, while advancing the broader knowledge in the field of motor rehabilitation. The final solution should find an answer to the following research questions:

- **Research Question 1:** How are MT strategies applied and what effects are reported in the literature for PD's victims? The answer is included in Chapter 2.

- **Research Question 2:** What are the VRMT strategies described in the literature that have a positive impact on motor effects? The answer is included in Chapter 2.

- **Research Question 3:** How does incorporating AO, MI, and real-time feedback into VRMT influence biomechanical adjustments in healthy population and a PD case study? The answer is included in Chapter 6.

1.3 Scientific Contribution

The dissertation makes several important scientific contributions. A review of the current state of motor rehabilitation using MT for patients with PD reveals that most studies employed randomized controlled designs with consistent training frequencies, leading to significant improvements in motor and cognitive functions when interventions were personalized. A review of various applications of VRMT for motor rehabilitation in different neurological disorders highlights a consistent trend where VRMT, particularly through immersive visual feedback, was shown to enhance motor function more effectively than traditional methods, despite variations in study implementation. A wearable VR-based tool for Parkinson's rehabilitation is developed as part of a VRMT training program to evaluate the motor effects of AO, MI, and real-time feedback across three distinct sessions, each combining these elements differently. Biomechanical data from both healthy individuals and a PD patient is thoroughly analyzed, with comparisons made between sessions to assess the individual and combined effects of AO, MI, and real-time feedback. The solution's immersiveness and usability are validated using two established questionnaires in the VR field, while the influence of MI is assessed through a specialized imagery task questionnaire.

1.4 Publications and Oral Communications

The research conducted has led to the publication of a conference paper in the adjunct proceedings of the 32nd ACM Conference on User Modeling, Adaptation, and Personalization (UMAP Adjunct '24), held in Cagliari, Italy, from July 1st to 4th, 2024. Beyond the publication, I actively participated in the conference by delivering a two-minute oral presentation, and preparing and displaying an A0 poster, which summarized the main objectives, methods, and findings of my research.

> Ana Henriques, Cristiana Pinheiro, and Cristina P. Santos. 2024. Combining Virtual Reality with a Biomechanical Model to Improve Parkinson's Movement: Solution Proposal and Reference Learning Data. In Adjunct Proceedings of the 32nd ACM Conference on User Modeling, Adaptation and Personalization (UMAP Adjunct '24). Association for Computing Machinery, New York, NY, USA, 92–97. https://doi.org/10.1145/3631700.3664876

1.5 Dissertation Outline

This document is organized into seven chapters. Chapter 2 provides a review of the state-of-the-art MT techniques for improving motor function in individuals with PD, as well as VRMT applications for motor rehabilitation in other neurological disorders. Chapter 3 provides a descriptive analysis of reference learning data obtained from healthy participants performing three MDS-UPDRS activities, commonly applied in clinical practice to assess specific PD symptoms. Chapter 4 describes the proposed VRMT system for PD rehabilitation, covering the VRE design and the strategies implemented to deliver real-time feedback. Chapter 5 unveils the pre-post randomized validation protocol conducted with both healthy participants and a PD patient, detailing the data acquisition and processing methods employed. Chapter 6 presents a critical analysis and discussion of the results from the validation protocol assessing the VRMT system's operability, effectiveness, and usability. Chapter 7 concludes the dissertation by addressing the research questions and suggesting directions for future work.

2 Review on VRMT for Parkinson's Rehabilitation

In this chapter, we delve into an in-depth literature review to explore the potential benefits of the topics under investigation in this dissertation, and we also uncover the challenges and limitations associated with these techniques to outline the course to the desired achievements. The literature review is structured into two main sections: the first section scrutinizes the current state of MT for motor rehabilitation of patients with PD, while the second section focuses on the various applications of VRMT in different neurological disorders. By conducting a critical analysis of the latest advancements in these areas, this chapter seeks to provide a comprehensive understanding of the developments shaping the field of movement enhancement for people afflicted by this disease. These developments encompass a wide range of technical and clinical aspects, including participant characteristics, clinical protocols, sensory and VR-based equipment employed, and the resulting motor effects.

2.1 State of The Art on MT for Parkinson's Rehabilitation

The choice of techniques to be implemented in this project is influenced by a variety of studies, including Caligiore *et al.* [11], Martin *et al.* [12] and Giannakopoulos *et al.* [13], which together offered a broad spectrum of findings on this issue. Caligiore *et al.* [11] sought to gather evidence for the use of AO and MI in the rehabilitation of PD. The focus was on understanding the different effectiveness of these approaches and exploring how they could be integrated into a unified method to improve patients' motor behavior. They also explored how research into the combined use of these techniques to improve motor function in healthy individuals may pave the way for therapeutic applications in PD. Giannakopoulos *et al.* [13] investigated AO protocols used in this disease and analyzed the intervention characteristics and outcome measures in relation to efficacy. Martin *et al.* [12] also examined the current scientific evidence on the effectiveness of MNS treatments (AO and MI) for treating gait disorders in PD patients. This subsection aims to conduct a literature review on the utilization of MT, encompassing AO and MI techniques, for the rehabilitation of motor function in PD patients. The research question addressed in this section is "How are MT strategies applied and what effects are reported in the literature for PD victims?".

2.1.1 Methods

In accordance with the guidelines of Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), this subsection has been carefully structured to safeguard the integrity of our research.

Search Strategy

The literature search was conducted using the reputable databases PubMed (Search tip: "Title/Abstract"; Article type: "Clinical Trial", "Randomized Controlled Trial") and Web of Science (Search field: "Topic"; Document type: "Article"), recognized for their credibility in hosting literature associated with medical, rehabilitation, and neuroscience topics. Only studies published in English or Portuguese were considered to secure accurate evaluation and interpretation based on the researcher's proficiency in the languages. To present the most relevant information according to current trends, the research between 2017 and 2023 was filtered, as a continuation of a previous study by Caligiore *et al.* (2017) [11]. The search string was meticulously crafted, considering the following keywords: **((mirror AND (therapy OR neurons)) OR "action observation" OR "motor imagery") AND (motor OR movement) AND (rehabilitation OR recovery) AND parkinson**. In this way, the search string strikes a balance by remaining specific enough to be consistent with the aims of the review, while avoiding excessive specificity that might limit the range of techniques found in the included papers. Subsequently, the results underwent further scrutiny, in which the title, keywords and abstract of each paper were analyzed and selected according to their importance to the dissertation's concrete objectives.

Selection Criteria

A rigorous selection process was undertaken to identify pertinent studies. This process was governed by a set of inclusion criteria to ensure the highest quality of research: (i) incorporation of a MT technique, whether in its traditional form or its fundamental concept; (ii) clinical interventions involving patients with PD; (iii) main objective of motor rehabilitation; and (iv) clinical assessment of motor (and non-motor) effects. Moreover, the search conducted on the PubMed database acquired articles discussing the combined or isolated use of AO and/or MI, with at least one of these being mandatory. However, upon recognizing the advantages of the combined approach, the selection criteria for the Web of Science database were refined to exclusively include articles that integrated both AO and MI. The selection process also considered a set of exclusion criteria: (i) no application of MT, AO or MI techniques; (ii) no Parkinsonian participants; (iii) negative impact on motor function; and (iv) no assessment of clinical motor effects within the context of PD. These criteria were carefully delineated to eliminate any extraneous data and guarantee that the selected studies directly contributed to the attainment of the dissertation's goals.

Data Extraction

Relevant information on the technical and clinical specifications was extracted by analyzing the selected studies: (i) the sensor devices used for data collection, and their respective placement; (ii) the PD participant characteristics that shaped their inclusion and exclusion criteria; (iii) the specific tasks assigned to ME, AO, and/or MI; (iv) the clinical protocols employed to validate MT; (v) the training schedules used to evaluate the extended efficacy of MT; (vi) the time points at which assessments were conducted to monitor the progression of interventions; (vii) the clinical outcome measurements evaluated to weigh MT's impact on PD recovery; (viii) the extraction of key performance indicators (KPIs) related to clinical outcomes derived from the experiments; and (ix) the MT's effects on motor rehabilitation for people with PD. Some metadata were retrieved from the papers, such as title, authors, publication year, keywords, and publication type, to achieve a better understanding of the research subjects described previously.

2.1.2 Results

In Figure 1, the search methodology initially identified 203 studies, 104 from PubMed and 99 from Web of Science. After eliminating duplicates, the number narrowed down to 198. Following a meticulous screening of titles and abstracts, a total of 157 were excluded. The remaining 36 were sought for retrieval, with one being inaccessible for free, resulting in 35 articles subjected to a full-text assessment for eligibility. This assessment yielded 10 studies that met the criteria. Additionally, 5 articles from a previous version of the review were included, bringing the inclusion of fifteen (15) studies in this literature review.

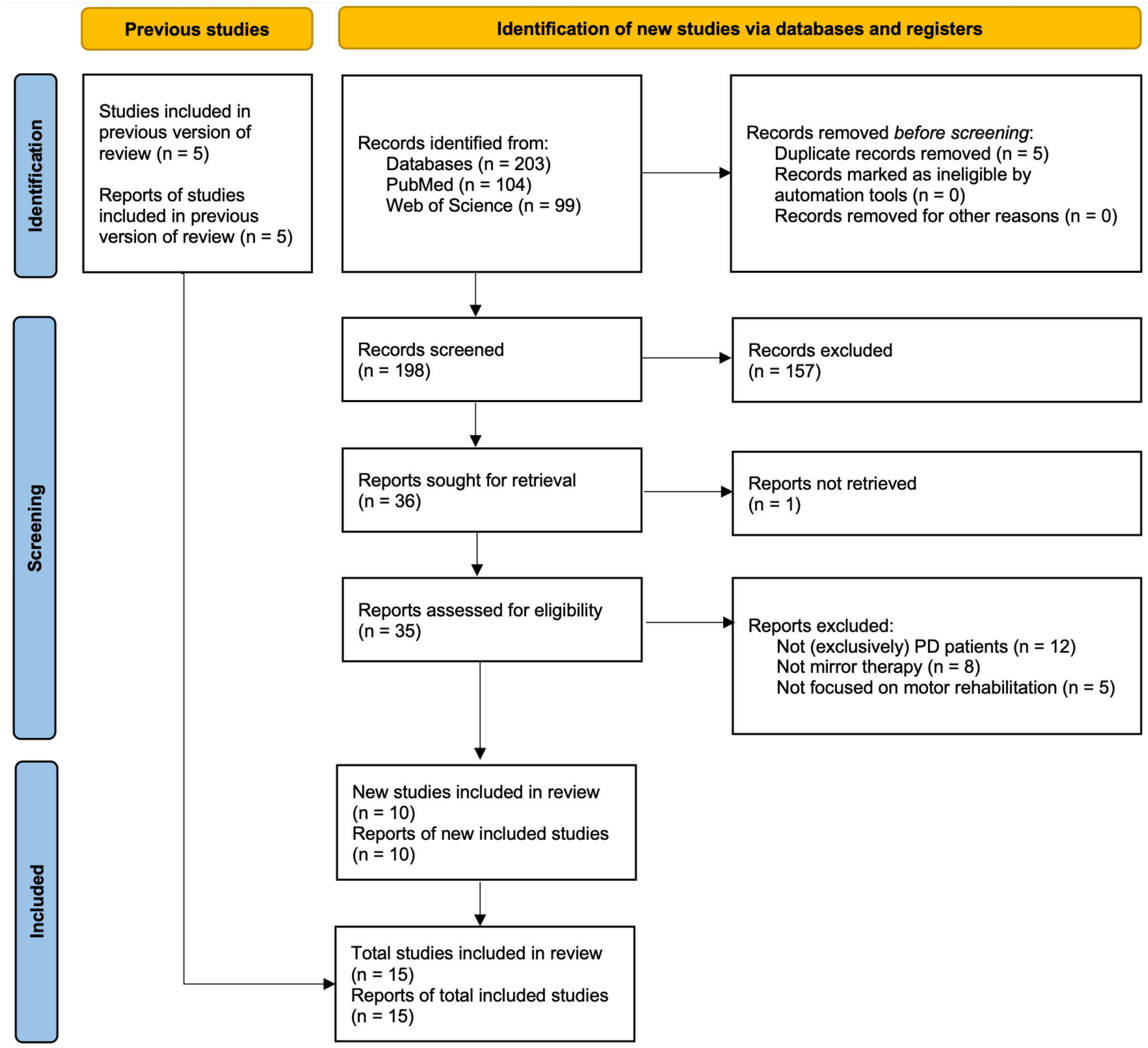

Figure 1: PRISMA flow diagram of the search strategy for first state of the art.

PD participants

The participants afflicted with PD had notable demographic and clinical characteristics, comprising 438 patients in total. The median sample size of the studies analyzed was 25. The study by Pelosin *et al.* [24] stood out as having the largest sample size with 64 patients in opposition to Goh *et al.* [25] and Caligiore *et al.* [26], who presented the smallest sample size with 10 PD participants each.

The predominant characteristics considered in these articles were age and gender, which were universally addressed (i.e. 100%) in all of them, reflecting their fundamental importance in research on this population. The age of the participants was between 40 and 80 years, roughly representing the middle-aged to older adult population. Male patients constituted more than half of the sample elements among 53.3% of the studies [17, 25–31]. In addition, 80% included the Hoehn and Yahr (H&Y) stage [17, 24–29, 31–35] and 73.3% included the disorder's duration [17, 24, 26–31, 34–36], providing information on the severity and progression of the disease. Other frequently evaluated factors, each accounting for 66.7%, were the Mini-Mental State Examination (MMSE) [17, 24, 26, 28–30, 32–34, 37] and the Unified Parkinson's Disease Rating Scale (UPDRS) III [24, 25, 27–33, 35], contributing to the assessment of cognitive and motor function, respectively. The educational level [17, 24, 26, 27, 32, 33, 35–37] and the Levodopa Equivalent Daily Dose (LEDD) [17, 24, 28–32, 35] were considered in 60% and 53.3% of the studies, respectively.

In contrast, the New Freezing of Gait Questionnaire (NFOGQ) [28–30, 35] was one of the less recurrent features, being comprised in 26.7%. The history or risk of falling [17, 25, 27], the Beck Depression Inventory (BDI) [28, 29, 37], the Montreal Cognitive Assessment (MoCA) [27, 33, 35] and the UPDRS II [17, 28, 29] appeared in 20% of the research papers, providing knowledge on non-motor symptoms. The Parkinson's Disease Questionnaire-39 (PDQ-39), the Modified Parkinson's Activity Scale (MPAS), the Berg Balance Scale (BBS) [28, 29], the Kinesthetic and Visual Imagery Questionnaire (KVIQ) [30, 31] and functional measurements, like the 6-Minute Walk Test (MWT), the Timed Up and Go (TUG) [28, 29] and the Trail Making Test [25, 37], were each employed in 13.3% of the articles analyzed.

In a minority of cases, single studies (6.7%) introduced unique features into PD participants, such as physical attributes like height and weight [34]. Jaywant *et al.* [32] examined visual acuity (logMAR) to underline the relevance of vision-related variables, and used the Beck Anxiety Inventory (BAI) to assess anxiety symptoms. Agosta *et al.* [37] contributed to the understanding of language and cognitive abilities by exploring phonemic and semantic fluency. Furthermore, Sarasso et al. [17] delved into the presence of mild cognitive impairment in their participants, adding a crucial cognitive dimension to the characterization of PD. Abraham et al. [27] considered a variety of factors, including the Composite Physical Function (CPF) scale, the number of comorbidities, the number of prescribed medications, the use of assistive devices, and prior experience with imagery. Lastly, Bezerra et al. [33] incorporated the Motor Imagery Questionnaire-Revised (MIQ-R) to evaluate MI abilities among their PD cohort.

The most common inclusion criteria were the requirement of H&Y scores within concrete ranges, generally encompassing stages 1 to 3 [17, 26–29, 31, 33, 34, 36], 2 to 4 [24, 35] or 1 to 4 [30, 32], which emphasizes the recruitment of individuals with mild to moderate severity of PD. Most studies required MMSE scores above 24 [17, 25, 26, 28–30, 33–35, 37], often in conjunction with the occurrence of FoG [17, 24, 25, 28, 29, 37], because comprehending its effects on gait and mobility was a central focus of their research. Half of the studies mandated the ability to walk independently over a certain distance [24, 25, 27, 30, 32–35] and being medically stable [17, 25, 26, 28, 29, 33, 35–37] for a specific time. On the other hand, the exclusion criteria were always careful to avoid people with other significant medical, psychiatric or neurological conditions [17, 24, 25, 27–29, 31, 32, 35–37] that could affect their results, as well as with visual abnormalities [17, 24, 32, 33, 35, 37]. This usually included people with severe orthopedic problems or comorbidities [24, 25, 28, 29, 31, 32, 35] that could impede mobility. In addition, the use of assistive devices [27–29, 32] or substance abuse [17, 32] were generally excluded, emphasizing the desire to isolate the impact of PD-specific conditions in the research.

Clinical protocols

Table 1 provides a summary of the clinical protocols extracted from the studies and includes relevant details such as: study design (the research plan and methodology used); sample size (the number of participants), distinguishing between the experimental (EG) and control groups (CG) where appropriate; technique applied (AO, MI and/or MI); training dosing (the frequency, duration and intensity of training sessions); and evaluation time points (the specific time frames at which assessments were conducted).

Table 1: Clinical specifications identified within the MT studies regarding their protocols

Study (Year)	**Study Design**	**Sample Size (EG/CG)**	**Technique**	**Training Dosing**	**Evaluation Time Points**
Jaywant *et al.* (2016) [32]	Randomized controlled design	23 (13/10)	AO + ME	1 session/day 7 days	PRE (day 1), and 1 day POST (day 8)
Agosta *et al.* (2017) [37]	Randomized controlled design	25 (12/13)	AO + ME + MI	60 min/day 3 sessions/week 4 weeks	PRE, POST, and 4 weeks follow-up.
Abraham *et al.* (2018) [27]	Randomized controlled design	20 (10/10)	MI + ME	2h/day 5 sessions/week 2 weeks	PRE and 2–5 days POST intervention.
Mezzarobba *et al.* (2018) [28]	Randomized controlled design	22 (12/10)	AO + ME	60 min/day 2 sessions/week 8 weeks	PRE, POST, at 1 month, and 3 months follow-ups.

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Study (Year)	Study Design	Sample Size (EG/CG)	Technique	Training Dosing	Evaluation Time Points
Pelosin *et al.* (2018) [24]	Randomized controlled design	64 (33/31)	AO + ME	45 min/day 2 sessions/week 5 weeks	PRE, POST, and 4 weeks follow-up
Myers *et al.* (2018) [30]	Non-randomized design	37 (37/0)	MI + ME	12 weeks	PRE- & POST-intervention
Bek *et al.* (2019) [31]	Non-randomized controlled design	48 (24/24)	AO + MI + ME	1 block of practice (4 trials) and 4 blocks of 30 trials each	Prior to MI instructions (AO), following MI instructions (AO+MI)
Caligiore *et al.* (2019) [26]	Non-randomized controlled design	20 (10/10)	AO + ME	45 min/day 3 sessions/week 4 weeks	1 month PRE, on the first day (PRE-test), on the last day (POST-test) and 1 month follow-up.
Nascimento *et al.* (2019) [36]	Single-blind, Randomized controlled design	40 (20/20)	AO + MI + ME	90 min/sessions 3 times/week 4 weeks	PRE, POST (week 5, 6) and 1 month follow-up (week 10).
Mezzarobba *et al.*(2020) [29]	Randomized controlled design	22 (12/10)	AO + ME	60 min/day 2 sessions/week 8 weeks	PRE, POST, and 1- and 3-months follow-ups.
Bommarito *et al.* (2020) [35]	Non-randomized controlled design	54 (33/21)	AO + ME	4.5 min (AO) 1 min (ME) 2 days	PRE- and POST-intervention.

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Study (Year)	Study Design	Sample Size (EG/CG)	Technique	Training Dosing	Evaluation Time Points
Sarasso *et al.* (2021) [17]	Randomized controlled design	25 (13/12)	AO + MI + ME	60 min/day 3 sessions/week 6 weeks	PRE, POST, and 8 weeks follow-up.
Goh *et al.* (2021) [25]	Uncontrolled design	10 (10/0)	AO + ME	60 min/visit 6-8 home visits over 6 weeks	PRE- (week 1) and POST-intervention (week 8).
Bezerra *et al.* (2022) [33]	Randomized controlled design	39 (21/18)	AO + MI + ME	60 min/day 3 sessions/week 4 weeks	PRE- and POST-intervention
Kashif *et al.* (2022) [34]	Randomized controlled design	44 (20/24)	AO + MI + ME	45 min/day 3 sessions/week 12 weeks	PRE, 6th week, 12fth week of therapy (POST) and 1 month follow-up

In the reviewed literature, 66.7% integrated a randomized controlled trial (RCT) [17, 24, 27–29, 32–34, 36, 37], 26.7% a non-randomized controlled design [26, 30, 31, 35] and 6.7% an uncontrolled design [25]. In the controlled trials, participants were allocated into an experimental group and a control group, both sharing identical minimum and median sample sizes, with values of 10 and 13 respectively. However, differences were found in the maximum sample size, with the EG reaching 33 and the CG 31. Only the RCTs allocated the EG in AO and/or MI therapy combined with ME, and the CG primarily in ME. Conversely, the non-randomized controlled studies exposed all participants to the intervention, with the majority considering healthy subjects as their CG [26, 31, 35] and another employing non-freezers as controls [30]. Table 3 reveals that 46.7% incorporated AO followed by ME [24–26, 28, 29, 32, 35], 13.3% included MI in addition to ME [27, 30], and 40% combined the three techniques [17, 31, 33, 34, 36, 37]. Nevertheless, one [36] of the AO+MI+ME studies applied AO to the entire sample, suggesting that its purpose was to exclusively determine MI effects on PD rehabilitation.

It is noteworthy that 40% of the studies preferred a longer time frame of 60 minutes [17, 25, 28, 29, 33, 37], while 20% opted for a 45-minute session length [24, 26, 34]. The outliers include Abraham *et al.* [27]

and Nascimento *et al*. [36] with extensive therapies of 2 hours and 90 minutes, respectively, whereas Bommarito *et al*. [35] reported the shortest intervention at 4 minutes and 30 seconds for AO and 1 minute for ME. The frequency of sessions per week varied widely from two times per week [24, 28, 29, 35] to weekday-only [27] and daily sessions [32]. However, thrice-weekly therapy was the most frequent, accounting for 40% of studies. The duration of interventions also varied, with 26.7% lasting 4 weeks and 13.3% each for 1, 6, 8 and 12 weeks. Singular studies provided unique temporal footprints, such as the short 2-week intervention of Abraham *et al*. [27] and the long 5-week training of Pelosin *et al*. [24]. In a nuanced distribution, 53.3% of studies included a follow-up, predominantly at one month, as this is also the minimum period, while the maximum follow-up interval is 3 months. Some studies introduced different assessment times, e.g. in Kashif *et al*. [34] one evaluation was conducted during the procedure (at week 6) and in Caligiore *et al*. [26] the assessment one month before the intervention.

In the context of RCTs s with MT through AO, Jaywant *et al*. [32] subjected the EG (N=13) to videos of healthy and parkinsonian gait presented by actors from lateral and anterior/posterior views. Meanwhile, the CG (N=10) watched landscape videos featuring moving water at different speeds and strengths. The AO phase, followed by gait training, was conducted daily for 8 days. Pelosin *et al*. [24] guided an equivalent study with a larger sample size for a longer period of time (5 weeks). Similarly, Agosta *et al*. [37] randomly assigned their participants to 60 minutes of physiotherapy, preceded by observing videos showing the performance of exercises, such as walking and shifting body weight between the feet, to avoid FoG episodes for the EG (N=12) and sequences of static images without live representations for the CG (N=13). The experimental protocol comprised a sequence of tasks that involved physical execution, imagination and observation. Moreover, Mezzarobba et al. (2018) [28] introduced EG (N=12) to a rehabilitation training with video-assisted motor gesture exercises, whereas CG (N=10) used visual or auditory cues to learn those movements. The AO therapy protocol consisted of: (1) observation of an actor performing various motor gestures on the screen; (2) repetitive practice of these gestures; and (3) re-performing the gestures while simultaneously re-observing the gestures. Later in 2020, Mezzarobba *et al*. [29] conducted another RCT in which they implemented the same AO protocol, where each video was composed of sounds obtained with the sonification procedure by converting the speed of the gestures into audio pitch variations.

On the other hand, Abraham *et al*. [27] focused on imagery skills, anatomical correction and postural enhancement. In this study, the EG (N=10) underwent a standardized session structure: (1) a DNI warm-up, (2) a DNI concept introduction and exercise, (3) a break, (4) another DNI concept introduction and exercise, (5) a DNI movement session utilizing elastic bands and balls synchronized to music, and (6) a DNI cool-down. Contrastingly, the CG performed only physical exercises guided by a health-related lesson folder and an exercise video with motor activities that targeted PD impairments.

Although their aim was to determine the results of MI on gait and electroencephalography (EEG) activity, Nascimento *et al.* [36] organized a RCTs that exposed their PD subjects to the combination of AO and MI. The 20 experimental participants first compared videos of their own gait to videos of typical normal gait, and then imagined themselves walking while correcting the previously identified issues. The control sample (N=20) did not participate in the imagery task, instead they only executed the gait exercises after watching a video of a PD patient's gait. In a final step, the two groups practiced some physical tasks. Sarasso *et al.* [17] integrated both AO and MI in dual-task exercises for the EG (N=13), whereas the CG only (N=12) executed dual-tasks with landscape videos. Participants were assessed by TUG with cognitive (TUG-COG) and manual dual task (TUG-MAN), which consisted of TUG while counting backwards by 7s from 100 and holding a glass full of water, respectively. Bezerra *et al.* [33] also conducted a RCT, in which the EG (N=21) watched gait videos in third and first person for comparison and, subsequently, imagined their gait in kinesthetic mode with eyes closed, guided by verbal instructions. To conclude the session, all participants had to complete a gait training exercise. Lastly, in a study by Kashif *et al.* [34], everyone performed stretching exercises. However, the EG (N=20) also played Nintendo Wii (Nintendo, Kyoto, Japan) sports via VR and then watched two videos, one with normal movements and the other with recordings of patients performing the same movements. The purpose was to compare the differences between these videos, and afterward, participants in the EG mentally rehearsed the movements they had seen.

In research by Caligiore *et al.* [26], people with idiopathic PD (N=10) formed the EG and the healthy individuals (N=10) served as the CG as well. The treatment proceeds in line with the following scheme: (1) watch videos of everyday tasks performed by an actor; (2) perform the observed actions and verbalize them; and (3) repeat the actions to add distracting tasks (i.e. simple mathematical operations, phonological tasks or narrating personal experiences) after 3 correct executions in a row. Bommarito *et al.* [35] employed a similar approach. In their study, PD victims (N=33) participated in 2 separate sessions: (1) gait assessment and (2) AO task with functional magnetic resonance imaging (MRI). During the AO task, participants were instructed to look into a mirror located in the magnet room that reflected a third-person video of human gait displayed on a screen. Healthy subjects (N=21) served as a CG. The two-day procedure involved randomly scheduled sessions. Participants completed one session on one day and the other on the next. Bek *et al.* [31] conducted a non-randomized controlled study with the following protocol: (1) a short practice block; (2) two blocks in which hand movements were observed and then performed as accurately as possible (AO); (3) two blocks in which the movements were imagined while watching the hand move on the screen (AO+MI). They splatted their participants into two groups: healthy individuals

(N=24) and individuals with mild to moderate PD (N=24).

Myers *et al.* [30], who investigated the effects of exercise on gait performance and neuronal activation during MI, constituted one of the uncontrolled studies by following a specific procedure for all participants: (1) a behavioral assessment at baseline and a MRI scan; (2) a 12-week exercise intervention; and (3) a post-assessment in which the initial behavioral evaluation and MRI scan were repeated. They divided their participants into groups according to whether they were freezers (N=13) or non-freezers (N=24). On the other hand, Goh *et al.* [25] enrolled 10 PD patients in a home-based intervention using VR to alleviate their FoG. In the first week, a baseline assessment of FoG and other mobility problems was conducted. Then, between weeks 2 and 7, the procedure involved: (1) using of an HMD to watch 180° videos of participants successfully applying their own strategies to overcome FoG in difficult situations; and (2) practicing them physically for 10 minutes. The intervention ended with a post-evaluation in week 8.

Motor activities and sensor-based assessment

In 66.7% of the studies, participants engaged in several walking activities: walking a certain distance [17, 24, 28–30, 32, 33, 35–37], walking around obstacles [33, 36], walking through a door [24, 28, 37], sitting and walking [28, 29], and walking with cognitive challenges [33, 36]. Moreover, 20% introduced cognitive tasks in parallel with motor activities, such as naming objects or doing mental calculations. Additional experimental tasks encompassed body weight shifting between feet [24, 28, 37], stretching [27, 30, 34], turning around (U-turn) [28, 37], hand movements [31], stepping over obstacles [37] and everyday tasks [26], like pouring water, brushing teeth and locking doors. As targeted body parts, 26.7% focused on the lower body (legs, ankles, and feet) [27, 30, 34, 37], while another 26.7% concentrated on the upper body (hands, wrists and fingers) [26, 31, 34, 37]. About 20% of the studies targeted specific muscles (neck, core, limbs) [27, 30, 34], but most of them (66.7%) required the whole body involvement in their motor activities [17, 24, 29, 30, 32–37].

In a remarkable 86.7% of the articles examined, the origin of the proposed tasks remained unclear, i.e. there was no information on whether they were derived from established questionnaires (e.g. UPDRS) or clinical tests. Only Nascimento *et al.* [36] and Bezerra *et al.* [33] explicitly acknowledged that they drew inspiration from previous study protocols, although both noted a commonality in their sources, with the former being one of the influences of the latter. Another trend is that 53.3% of the studies progressively increased the complexity of experimental tasks over successive sessions [24–27, 33, 36, 37], e.g. by adding distracting cognitive tasks, and 26.7% reported adjusting complexity in response to participants progress following the accurate completion of activities [25–27, 34]. Goh *et al.* (2021) [25] stated that this accuracy was based on clinical judgment and participants' self-assessment.

Regarding instrumentation, 26.7% of the research employed MRI scanners [17, 30, 35, 37], whereas 20% did not specify the equipment used [24, 27, 28]. Some studies took advantage of cameras to record participants' performance, with Bezerra *et al.* [33] strategically placed them in both coronal and sagittal planes, and Goh *et al.* [25] opted for a three-dimensional (3D) camera. Bek *et al.* [31] took a unique approach by attaching motion sensors to participants' index fingers and using occluding boxes to restrict the direct view of their own hands. Other studies incorporated specialized devices to capture spatiotemporal gait parameters, such as a sensorized mat [35] and triaxial accelerometers positioned at each ankle [32]. Moreover, Kashif *et al.* required Wii equipment for sports activities, and Nascimento *et al.* used a digital sphygmomanometer for blood pressure monitoring, noise-cancelling earphones to create a quiet environment during MI, and the Emotiv EPOC+ to measure EEG activity.

Clinical outcomes and KPIs

Table 2 summarizes all clinical outcomes measured in the research papers, along with the respective KPIs (% increased ↑ or decreased ↓ for both groups) obtained at the conclusion (POST) of the experiment. These values are associated with a *p*-value representing the comparison between groups, with a small *p*-value (usually less than 0.05) indicating statistical significance, while a *p*-value closer to 1 suggests insufficient evidence to reject the null hypothesis. Unless explicitly designated, outcomes that are not categorized as primary or secondary will be considered primary.

Table 2: Outcomes of the experimental procedures identified in the studies and their KPIs

Outcome	Category	Study	Primary?	KPI (PRE vs. POST)		
				EG	CG	p-value
PDQ-39	HRQL[1]	Jaywant *et al.* (2016) [32]	✓	↓ by 4.8%	N/A	0.01
		Agosta *et al.* (2017) [37]	✓	↓ by 23.1%	↓ by 30.7%	0.94
		Mezzarobba *et al.* (2018) [28]	X	N/A	N/A	0.05 (mobility) 0.001 (discomfort)

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Outcome	Category	Study	Primary?	KPI (PRE vs. POST)		
				EG	CG	p-value
		Sarasso *et al.* (2021) [17]	X	↓ by 25.3%	↓ by 3.3%	0.38
ABC[2]	Cognitive	Abraham *et al.* (2018) [27]	✓	↓ by 5.1%	↑ by 1.4%	0.94
		Sarasso *et al.* (2021) [17]	X	↑ by 16.1%	↑ by 3.2%	0.01
		Kashif *et al.* (2022) [34]	✓	↑ by 36.7%	↑ by 21%	$<$ 0.001
UPDRS II	Motor and non-motor	Agosta *et al.* (2017) [37]	✓	↓ by 11.3% (ON[3]) ↓ by 29.6% (OFF)	↑ by 25% (ON) ↓ by 7.7% (OFF)	0.20 (ON) 0.24 (OFF)
		Abraham *et al.* (2018) [27]	✓	↓ by 14.5%	↓ by 14.3%	0.9
		Mezzarobba *et al.* (2018) [28]	X	N/A	N/A	Not significant
		Caligiore *et al.* (2019) [26]	✓	↓ by 17.5%	N/A	Significant
		Kashif *et al.* (2022) [34]	✓	↓ by 40.6%	↓ by 16.3%	$<$ 0.001
FoG-Q	Motor	Agosta *et al.* (2017) [37]	✓	↓ by 17%	↓ by 13.5%	0.77
		Pelosin *et al.* (2018) [24]	✓	↓ by 21.1%	↓ by 16.7%	$<$ 0.001
		Bezerra *et al.* (2022) [33]	✓	↓ by 5.4%	↓ by 10.8%	Not significant

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Outcome	Category	Study	Primary?	KPI (PRE vs. POST)		
				EG	CG	p-value
NFOGQ	Motor	Mezzarobba *et al.* (2018) [28]	✓	N/A	N/A	0.001
		Sarasso *et al.* (2021) [17]	X	↓ by 33.2%	↓ by 35.2%	1.0
		Bommarito *et al.* (2020) [35]	✓	N/A	N/A	0.024 (FOG+) 0.012 (FOG-)
		Goh *et al.* (2021) [25]	X	N/A	N/A	Not significant
UPDRS III	Motor	Agosta *et al.* (2017) [37]	✓	↓ by 15.6% (ON) ↑ by 6.4% (OFF)	↑ by 3% (ON) ↑ by 1.2% (OFF)	0.03 (ON) 0.75 (OFF)
		Abraham *et al.* (2018) [27]	✓	↓ by 17.7%	↓ by 2.8%	0.05
		Mezzarobba *et al.* (2018) [28]	X	N/A	N/A	0.001
		Caligiore *et al.* (2019) [26]	✓	↓ by 20%	N/A	Not significant
		Sarasso *et al.* (2021) [17]	X	↑ by 6.8% (ON) ↓ by 12.3% (OFF)	↓ by 12.4% (ON) ↓ by 17% (OFF)	0.35 (ON) 1.0 (OFF)
		Kashif *et al.* (2022) [34]	✓	↓ by 53.6%	↓ by 19.9%	$<$ 0.001
MiniBESTest[4]	Motor	Abraham *et al.* (2018) [27]	✓	↑ by 3.6%	↓ by 2.8%	0.22
		Sarasso *et al.* (2021) [17]	X	↑ by 15%	↑ by 1.5%	0.01

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Outcome	Category	Study	Primary?	KPI (PRE vs. POST) EG	CG	p-value
		Bezerra *et al.* (2022) [33]	✓	↑ by 6%	↑ by 2.6%	Not significant
10MWT	Motor	Agosta *et al.* (2017) [37]	✓	↓ by 8.9% (comfortable speed)	↓ by 10% (comfortable speed)	0.56
		Pelosin *et al.* (2018) [24]	X	↓ by 23%	↓ by 16.2%	0.464
		Sarasso *et al.* (2021) [17]	X	↓ by 10.2% (comfortable speed)	↓ by 2.0% (comfortable speed)	0.045
		Goh *et al.* (2021) [25]	X	N/A	N/A	Not significant
TUG (sec)	Motor	Abraham *et al.* (2018) [27]	✓	↓ by 6.7% ↓ by 18.8% (COG) ↓ by 18.0% (MAN)	↑ by 4.2% ↑ by 22.3% (COG) ↑ by 2.3% (MAN)	0.15 0.09 (COG) 0.05 (MAN)
		Mezzarobba *et al.* (2018) [28]	X	N/A	N/A	Not significant
		Pelosin *et al.* (2018) [24]	X	↓ by 24.2%	↓ by 22.5%	0.033
		Nascimento *et al.* (2019) [36]	X	N/A	N/A	N/A
		Sarasso *et al.* (2021) [17]	✓	↓ by 18.8% ↓ by 46.0% (COG) ↓ by 18.1% (MAN)	↓ by 16.1% ↓ by 23.3% (COG) ↓ by 23.0% (MAN)	1.0 <0.001 (COG) 0.21 (MAN)
		Goh *et al.* (2021) [25]	X	N/A	N/A	Not significant

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Outcome	Category	Study	Primary?	KPI (PRE vs. POST)		
				EG	CG	p-value
BBS	Motor	Agosta *et al.* (2017) [37]	✓	↑ by 5.3%	↑ by 4.2%	0.66
		Mezzarobba *et al.* (2018) [28]	X	N/A	N/A	Not significant
		Pelosin *et al.* (2018) [24]	X	↑ by 10.8%	↑ by 8.5%	0.043
		Kashif *et al.* (2022) [34]	✓	↑ by 31.9%	↑ by 13.8%	< 0.001
KVIQ	Imagery	Abraham *et al.* (2018) [27]	✓	↑ by 18.9% (Kinesthetic) and ↑ by 20.1% (Visual)	↓ by 10.2% (Kinesthetic) and ↓ by 13.9% (Visual)	0.01 (Kinesthetic) 0.02 (Visual)
		Bek *et al.* (2019) [31]	✓	↑ by 25% (Kinesthetic) and ↑ by 16.7% (Visual)	↑ by 150% (Kinesthetic) and ↑ by 100% (Visual)	0.34 (Kin.) 0.98 (V)

The literature contained a substantial focus on the evaluation of motor function, with TUG [17, 24, 25, 27, 28, 36] and UPDRS III [17, 26–28, 34, 37] each accounting for 40% of the research. This was closely followed by the 10MWT [17, 24, 25, 37], the NFOGQ [17, 25, 28, 35] and the BBS [24, 28, 34, 37], which featured in 26.7%. Other motor tests included the Mini-Balance Evaluation Systems Test (MiniBESTest) [17, 27, 33] and the FoG-Q [24, 33, 37], each at 20%, and the 6MWT [27, 28] at 13.3%. As less frequent outcomes, Abraham *et al.* integrated the 30-Second Chair Stand and the 360-Degree Turn Test, whereas Mezzarobba *et al.* (2020) [29] analyzed the dynamics of center of mass (COM) and center of pressure (COP). Jaywant *et al.* [32] assessed stride length, walking speed and asymmetry of gait. Stride length was also determined by Myers *et al.* [30], along with blood oxygen-level dependent (BOLD) signal during MI training. Furthermore, EEG activity took precedence as one of outcomes in Nascimento *et al.* [36].

[1] Health-Related Quality of Life
[3] On medication
[4] Mini Balance Evaluation Systems Test
[2] Activities-Specific Balance Confidence

The measurements of cognitive function were well represented in the studies conducted by Abraham *et al.* [27] and Caligiore et al. [26], both of which examined the Trail Making Test. The first study also integrated the Brooks Spatial Memory Task and the Body Position Spatial Task. In contrast, the second study included the Rey Auditory Verbal Learning Test, the Rey-Osterrieth Complex Figure Test and the Semantic Fluency Test. However, the UPDRS II [26–28, 34, 37] stood out as the predominant assessment tool applied in 33.3% of the articles reviewed. Other notable instruments include the ABC scale [17, 27, 34], being mentioned in 20% of the studies. Some research underscored the disease severity and its psychological impact, with the PDQ-39 [17, 28, 32, 37] appearing in 26.7% of the studies. Abraham *et al.* [27] also conducted an analysis using the Brief Pain Inventory (BPI) and the BDI, while Goh *et al.* [25] encompassed the Parkinson Anxiety Scale (PAS). In addition, some studies looked at the evaluation of motor imagery, with the KVIQ [27, 31] being the most regular at 13.3%.

Motor and non-motor effects

Outstanding effects were consistently observed in the research. After the experimental procedures, 60% and 26.7% of the studies explicitly confirmed a recognizable improvement in motor [17, 24, 27–29, 31, 32, 34, 37] and cognitive [17, 26, 27, 34] functions, respectively. Furthermore, an enhancement in balance [17, 24, 25, 28, 37] was reported in 33.3% of the studies, and a similar percentage highlighted a reduction in the severity of FoG [17, 24, 25, 28, 37]. The quality-of-life aspect was not overlooked either: 20% of the studies explicitly indicated a positive impact in the well-being of PD patients [28, 34, 37]. Impressively, 26.7% of the studies reported long-lasting effects [17, 24, 28, 34] after completion of the intervention.

The research conducted by Agosta *et al.* [37] showed an augmented recruitment of motor regions and the fronto-parietal MNS in response to AO therapy. After 4 weeks, the CG showed reduced activity in certain brain regions during the execution of foot movements and MI tasks, while the EG showed increased activity in the corresponding areas. Goh *et al.* [25] found minimal changes in the severity of FoG, but identified the effectiveness of the intervention in reducing anxiety in individuals with high levels of anxiety associated with FoG. The findings of Abraham *et al.* [27] contributed to the discussion by establishing a correlation between gains in imagery ability and enhanced motor and non-motor skills. The correction of body posture and biomechanics proved to be a crucial element in favor of additional sensory information to optimize motor learning. Sarasso *et al.* [17] presented a specific functional reorganization of brain areas involved in motor control and executive-attentive abilities, after AO and MI were combined in a dual-task gait/balance training. In a study by Bek *et al.* [31], the groundbreaking quantification of hand movement modulation demonstrated a promising therapeutic avenue for PD by underscoring the potential of AO to facilitate MI and thus improve imitation. While the results of Bezzera *et al.* [33] did not show immediate changes in balance and FoG parameters, they also suggested the inclusion of AO and MI in the broader treatment landscape for PD. Kashif et al. [34] demonstrated very positive and sustained effects in the recovery of motor function, activities of daily living (ADLs) scale, balance and fall risk in the EG compared to the CG.

In contrast, Myers *et al.* [30] reported no significant effects on backward velocity, string length or BOLD signal during MI. Similarly, even though Caligiore *et al.* [26] indicated positive impact on cognitive deficiencies, particularly in memory development, they raised questions about targeting cognitive goals due to the absence of significant improvement in motor function.

In the overall analysis of studies assessing FoG parameters, including FOG-Q and NFOGQ, 42.9% reported significant improvements (i.e. p-value between groups below 0.05) [24, 28, 35]. Remarkably, ABC [17, 34] and UPDRS III [27, 28, 34, 37] showed more favorable results, with 66.7% of the studies that assessed them each achieving p-values between groups below 0.05. BBS [24, 34], PDQ-39 [28, 32], KVIQ [27] and TUG [17, 24, 27] also demonstrated notable improvements, with 50% of the literature that addressed each showing significant results. On the other hand, UPDRS II [26, 34], MiniBESTest [17] and 10MWT [17], showed less favorable results. Only 40%, 33.3% and 25% of the articles analyzing them, respectively, yielded p-values between groups below 0.05.

2.1.3 Discussion

Most of the literature reviewed employed a randomized controlled design, supporting their findings with a median training frequency of 3 times a week over a 4.5-week median period, with each session lasting 60 minutes. The observed interventions varied in frequency, ranging from a minimum of 1 session to a maximum of 12 weeks. Session durations ranged from lasting less than 10 minutes to extending up to 2 hours. Despite this trend, the duration of interventions varied across the studies, with the efficacy of low-to moderate-frequency protocols comprising 2 to 3 sessions per week recommended for PD patients [13]. Evaluation time points were consistently scheduled before and after training, supplemented by a follow-up assessment usually conducted 1-month post-training. Caligiore *et al.* (2017) [11] have shown that, in individual sessions, AO therapy appears to improve the execution of spontaneous movements whereas, in long-term experiments, both AO and MI separately seem to enhance motor skills, especially when applied in the early stages of the disease and combined with ME. Therefore, it is imperative that future research takes longitudinal approaches and extends the investigations to determine the lasting effects of the experimental procedures over longer periods. This is critical to understanding the factors that contribute to sustained therapeutic benefits, as concluded by Bezerra *et al.* [33] after their experiment yielded no significant changes in parameters related to balance and FoG for PD victims.

The literature consistently focused entirely on males with PD aged between 40 and 80 years, taking into account their level of education and mental status. Inclusion criteria typically included H&Y scores between 1 and 3, MMSE scores above 24, ability to walk a certain distance independently and medical stability. Participants were also characterized using the UPDRS, while exclusion criteria commonly encompassed the absence of other neurological disabilities or orthopedic problems. A significant gap in the existing literature concerns the origin of tasks embedded in experimental protocols. In particular, there is a lack of explicit documentation on the sources of these interventions (e.g., clinical questionnaires or previous research), which raises legitimate concerns about standardization and reproducibility in this area. This requires that future research initiatives ensure that the efficacy of certain activities in PD rehabilitation is firmly established through credible sources in the field. Additionally, it may be advantageous to identify the ailment's symptoms targeted by the treatment to facilitate the selection of the most appropriate activities. This comprehensive approach will contribute to more robust and reliable study methods. Moreover, Giannakopoulos *et al.* [13] suggested combining intransitive actions, characterized by less complexity, with transitive actions that take into account the patient's degree of impairment or progress during therapy. This underlines the importance of tailoring therapeutic approaches to the patient's individual needs and characteristics to optimize outcomes without overwhelming them.

Centering on the techniques implemented in the studies, it is clear that visual stimuli, including the type of movement viewed and the perspective of observation, play a notable role in shaping the effectiveness of AO therapies [13]. For instance, in activities that only involve hand movements, it may be beneficial to focus entirely on visualizing the hands to preserve the participant's concentration. Conversely, for tasks that require the manipulation of the whole body, it becomes imperative to choose a perspective that adequately reflects the nature of the exercise. Whether opting for a side, diagonal, frontal or back view, the selection should be geared towards showing the full physical dynamics of the activity. In opposition to AO, the conclusions drawn from the existing evidence on MI therapy seem less robust, prompting inquiries into the potential of this approach. In the majority of studies, participants are in a relaxed and controlled setting – seated, comfortable, in silence and with their eyes closed – creating an optimal environment for imagery practice. A study by Kashif *et al.* [34] highlights that incorporating MI into dual-task gait/balance training in PD patients has shown significant improvements in mobility and balance, while merging it with traditional physiotherapy augments motivation and concentration. However, when MI is investigated in isolation and not in combination with AO, it does not achieve significant results on its own [12, 13]. Therefore, more extensive research efforts (e.g. larger sample sizes) are essential to strengthen the evidence base on this technique and to foster more confidence in clinical practice.

A notable evolution of methods over time is emerging, with studies conducted between 2019 and 2022 predominantly pursuing the AO+MI+ME paradigm. This represents a recognition of the synergistic advantages of combining these three elements and indicates a paradigmatic shift towards a more integrated approach. The correlation between improved motor function and cognitive ability has been consistently found across articles. The application of the AO+MI+ME intervention not only enhances motor skills, but also brings cognitive benefits at the same time. In fact, it promotes corticospinal excitability, which expands its success into dual-task paradigms between motor functions, including gait and balance training, and cognitive functions, for instance by challenging participants to solve simple mathematical operations or verbalize what they are doing while performing everyday tasks such as pouring water into a glass or eating. Sarasso *et al.* [17] confirmed, for example, that the application of these three techniques as part of dual-task training can lead to targeted brain reorganization, and potentially lasting improvements in mobility and balance for those with PD, postural instability and gait difficulties. Nevertheless, the challenges identified by Kashif *et al.* [34] in ensuring the accuracy of the PD patients' perceptions of activities, particularly in terms of imagery performance or frequency of mental rehearsals, is a limitation that demands a comprehensive method to balance the complexity of tasks.

The synthesis of different clinical outcomes represents an in-depth assessment that includes both motor and non-motor dimensions. The predominant motor activity identified in the research centered around walking exercises involving the whole body. Both groups in the studies yielded great results for the variables investigated, namely disease severity, freezing of gait, quality of life, balance, as well as motor and cognitive functions. Interestingly, these improvements were largely maintained at follow-up in the EG, suggesting that interventions based on the MNS enable long-lasting effects [12]. In addition to walking, other tasks involving the upper or lower body also showed positive impacts, supporting the broader effectiveness of interventions that incorporate MNS into PD rehabilitation.

In the motor function domain, significant improvements were observed in the UPDRS III, TUG and BBS outcomes. Conversely, in the realm of cognitive function, disease severity, and motor imagery assessment, ABC, PDQ-39 and KVIQ, respectively, showed more significant improvements. However, disparities emerged when comparing the results between the two groups in relation to certain assessments. Bezerra *et al.* [33] found no significant differences between the CG, which only completed physical training with walking exercises, and the EG, which additionally completed AO and MI before ME. In contrast, the studies by Pelosin *et al.* [24], Sarasso *et al.* [17] and Kashif *et al.* [34] achieved significant improvements in the EG through group comparisons. Pelosin *et al.* [24] and Sarasso *et al.* [17], despite integrating tasks that targeted the whole body, diverged in their therapeutic approaches, where the former solely employs AO with ME and the latter incorporates MI with the same combination. Kashif *et al.* [34] innovatively used the immersive nature of VR to motivate the EG to practice motor and cognitive functions with sport games. This variance in therapies illustrate the effects on the observed outcomes and the potential efficacy of multifaceted rehabilitation strategies in the treatment of PD.

UPDRS III emerged as the motor outcome demonstrating more significant improvements. Mezzarobba *et al.* (2018) [28] engaged participants in observing and executing activities encompassing walking and shifting body weight between feet. Abraham *et al.* [27] introduced stretching exercises, such as pelvis movements, and suggested imagining these exercises before performing them. Agosta *et al.* [37] conducted an intervention with AO, MI and ME, in which participants executed various activities, including walking, body weight shifting, and U-turns. Similarly, Kashif *et al.* [34] integrated AO, MI and ME into their protocol by combining stretching with VR-based Wii sports games, such as bowling and tennis. Additionally, BBS showed considerable improvements in both the Kashif *et al.*'s [34] and Pelosin *et al.*'s [24] studies, the latter of which introduced walking and body weight shifting as motor tasks to be observed and then performed. Mezzarobba *et al.* (2018) [28] did not differentiate between the EG and the CG, and Agosta *et al.* [37] and Abraham *et al.* [27] reported more pronounced rehabilitation in EG. However, the remaining studies showed that both groups had significant improvements in motor function.

2.2 State of The Art on VRMT in Other Neurological Diseases

Although not combined in the traditional way, mirror therapy strategies embedded in VR are promising for future research efforts. They offer the ability to simulate real-world scenarios in a controlled environment and represent a unique technique to help people overcome motor challenges. Moreover, VRMT has the potential to alleviate discomfort by distracting patients from pain and providing alternative sensations [38]. This literature review on VRMT for motor rehabilitation serves as a continuation of the work initiated by Darbois *et al.* [39], which contributed critical insights into the current landscape of using robotics or VR in MT. The conclusion of this study highlights the overall low quality of research dedicated to second-generation MT, underscoring the need for rigorous evaluation of existing devices with well-conducted RCTs before investing in the development of new devices. Similarly, but in PD, Kwon *et al.* [20] asserted the crucial impact of recent technological advances on the rehabilitative effects of VR technology compared with conventional treatments. The primary research question addressed in this section is "What are the VRMT strategies described in the literature that have a positive impact on motor effects?".

2.2.1 Methods

In alignment with the previous subsection, the structure of this subsection has been meticulously organized following the guidelines of PRISMA, ensuring the research's methodological integrity and rigourh.

Search Strategy

The literature search was carried out in the databases PubMed (Search tip: "Title/Abstract"; Article type: "Clinical Trial", "Randomized Controlled Trial", "Review", "Systematic Review"), Web of Science (Search field: "Topic"; Document type: "Article" and "Review Article") and Scopus (Search field: "Title/Abstract/Keywords"; Document type: "Article"), with a focus on studies published in English or Portuguese from 2018 to 2023, with free access. This time range is selected as a continuation of a previous study by Darbois *et al.* [39]. The search string was meticulously crafted, considering the following keywords: **"virtual reality" AND (mirror AND (neurons OR therapy)) AND "action observation" AND ((motor OR mobility) AND (rehabilitation OR recovery))**. In this way, the search string strikes a balance by remaining specific enough to match the aims of the review, while avoiding excessive specificity that might limit the range of VRMT approaches found in the included papers. As observed in the analysis of the previous state of the art, the search did not concentrate on PD due to the lack of literature examining the use of VRMT in this disorder. In addition, since the dissertation intends to explore the integration of VR as a mediator for AO, the search string was broadened to encompass the keyword "action observation". Subsequently, the results underwent further scrutiny, in which the title, keywords and abstract of each paper were analysed and selected according to their relevance to the dissertation's concrete objectives.

Selection Criteria

A rigorous selection process was undertaken to ensure that the selected studies were directly connected to the use of VR in MT to enhance motor and non-motor parameters. Being an innovative approach within PD, articles on other neurological disorders were also accepted. This process was governed by a set of inclusion criteria to ensure the highest quality of research: (i) preference for up-to-date studies; (ii) incorporation of a VRMT technique; (iii) therapeutic interventions involving immersive VRE; (iv) characterization of the implemented environment and how the participants interacted with it; (v) main focus on VRMT for motor rehabilitation; and (vi) assessment of motor (and non-motor) effects. The selection process also considered a set of exclusion criteria: (i) no application of MT or VR techniques; (ii) not an immersive VRE; (iii) negative impact on motor function; and (iv) no assessment of motor effects. These criteria were carefully delineated to eliminate any extraneous data and guarantee that the selected studies directly contributed to the attainment of the dissertation's goals.

Data Extraction

Relevant information about the implementation and interaction with a VRE was extracted through the analysis of the selected studies: (i) the VR and sensor devices used for data collection, and their respective placement; (ii) the specific tasks assigned to ME, AO, and/or MI; (iii) the implementation of a VRE and how participants interacted with it; (iv) the introduction of feedback; (v) the experiment protocols employed to validate MT; (vi) the training schedules to assess the extended efficacy of VRMT; (vii) the time points at which assessments were conducted to monitor the progression of interventions; and (viii) the MT's effects on motor rehabilitation. Some metadata were retrieved from the papers, such as title, authors, publication year, keywords and publication type, to achieve a better understanding of the research topics.

2.2.2 Results

In Figure 2, the search methodology initially identified 398 studies, 89 from PubMed, 164 from Web of Science and 145 from Scopus. After eliminating duplicates, the number narrowed down to 369. Following a meticulous screening of titles and abstracts, 304 were excluded. The remaining 67 were sought for retrieval, with 2 being inaccessible for free, resulting in 65 articles subjected to a full-text assessment for eligibility. This yielded 14 studies that met the criteria. Additionally, one article from a previous version of the review was included, bringing the inclusion of fifteen (15) studies in this literature review.

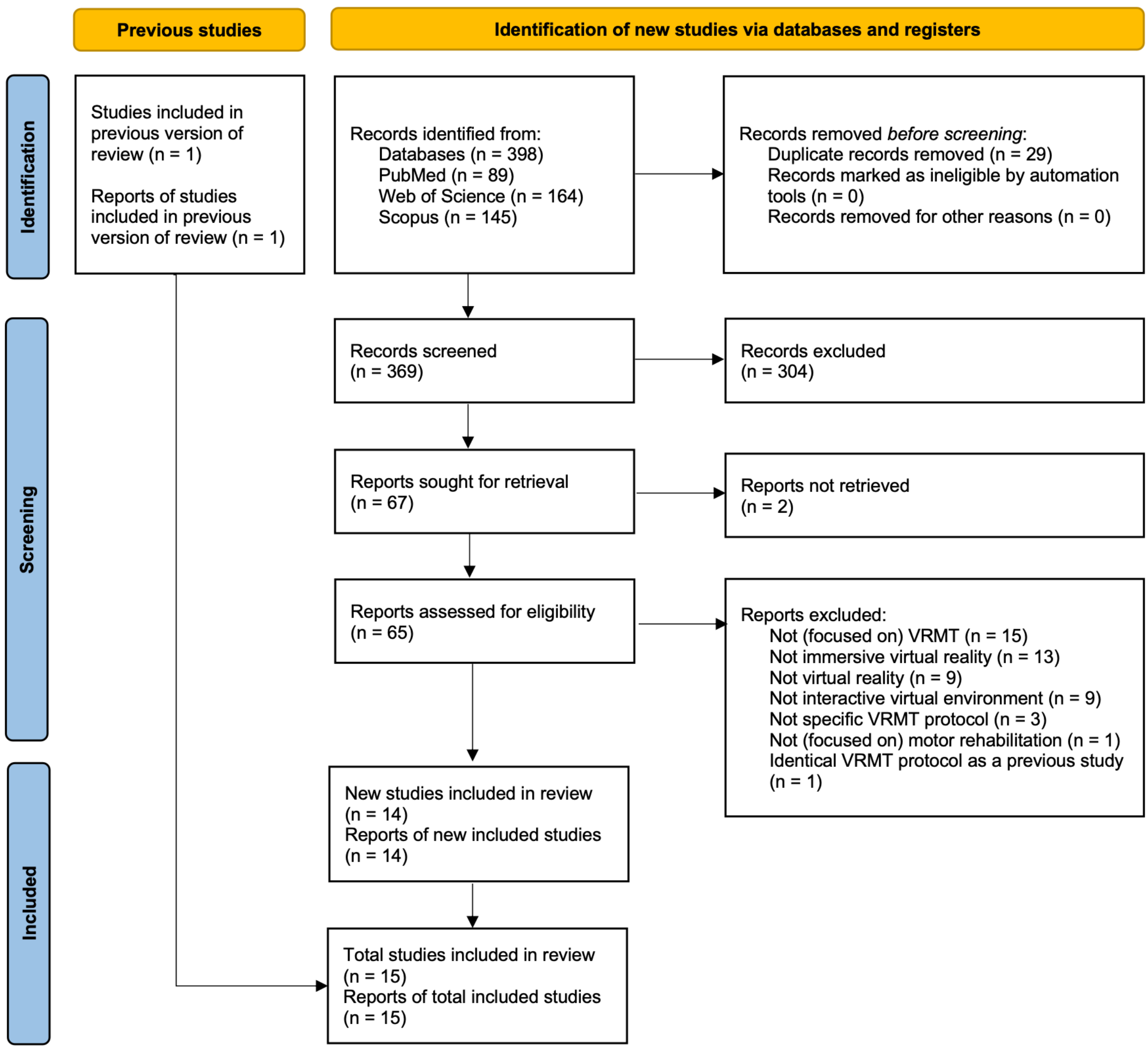

Figure 2: PRISMA flow diagram of the search strategy for second state of the art.

Experimental protocols

Table 3 presents a concise overview of the experimental protocols derived from the examined studies, encompassing relevant information on technical and clinical specifications. This includes details such as the sample size (with a distinction between the experimental and control groups when applicable); the sensors and VR equipment employed; the techniques applied (AO, MI and/or ME); the dosing of training (comprising the frequency, duration, and intensity of training sessions); and the evaluation time points (indicating the specific time frames for conducted assessments).

Table 3: Specifications identified within the VRMT studies regarding their protocols

Study (Year)	Sample Size (EG/CG)	Sensors & VR Devices	Technique	Training Dosing	Evaluation Time Points
Weber *et al.* (2019) [40]	10 (10/0)	Oculus Rift two hand controllers	AO + ME	30 mins/session 12 sessions 4 weeks	PRE- and POST-intervention
Hülsmann *et al.* (2019) [41]	35 (35/0)	CAVE with two projection walls, 3D glasses, OptiTrack suit	AO + ME	2h on the 1st day 1h on the 2nd day	PRE, POST, 1 day follow-up
Vourvopoulos *et al.* (2019) [42]	4 (4/0)	Oculus Rift HMD and controllers with 6-DoF, Starstim 8 (EEG), Delsys Trigno Wireless System (EMG)	AO + ME	1.5 h/session 8 sessions 6 weeks	PRE-, during and POST-intervention
Lin *et al.* (2021) [43]	18 (9/9)	Oculus Rift, Leap Motion Camera	AO + ME	50 minutes/day 2 days/week 9 weeks	PRE- and POST-intervention
Emedoli *et al.* (2021) [44]	1 (1/0)	Oculus Rift	AO + ME	1 h/session 5 sessions/week 3 weeks	PRE- and POST-intervention
Mekbib *et al.* (2021) [45]	23 (12/11)	HMD, HTC Vive tracking stations, Leap Motion tracking	AO + ME	1h VR + 1h OT/day 4 days/week 2 weeks	PRE- and POST-intervention
Rey *et al.* (2022) [46]	20 (20/0)	Meta Quest HMD and controllers	AO + ME	30 min/session 1 session	Initial, middle and final parts of the training

(Table 3 continues on next page)

(Table 3 continued from previous page)

Study (Year)	Sample Size (EG/CG)	Sensors & VR Devices	Technique	Training Dosing	Evaluation Time Points
Kashif *et al.* (2022) [34]	44 (20/24)	Wall-mounted display Wii box, remote and fit board	AO + MI + ME	45 min/day 3 sessions/week 12 weeks	PRE, 6th week, 12th week of therapy (POST) and 1 month follow-up
Errante *et al.* (2022) [47]	20 (10/10)	VR Rehabilitation System, 3D motion tracking system	AO + MI + ME	1 h/session 16-20 sessions 4 days/week 5 weeks	PRE, POST and 6 months follow-up
Cates *et al.* (2022) [48]	30 (30/0)	trakSTAR (Magnetic motion trackers), HTC Vive	AO + ME	N/A	After each condition.
Lin *et al.* (2023) [49]	8 (8/0)	Helmet-mounted display, g.HIamp acquisition system	AO + MI	30 min/experiment 1 experiment/day 4 days	After MI, after AO and after AO+MI
Batista *et al.* (2023) [50]	19 (-/-)	EEG system, Oculus Rift CV1, Oculus Rift hand controllers	AO + MI + ME	8.19 min per MI and/or AO, 3.49 min for ME 1 day	After each condition
Chang *et al.* (2023) [51]	14 (7/7)	HMD (HTC VIVE), EEG system, Motion sensor	AO + ME	90 sec of exercising 60 sec of resting 1 day	POST-intervention
Sip *et al.* (2023) [52]	20 (-/-)	Oculus Quest 2 module	AO + ME	30 min/session 1 session/day 18 days	PRE- and POST-intervention

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Study (Year)	Sample Size (EG/CG)	Sensors & VR Devices	Technique	Training Dosing	Evaluation Time Points
Lakshminarayanan *et al.* (2023) [18]	15 (15/0)	Oculus Rift-S, EEG system	AO + MI + ME	9 sec/trial 10 trials/session 5 sessions/block 3 blocks	During MI

The majority of the studies (53.3%) used an uncontrolled design [18, 40–42, 44, 46, 48, 49], while the remaining integrated a randomized controlled design [34, 43, 45, 47, 50–52]. The median sample size was 19, with a minimum of 1 and a maximum of 44. In the controlled trials, participants were divided into an experimental and a control group, with identical minimum and median sample sizes of 7 and 10, respectively. However, the EG reached a maximum sample size of 20 and the CG of 24. Regarding the MT techniques, 66.7% of the studies incorporated AO+ME [40–46, 48, 51, 52], 26.7% AO+MI+ME [18, 34, 47, 50] and only one study integrated AO+MI without physical execution [49]. When considering session duration, 33.3% of the research papers preferred periods longer than 30 minutes (up to 2 hours) [34, 41–45, 47], 26.7% adopted a 30-minute session length [40, 46, 49, 52] and 20% had sessions of less than 30 minutes [18, 50, 51]. The experiments varied in frequency, with 26.7% featuring a single session on just one day [18, 46, 50, 51], while others included 2 to 8 [41, 42, 45, 49], 12 to 15 [40, 44], and more than 18 [34, 43, 47, 52] sessions. In 26.7% of the studies, therapies lasted between 2 and 4 weeks [40, 44, 45] and, in another 26.7%, between 5 and 12 weeks [34, 42, 43, 47]. Evaluation strategies also differed, with 66.7% involving PRE- and POST-intervention assessments [34, 40–47, 52], while 26.7% solely relied on POST-intervention assessments [49–51]. Moreover, 26.7% performed evaluations during the intervention [18, 34, 42, 46] and 20% included a follow-up [34, 41, 47].

Sensors and VR-based equipment

head-mounted displays (HMDs) were used to achieve an immersive virtual experience in 73.3% of the reviewed literature [18, 40, 42–46, 48, 50–52], with 40% incorporating Oculus Rift [18, 40, 42–44, 50], 20% HTC VIVE [45, 48, 51] and 13.3% Oculus Meta Quest [46, 52]. Moreover, 26.7% integrated HMD hand controllers [40, 42, 46, 50] to enhance user interaction with the VRE. In the studies where HMDs were not selected, alternative devices were employed to guarantee an immersive experience within the VRE.

These included helmet-mounted [49] and wall-mounted displays [34], as well as cave automatic virtual environment (CAVE) systems with two projection screens and 3D glasses [41]. Motion tracking technology emerged as the leading choice (40%) [41, 43, 45, 47, 48, 51] for sensor devices, particularly with optical methods (i.e. camera-based systems). Following closely behind, 33.3% used EEG systems [18, 42, 49–51] for neural monitoring. Two studies also included an electromyographic (EMG) system [42, 49].

Exploring the convergence of VR and rehabilitation reveals diverse applications of this technology in examined articles. Weber *et al.* [40] harnessed the immersive capabilities of Oculus Rift through head-mounted goggles, infrared LED sensors and hand controllers to achieve positional tracking, 3D imaging and audio integration. Lin *et al.* (2021) [43] followed a similar path, integrating a Leap Motion camera (Figure 3c) and infrared LED transmitters to identify precise hand movements during therapeutic activities. This technology was also adopted by Emedoli *et al.* [44], projecting facial expression sequences into Oculus Rift. Venturing into the advancements of Oculus Meta Quest, Sip *et al.* [52] incorporated it into their SciMed system, utilizing its sensors to trace hand motion without additional hardware. Rey *et al.* [46] underlined the standalone capabilities of Oculus Meta Quest, presented in Figure 3a, emphasizing wrist-strap controllers and finger gesture detection for an enriched and autonomous virtual experience.

Shifting attention to other sensors, Vourvopoulos *et al.* [42] and Lin *et al.* (2023) [49] investigated the combination of EEG systems with VR-based devices. Vourvopoulos *et al.* [42] connected EEG systems to the Oculus Rift HMD, facilitating bidirectional communication between hardware and virtual elements. Lin *et al.* (2023) [49] employed g.HIamp for EEG and surface EMG signal capture alongside the HTC VIVE PRO EYE, a helmet-mounted display, for vivid embodiment. Similarly, Chang *et al.* [51] integrated HTC VIVE with motion sensors on the hand, analyzing EEG data from central and parietal lobes. Mekbib *et al.* [45] also delved into HTC VIVE, employing tracking stations and a Leap Motion for 3D spatial location tracking and hand posture detection. Meanwhile, Batista *et al.* [50] created an experimental setup involving EEG systems, an HMD and controllers for vibrotactile feedback.

Contrastingly, Kashif *et al.* [34] diverged from this trajectory by employing a VR system with a wall-mounted display, a Wii box, a Wii remote and a Wii fit board for interactive games. Errante *et al.* [47] introduced the Virtual Reality Rehabilitation System (VRRS), incorporating a 3D motion tracking system for a semi-immersive experience with improved movement tracking through kinematic sensors. Cates *et al.* [48] embraced magnetic motion tracking with trakSTAR, attaching kinematic motion trackers to the upper limbs, and integrated a VR headset for motion imitation tasks. Hülsmann *et al.* Finally, [41] implemented a CAVE setup with two projection walls, leveraging passive INFITEC filters and OptiTrack's outside-in tracking system for whole-body motion capture, illustrated in Figure 3b.

(a) Meta Quest HMD & controllers [46] **(b)** Marker suit [41] **(c)** Leap motion camera [43]

Figure 3: Sensors and VR-based equipment used in the literature.

Design of virtual environments and user interactions

Concerning the development tools and the user interactions within the virtual world, a significant trend (46.7%) involves employing the Unity cross-platform game engine (Unity Technologies, San Francisco, CA, USA) for the development of the VRE [18, 42, 43, 45, 46, 48, 49]. Among the studies, 53.3% specifically leverage virtual objects for user interactions in the VRE [34, 40, 42, 45–47, 49, 50]. It is noteworthy that, although hand representation from the user's viewpoint dominated virtual scenarios in 60% of the research [43, 45–52], an additional 46.7% implemented facial or full-body avatars [18, 34, 40–42, 44, 48]. In a particular study [48], different perspectives were presented, including the observation of both virtual hands and a full-body avatar, which expanded the spectrum of user interaction beyond activities centered solely on hand motion. For instance, Emedoli *et al.* [44] innovatively used augmented facial feedback to combine conventional physiotherapy with the observation of an avatar's facial expressions (Figure 4b).

In alignment with the trend of observing virtual hands that mirror the user's own hand movements, Lin *et al.* (2023) [49] created a Unity3D-based basketball training simulation, in which participants were instructed by voice commands to imagine themselves shooting a basketball while their bodies remained still. The intervention integrated other experimental conditions, starting with the observation of virtual hands in the first-person perspective performing the activity without voice instructions and then imagining these movements again while observing them, with auditory guidance. The study by Mekbib *et al.* [45] also utilized this cross-platform to implement tasks like gripping, transporting and releasing balls in a virtual scenario. The system provided a user interface for patient data management, therapy session control and upper extremity rehabilitation training. The VRE featured a room with paintings and tables, in which the participant was seated on a chair. The balls popped up on white circles equally spaced on the tables, with an aerial view map to indicate their locations. Similarly, Rey *et al.* [46] employed the Unity engine for a home-based VRE, allowing users to grasp virtual objects with virtual hands (Figure 4c). The scenario comprised furniture, tables, a sofa, and shelves with books, providing dynamic viewing angle adjustments based on head and hand movements. The system recognized gestures, such as open and closed hands, through button inputs. Lin *et al.* (2021) [43] also harnessed Unity for a VRMT software designed for stroke survivors, where one hand was unmirrored and the other mirrored. The software guided users to observe and, at the same time, execute seven hand rehabilitation activities, such as thumb-to-fingertip movement and wrist flexion/extension, combining real and virtual hand movements for enhanced rehabilitation. In addition, Sip *et al.* [52] immersed patients in a virtual outer space scenario, who executed finger and hand exercises, including flexion and extension of the fingers, touching the fingertips with the thumb and dorsal and palmar flexion of the hand in the wrist joint.

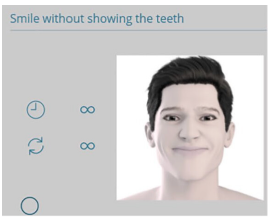
Beyond the representation of virtual hands, numerous studies have investigated the potential of observing full-body avatars in VR applications. Weber *et al.* [40] utilized WiseMind Software® (Realiteer, San Francisco, CA, USA) to create an immersive MT, which embodies a first-person perspective of an avatar mirroring movements, such as flexion/extension, abduction/adduction and grasp/release exercises, without interacting the virtual world. The software allowed customization based on the participants' physical characteristics, who performed other functional tasks (e.g. stacking plates, setting up a tea service and moving fruit between plates) in a simulated dining room, presented in Figure 4a. Lakshminarayanan *et al.* [18] also ventured into realistic avatar modeling with Blender software (Blender Foundation, Amsterdam, The Netherlands), capturing participants' faces in 3D. These avatars, gamified using Unity, executed actions such as drinking from a cup, flexion extension of the right wrist and grabbing objects. This aimed to augment cortical activity through MI within VR, with two experiments involving kinesthetic MI (KMI) with and without visual aids. Cates *et al.* [48] presented avatar calibration for participant-specific mirroring scenes downloaded from Modern People 2 in the Unity Asset Store. The calibration process involved aligning the observer avatar's movements with the participant's real arm using HTC Vive controllers. In different conditions, participants observed virtual arms or a mirrored/anatomical avatar (Figure 4d) mimicking the demonstrated movement to ensure consistent movements across scenarios.

When integrating EEG systems into VR, Batista *et al.* [50] utilized NeuXus, an open-source Python toolbox for real-time biosignal processing, in the Brain-Computer Interface Virtual Reality (BCI-VR) training paradigm of NeuRow, a multiplatform VRE developed in Unity. Participants have to mentally simulate rowing a boat and try to collect as many flags as possible within a certain time frame, relying solely on mental imagery. In line with the previous experiments, virtual arms were presented by an avatar in the first-person perspective. Moreover, Vourvopoulos *et al.* [42] introduced personalized avatars in Unity for a VR paradigm involving stretching trials, with the virtual arm responding to sensorimotor brain activity.

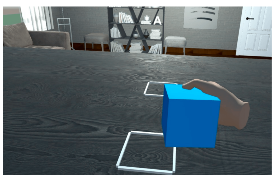
Chang *et al.* [51] focused on MI therapy through a virtual hand mirroring approach, instructing to extend and release the unaffected wrist while watching the virtual hand. The VRE contained a table and an avatar with the same posture as the participants by placing their upper limbs on the table.

Other studies explored different approaches by either implementing established games in a virtual setting or introducing novel forms of immersive experiences. Kashif *et al.* [34] incorporated Wii peripherals for balance exercises into a wall-mounted display. Patients stood on a Wii Fit Board to play interactive balance games and then sports like bowling, tennis, kicking, and boxing. Rather than implementing a VRE, the study took advantage of the benefits of Wii sports activities. Errante *et al.* [47] employed the Khymeia VRRS, integrating videos from the lateral perspective of one- or two-manual actions. The exercises range from "no-gravity" movements such as sliding to reach for a target located in different positions, to complex bimanual actions of daily life, such as wear sunglasses or draw a line with a ruler, with kinematic sensors facilitating tracking and interaction with virtual objects. Hülsmann *et al.* [41] immersed participants in a low-latency CAVE room, where novices engaged in squat movements in front of a virtual mirror. Participants assigned to three different groups, either watched and mimicked their own avatar performing full-body movements (Own), or viewed the movements of a skilled avatar superimposed on their own avatar, with the frontal (Own+skilledFront) or lateral (Own+skilledSide) perspective.

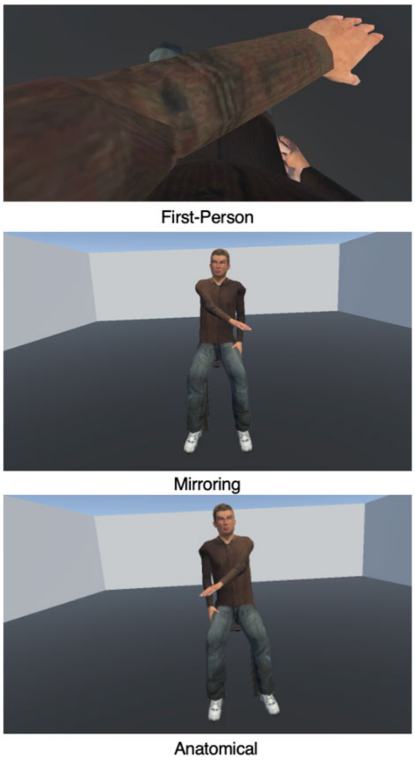
(a) Dining room [40]



(b) Facial gestures [44]



(c) Grasp virtual objects [46]



(d) Perspectives of observation [48]

Figure 4: Different AO perspectives, interactive exercises and VR scenarios in the literature.

Multifaceted feedback mechanisms in virtual environments

Feedback mechanisms played an important role in the literature reviewed, with 73.3% containing a variety of approaches [34, 41–44, 46, 48–52]. Among these studies, 33.3% utilized specific visual feedback techniques [41, 42, 46, 48, 51]. For example, Rey *et al.* [46] used VR to induce embodiment by employing mirror visual feedback (MVF) to monitor limb movements and generate mirrored representations. Cates *et al.* [48] incorporated live tracking systems to provide visual feedback on arm motion within a VR headset, acknowledging imperfections but highlighting its effectiveness. Similarly, Hülsmann *et al.* [41] investigated concurrent visual feedback during full-body movements in front of a virtual mirror, assessing the impact on motor performance, cognitive function, and subjective judgments.

Moreover, 13.3% of the studies integrated EEG-based neurofeedback for visual representation. Chang *et al.* [51] analyzed recorded EEG during tasks and correlated the virtual MVF experience of the upper limb with the mu-band desynchronization and coherence. Vorvoupoulos *et al.* [42] implemented a BCI-VR intervention, combining EEG-based neurofeedback with simultaneous EMG acquisition, and integrated 2 Oculus Touch controllers to provide vibrotactile feedback on each virtual hand engaged in MI from the cue onwards, throughout each trial. Together with the intervention by Batista *et al.* [50], which included MI trials with the virtual hand, 13.3% of the research used vibrotactile feedback. A further 13.3% of the studies provided direct feedback from therapists, such as Kashif *et al.* [34] who employed therapist-led activities, while Lin *et al.* (2021) [43] enlisted an occupational therapist to guide exercises.

The rest of the literature presented other feedback mechanisms. Sip *et al.* [52] incorporated motion detectors and 3D cameras for biofeedback, wherein the built-in cameras automatically recognize the patient's hands and generate an image based on this information. This way, patients and practitioners can continuously monitor the correctness of the performed sequence of movements. Emedoli *et al.* [44] combined augmented feedback with voluntary facial movements in a VR setting, with a motion multiplier that initially allowed to see an amplified representation of their movements on the screen, especially beneficial for those with limited facial movements. As the sessions progressed, this multiplier was dynamically adjusted to the width of the participant's facial movements, providing tailored feedback that scaled and reduced amplification according to the individual's progress and needs. Lastly, Lin *et al.* (2023) [49] monitored MI training using EMG-based feedback, building on recent research suggesting that MI has effects on muscle activity by indirectly increasing the excitability of the corticospinal cord and motor neuron pool. In line with these findings, the study measured EEG in the alpha and beta frequency bands to assess brain activation, while participants' muscle activity was assessed by EMG feedback.

Motor and non-motor effects

Integrating the insights retrieved from the experimental protocols' analysis provided a comprehensive understanding of the multifaceted effects associated with VRMT. A predominant finding highlighted the superior improvement in motor performance attributed to VRMT [18, 34, 41, 43–46, 52] when compared to conventional MT [41, 43, 52]. One third of the research revealed the therapy's capacity to induce increased brain activation [18, 43–45, 49], with a subset particularly affecting corticospinal activity [18, 43, 44]. Concerning the outcomes of EEG and EMG, Vourvopoulos *et al.* [42] suggested that EEG-based BCI for motor rehabilitation in VR underscored the feasibility and tolerability of the paradigm, with potential benefits even more prominent in individuals with severe motor impairments. Lin *et al.* (2023) [49] reinforced the effectiveness of this combined therapy when incorporating real-time EMG feedback, which resulted in higher muscle strength scores. The VRMT paradigm successfully promoted brain activity during MI and augmented event-related desynchronization (ERD) when integrating AO.

Furthermore, the reviewed literature unveiled pronounced impact on sensorimotor function [18, 43, 51] and promotion of motor learning [34, 41, 47], with repetitive exercises leading to global reduction in performance time. Lin *et al.* (2021) [43] accentuated the benefits of VRMT over traditional MT, showcasing superior improvements in motor function. The study underlined the clinical feasibility of the intervention and its positive effects on sensorimotor control and neuroplasticity. Emedoli *et al.*'s [44] findings proposed positive outcomes in ADLs, functional mobility and facial movements through an immersive VR-based arm feedback, facilitating intensive repetitions for better corticalization of facial gestures. Kashif *et al.* [34] also affirmed significant positive effects on motor function, balance and ADLs in 95% of PD patients with the combined therapy of VR, AO and MI. These outcomes persisted even after the intervention ended, highlighting its long-lasting effects. Hülsmann *et al.* [41] included VR-based visual feedback in a VRE to improve motor performance and cognitive representation. Low-latency VR feedback was proven to be more efficient in improving motor skills than setups with higher latency. In addition, the groups that observed two avatars demonstrated an advantage over those who only observed their own performance, enhancing mobility and cognitive function in memory compared to those without visual feedback. Conversely, those lacking visual feedback exhibited a deterioration in performance, underscoring the crucial role of augmented feedback, beyond mere repetition, in motor learning.

When exploring the application of different cues, Lakshminarayanan *et al.* [18] detected greater ERD during VR-KMI in contrast to non-visual aided KMI, suggesting an improved MI execution substantiated by spatial patterns and indicating stronger potential at the contralateral sensorimotor area. The results also affirmed the impact of repeated MI training on cortical activity. In another context, Batista *et al.* [50] identified a stronger contralateral alpha ERD during MI with a VRE and vibrotactile haptic feedback. Continuous hand movements in AO+MI conditions contributed to the maintenance of vivid imagery, underlining the interplay of these elements in eliciting a robust neural response. Chang *et al.* [51] found considerable mu suppression in the ipsilesional motor cortex and the parietal lobe, triggered by an immersive VR-based MVF. In fact, MVF led to decreased mu coherence in both hemispheres in patients, while it had no significant effect in healthy controls. Cates *et al.* [48] investigated the impact of spatial cuing perspective on imitation accuracy in VR, with first-person perspective guiding to higher accuracy and faster reaction times in comparison to the anatomical condition.

Safety, adherence and tolerance were found to be key aspects of VRMT feasibility [40, 42–44], with no reported adverse events such as simulator sickness. Weber *et al.* [40] reported that patients engaging in immersive VRMT experienced enjoyment and were entertained from watching their paretic arm move normally and reach positions usually restricted by contractures. However, the involuntary movements manifested while mimicking actions of their intact limb added an extra layer of complexity to the observed effects. Rey *et al.* [46] attested to the good usability of a VR system for motor recovery and a high level of presence among participants, 80% of whom reported positive responses to the virtual experience.

2.2.3 Discussion

The literature review revealed a balanced distribution of study designs, encompassing both uncontrolled designs and RCTs, with a slight prevalence of the former. The selected studies adopted a consistent median training frequency of 2 sessions per week, conducted over a median period of 2 weeks. Each session was characterized by an average duration of 38 minutes. Evaluation time points were consistently scheduled after the intervention and a majority also included an additional assessment before the training, although not universally. One notable limitation was the lack of follow-up assessments, with only a few conducting them at 1-day, 1-month or 6-month intervals after training. An important observation concerned the short-term nature of the MI and AO trials, which may potentially influence the EEG results. Lin *et al.* (2023) [49] therefore emphasized the necessity for longer engagement in order to obtain meaningful neurophysiological results. Future research is recommended to explore the long-term effects of VRMT on motor deficits [43] and the necessity for additional trials to consolidate hypotheses and validate the positive effects of immersive interventions [44]. Through such endeavors, the field can gain a more nuanced understanding of the therapeutic potential of VRMT in the treatment of motor impairments. Another limitation identified in the literature is related to the limited sample sizes, which contributed to the inability to detect meaningful changes in outcome scores that reached the minimum detectable change, given the differences in participant performance. To mitigate this constraint and reduce intersubject variability, it is strongly recommended that future investigations consider the enlistment of larger and more diverse participant groups, as well as the inclusion a third group of healthy participants for comparative findings. This strategic approach not only augments the robustness of the results, but also increases the statistical power of the analysis, essential for the advancement of the field.

Some studies demonstrated that VRMT contributes to more improvement in motor function than traditional MT [41, 43, 52] due to the immersive and immediate visual representation of bilateral hand movement. Nevertheless, the VR's effectiveness alone in achieving such results is disputed. Batista *et al.* [50] claimed that haptic feedback holds more importance than the virtual experience in inducing strong ERD. They introduced the use of HMD and vibrotactile controllers during MI training with NeuRow and established that this combination led to significantly greater contralateral alpha ERD. In addition, the study by Weber *et al.* [40] advocated for the inclusion of haptic feedback in future investigations. More conflicting results were discussed by Cates *et al.* [48] who found no significant differences between mirroring and anatomical conditions. In mirroring, an instructor is observed and imitated with opposite limbs/movement directions, similar to looking into a mirror. In contrast, in anatomical, the same limbs/movement directions are observed and imitated, which demands complex mental transformations and can lead to slower, error-prone performance [48]. Problems with the avatar embodiment, the speed of movement and the participants' perception of the upper limb movements might have influenced task execution. Hülsmann *et al.* [41] also underlined the positive impact of visual feedback, stating that the participants who watched their avatars significantly improved their motor skills compared to those who didn't, with different perspectives presenting additional gains in motor learning. Although the first-person perspective (alone or superimposed) needs to be further explored, manipulating MVF in VR has proved to enhance motor performance through shared neural representations in the AO network, with low-latency VR feedback being more effective. Despite these benefits, adverse events in the form of headaches, dizziness, nausea or blurred vision are well-documented negative consequences of the technology.

Most of the VREs described in the literature were developed using Unity and incorporated virtual objects that either assisted in experimental activities, e.g. rocks, cups and basketballs, or characterized the scenario itself, e.g. curtains, paintings and tables. In contrast, other scenarios took a minimalist approach with few details, so as not to distract participants from the tasks. After recognizing the limitations of a less realistic visual representation, Lin *et al.* (2021) [43] recommended the development of more authentic virtual scenes to increase patient commitment to the intervention. Technical factors impacting the influence of VR therapy involved isolation from the surrounding environment, focused engagement with the activity, realistic limb representation and simple instruction of exercises with immediate biofeedback response, addressing concerns about insufficient treatment intensity, which is seen as the main factor for the rehabilitative benefit of the therapy. Lakshminarayanan *et al.* [18] confirmed the impact of repeated MI training and emphasized the effectiveness of VR-based AO in improving MI classification performance. Combining immersive AO in VR with kinesthetic MI showed a greater ERD response and increased spatial discrimination of hand task-related brain activity in comparison to kinesthetic MI alone. Despite the absence of EMG data in the study, using this data to measure muscle activation during imagery tasks is a necessity for the interpretation of the results. Lin et al. (2023) [49], as a result, concluded that a VR-based MI training system with real-time EMG feedback was successful in promoting brain activity during imagery sessions. The study highlighted the need for more diverse VR training scenarios, research into additional physiological parameters, increased EEG channel coverage and optimization of muscle strength computation from EMG data. The studies that included avatars in their experiments either used software tools such as Blender and WiseMind for modulation or purchased avatars from the Unity Asset Store.

The conclusions drawn from this literature align with the findings obtained from the study by Kwon *et al.* [20], which investigated the benefits of VR-based rehabilitation for patients with PD. The positive effects of VR-based interventions on balance function are noted, with Kwon *et al.* [20] highlighting a positive correlation between the publication year and improvements in balance. However, it is also acknowledged that current virtual interventions are only partially effective in improving gait ability, ADLs, motor function and quality of life, and that it is therefore important to make technological advances to address these limitations. Furthermore, both literature reviews agree on the benefits of game-based programs, real-time performance observation and immediate feedback to increase patient motivation and overall motor outcomes. Recognizing the implications of motor asymmetry and MI asymmetry becomes paramount when addressing PD, effectively tackled with VRMT by providing personalized interventions that correspond to specific motor and mental simulations. Moreover, the dynamic nature of VR facilitates the conversion of simple movements into functional tasks, delivering a more immersive and meaningful therapeutic experience for patients. Although VRMT may be associated with rare adverse events, both sources call for further research to study its benefits for different patient subgroups, make comparisons with other types of treatment and develop customized outcome measures.

2.3 General Conclusions

In the exploration of MT within the realm of PD, **AO therapy emerged as a significant contributor to positive outcomes**, demonstrating improvements in balance, FoG, disease severity, and various motor and non-motor skills. While there is evidence for the potential of MI tasks in dual-task gait and balance training, the results do not match those of AO. Consequently, further high quality RCTs are required to establish robust evidence of the efficacy of MI as a technique. The comprehensive review of MT interventions revealed a consistent pattern of positive outcomes for the identified parameters within the EG. Even though the EG consistently outperformed the CG for disease severity, quality of life and gait, the results for balance showed some variability between studies. The inclusion of **AO and MI in long-term treatment showcased enhanced motor learning and cognitive function**, emphasizing the potential synergies between these therapeutic modalities. Transitioning to the incorporation of VR into MT, the second state of the art explores a distinctive paradigm compared to conventional MT. It introduces a technique in which the illusion of the non-paretic arm remaining motionless is created while movement is transferred to the visual representation of the impaired arm. This additionally opens up opportunities for cognitive and dual-task training, with the potential to translate these advantages into real-life situations.

The integration of visual feedback into VRMT stands out as a successful strategy for enhancing motor function because of the immediate feedback on movement and balance control, facilitated by real-time performance observation. In summary, **VR-based rehabilitation emerges as a powerful tool, offering a heightened level of immersion, individualized training and motivation through a game-like experience**. However, despite the commonly reported rare and mild adverse events associated with VR-based rehabilitation, caution is advised as immersion levels increase. Therefore, ensuring safe training sessions and conducting long-term follow-ups to assess sustained benefits are crucial. The recent advances in technology, particularly in creating realistic VREs, contribute to improved accessibility and affordability, positioning VRMT as a promising avenue for future research in PD's treatment.

3 Solution Description: Reference Learning Data

This chapter provides a descriptive analysis of reference learning data obtained from twelve healthy participants performing the MDS-UPDRS activities of lifting the leg, arising from a chair, and touching the nose, which are applied in clinical practice to assess bradykinesia, balance, and tremors in PD patients [53]. Descriptive analysis of these activities can foster the development of control strategies for VRMT and other technological solutions such as exoskeletons targeting assistance and/or rehabilitation of Parkinson's end-users. Other pathological diseases, such as stroke [54], multiple sclerosis [55], progressive supranuclear palsy, corticobasal syndrome, multiple system atrophy, and dementia with Lewy bodies [56], are also commonly associated with these movement-related symptoms. Healthy characterization of these activities can act as reference control on these technological solutions so during VRMT the patients can observe (AO), imagine (MI), and train (ME with feedback) to match the target healthy reference having into consideration the inherent variability of the healthy population.

3.1 Solution Proposal

The proposed VRMT solution includes three sessions Figure 5, each conducted in randomized order to evaluate the influence of AO, MI, and real-time feedback (Figure 5). Session A focuses solely on AO, beginning with pre-VRMT (before VRMT) without visual aids outside of VR, transitioning to AO within VR to enhance understanding of the reference movements' characteristics [26], and concluding with post-VRMT (after VRMT) outside of VR. This sequence is mirrored in Session B, which adds MI after AO [12, 13]. Session C integrates AO, MI, and VRMT with real-time feedback.

These MT tasks occur in a VR-based environment featuring two distinct avatars controlled by a biomechanical model: one for exercise instruction during AO and another for realistic self-movement observation during during ME with real-time feedback, both designed to resemble the participant for a personalized learning experience. During MI, two static avatars will display the initial and final positions of each activity, allowing participants to keep their eyes open, focusing on the avatars, or closed. In session C, real-time feedback is provided visually by a smiling emoji and audibly through informative sounds when a target threshold is reached. The virtual scenarios will strike a balance between realism and minimalism to maintain participant concentration [52].

Data from the biomechanical model, obtained from twelve healthy participants performing the activities, will serve as reference learning data for the instructional avatar during AO. Although the healthy participants performed the activities proficiently, most expressed uncertainty about their performance, highlighting the importance of providing real-time feedback during ME. To evaluate the VRMT solution's immersiveness and usability, two well-established and highly reliable VR questionnaires will be employed after each session: the Igroup presence questionnaire (IPQ) [57] and the Intrinsic motivation inventory (IMI) [58]. The KVIQ will also be used to measure the participant's imagery vividness during the exercises.

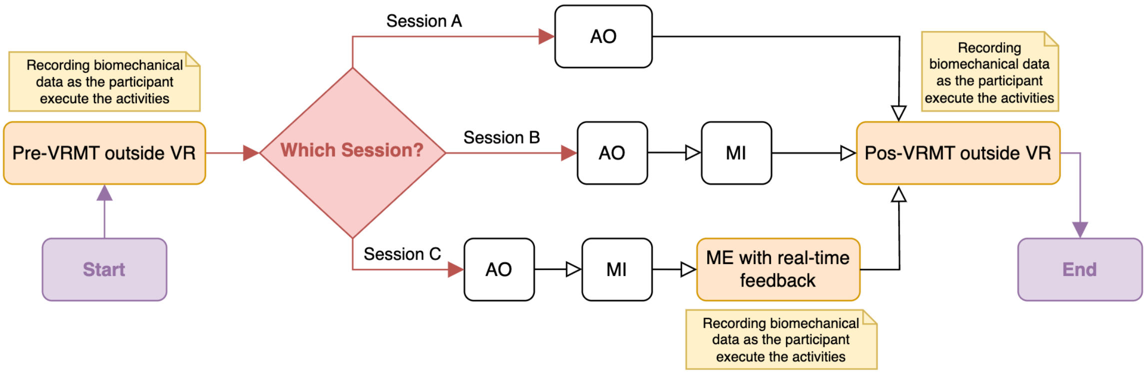


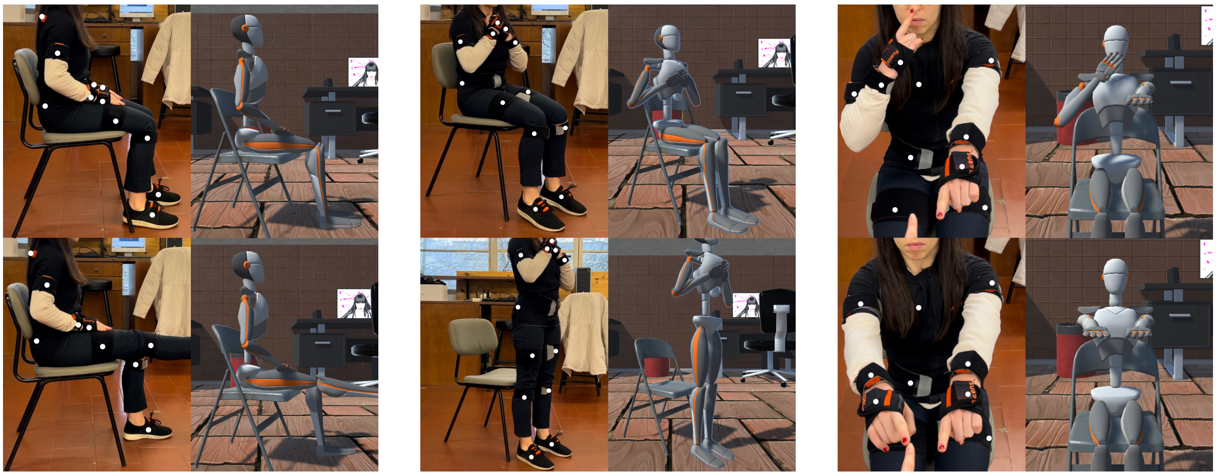
Figure 5: Flowchart illustrating the three sessions of the VRMT solution. Session A includes AO, Session B adds MI, and Session C combines AO, MI, and real-time feedback.

3.2 Participants

The reference learning data collection involved twelve healthy subjects, selected beyond the ethical committee CEICVS 006/2020 at the University of Minho, with a mean (standard deviation) age of 24 (±2) years and a height of 1.71 (±0.09) meters. All subjects signed an informed consent form to participate in this data collection following the Declaration of Helsinki and the Oviedo Convention. Eligibility criteria required that participants to be free from any significant medical, psychiatric, or neurological disorders.

3.3 Motor Activities

From the MDS-UPDRS III, a widely recognized and validated instrument for assessing the severity of PD [34], three motor and multidomain activities have been carefully selected for the VRMT intervention to address specific symptoms. The first proposed exercise is the item 3.8, labeled "Leg agility" (Figure 6a), which targets bradykinesia. Here, participants raise each foot as fast and high as possible with feet parallel to the ground when descending, observing the lower limbs from a lateral perspective. Introduced to improve balance, another activity is the item 3.9, named "Arising from chair" (Figure 6b), which instructs the participant to sit on a chair, cross their arms over their chest and make an effort to stand up. Participants first observe the exercise from a diagonal perspective of the whole avatar body before executing it in the virtual world. The subsequent activities, items 3.15 and 3.16, entitled “Postural tremor of the hands” and “Kinetic tremor of the hands” respectively, are selected to target hand tremors. In the former, participants stretch their arms forward with their palms facing down and hold this position for 10 seconds. In the latter, they start with outstretched arms and then perform finger-to-nose movements with each hand (Figure 6c). The observation perspective remains frontal and focuses exclusively on the upper limbs.



(a) Lifting the leg **(b)** Arising from chair **(c)** Touching the nose

Figure 6: MTw sensors (white dots) attached to key body segments, and corresponding avatar representations in the VRE, while performing the three motor and multidomain activities.

3.4 Experimental Protocol

The experimental protocol began with placing the Xsens MVN Awinda’s inertial measurement units to the user’s body, and anthropometric measurements were taken for the biomechanical model to be scaled with user’s body dimensions.The biomechanical model, as described in Section 4.1, was subsequently calibrated by aligning the motion trackers to the subject’s body segments using the “Npose + Walk” routine in MVN Analyze Pro software. Before performing each activity, users received instructions on proper execution and practiced the exercise to guarantee familiarization before recording. Biomechanical data acquisition included the position and linear velocity of the feet on the Z-axis, along with knee flexion/extension joint angles. In activity of arising from a chair, participants stood up from a seated position. The same chair was used during the entire protocol located with a fixed orientation. The position of the mediolateral (ML) and anteroposterior (AP) COM, as well as the ZXY position and linear velocity of shoulders and upper legs, were collected. The activity of touching the nose consisted of slow arm movements at shoulder’s height with the index fingers extended forward, gathering data on the hands’ ZXY position and linear velocity. Participants touched their nose and then reached for the examiner's finger (middle point between user's stretched hands) and finished the exercise by returning to the starting position. Each activity was repeated 10 times during data recording. Table 4 describes each activity, and the corresponding MDS-UPDRS item, the observational perspective and the biomechanical data recorded.

Table 4: Description of each activity, including the observational perspective and the recorded biomechanical data

Activity ID	Instruction Details	Perspective	Biomechanical Data
Activity 1 (Item 3.8)	Sit in a chair with both feet comfortably on the floor. Then, raise each foot one at a time, as quickly and as high as possible.	Lateral view of lower limbs	• Linear velocity (Z axis) of feet • Foot position (Z axis) • Knee joint angle (sagittal plane)
Activity 2 (Item 3.9)	Sit in a chair with your arms crossed across your chest and both feet firmly on the floor, and stand up at your own pace.	Diagonal view of full-body	• ML and AP COM position • Position of shoulders and upper legs
Activities 3.1 (Item 3.15) & 3.2 (Item 3.16)	Extend your arms forward for 10 seconds. Then, touch your nose with your index finger, and extend your arm to touch the examiner's finger.	Frontal view of upper limbs	• Hand position (ZXY axes) • Hand linear velocity (ZXY axes)

3.5 Data Processing

`Numpy`, `pandas`, `matplotlib` and `scipy.interpolate` Python libraries were used for data processing. Biomechanical data from each activity for a single participant generated one dataset, resulting in three datasets per participant. A specific position parameter within each dataset was segmented into movement cycles. The right-foot and right-hand position parameters, for the first and third activities, respectively, were used to segment data for the right side of the body, whereas the corresponding left-side parameters segmented the left-side data. In the activity of arising from a chair, segmentation was depending on the COM position along the Y-axis. The remaining parameters in each dataset were segmented using the indices derived from the segmentation. Within each participant's dataset, position and velocity parameters were reset to set the right-foot as the origin and then normalized to the participant's height. Finally, interpolation was applied to each segment, producing curves with an equal number of samples to calculate the mean curve and standard deviation of each parameter across all participants.

3.6 Results and Discussion

Figure 7 shows the mean curves for the foot position and linear velocity along the Z-axis and the knee joint angles, in the sagittal plane, during the activity of lifting the leg. In Figure 8, the mean curves and standard deviations are associated to the position of COM, shoulders and upper legs, along the ZXY axes, obtained from arising from a chair. The first graph demonstrates the change in the AP COM (Y-axis) in relation to the ML COM (X-axis). Figure 9 shows the mean curves and standard deviations depicting the hand position and linear velocity along the ZXY axes, during the nose-touching activity. However, the plots capture the data from when the nose is touched until the arm is extended again. The initial two plots represent the hand position while extending them forward for 10 seconds.

Activity of lifting the leg The right-foot position and linear velocity reached a maximum of 0.27 (±0.04) and 0.79 (±0.26) per second, and a minimum of 0.08 (±0.01) and -0.75 (±0.21) per second, respectively. To assess foot velocity without lifting the knee, Figure 7 shows that the knee joint angle reached a mean maximum of 76.96 (±12.87) degrees. This indicates that the feet could be lifted to a mean maximum height of 0.26 (±0.04). As the movement ascended to its highest point, the linear velocity reached an absolute maximum value of 0.79 (±0.26) per second before falling to zero at the highest point. While the extreme points were almost the same due to the expected healthy symmetry between limbs [59], the shaded area revealed greater variation in the left foot compared to the right foot, emphasizing the smoother movement of the right foot (dominant foot for most participants).

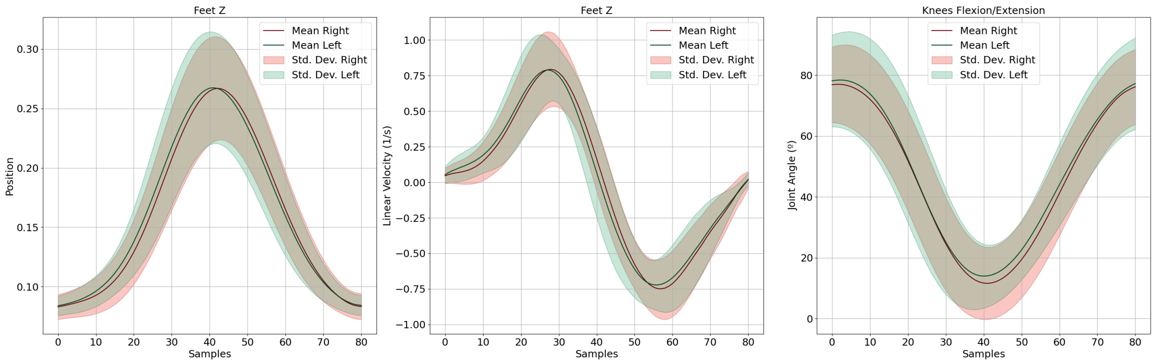


Figure 7: Mean (line) and standard deviation (shaded area) of feet position and linear velocity (1/s) along the Z-axis, and knee joint angles (deg) across all participants for activity of lifting the leg.

Activity of arising from a chair The AP COM position ranged from a maximum of 0.02 (±0.05) to a minimum of -0.18 (±0.07), whereas the ML COM position reached a maximum of -0.10 (±0.05) and a minimum of -0.13 (±0.07). In Figure 8, a linear progress in the AP COM in relation to the ML COM was observed while arising from a chair. This suggests a coordinated shift of the body's COM both front-to-back and side-to-side, which results in effective weight distribution as transitioning from a seated to a standing position and controlled muscle and joint actions, contributing to maintain balance throughout the activity [60]. The side-to-side movement was significantly lower compared to front-to-back movement, with a mean maximum of -0.10 (±0.05) and a mean minimum of -0.13 (±0.07). The smaller the side-to-side movement, the greater the balance. The biomechanical data on the shoulders and upper legs show a remarkable similarity, which is indicative of synchronized postural control in which the lower body moves in coordination with the upper body [60, 61]. Moreover, the restraint in the lateral movements along the X-axis also emphasize the maintenance of healthy postural stability. For example, the observed range of the left upper leg's movement varied from a maximum of -0.15 (±0.05) to a minimum of -0.18 (±0.07).

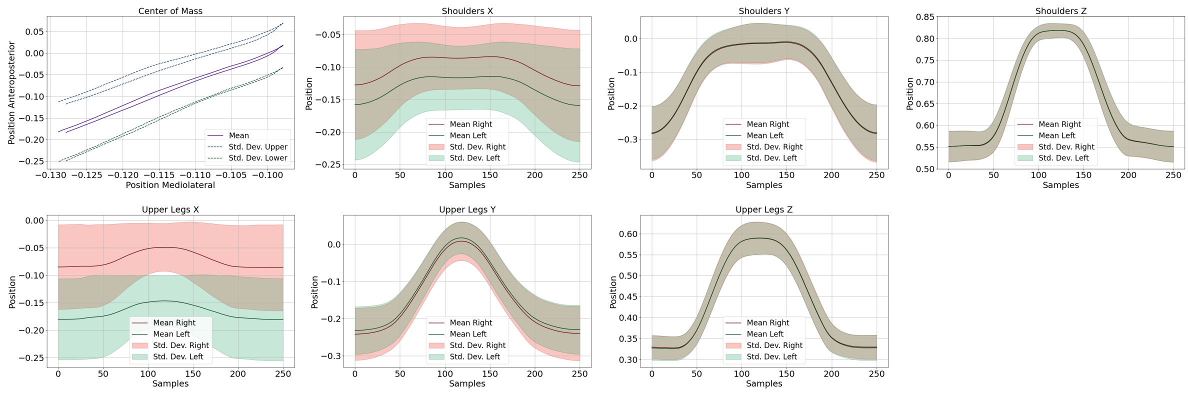


Figure 8: Mean (line) and standard deviation (shaded area) of the position of the center of mass, shoulders and upper legs, along the ZXY axes, across all participants for activity of arising from a chair.

Activity of touching the nose The Y-axis right-hand position varied from a maximum of -0.06 (±0.06) to a minimum of -0.23 (±0.06), with linear velocity ranging from 0.28 (±0.08) to -0.26 (±0.08) per second. In Figure 9, the position and linear velocity results during the finger-to-nose movements exhibited nearly symmetrical patterns in the X-axis graphs, resulting from the opposite movements of the left and right hands as moving toward the nose; while one varies from negative to positive direction of the X-axis, the other does the opposite. The hand position values on the Y-axis fluctuated more than on the X and Z axes, because the exercise primarily involves changes in position front-to-back axis, with hands maintained at shoulder height, following a trajectory in front of the nose, with minimal vertical and ML shaking. The maximum and minimum values of the right-hand position were 0.59 (±0.05) and 0.54 (±0.05) on the Z-axis, -0.01 (±0.06) and -0.05 (±0.06) on the X-axis, and - 0.06 (±0.06) and -0.23 (±0.06) on the Y-axis, respectively. The first two plots showed a minimal hand position variation while stretched forward for 10 seconds, indicating no significant tremors. The standard deviation for the X, Y, and Z axes were 0.04, 0.06 and 0.05, respectively. The linear velocity values revealed an almost zero speed at the start and when touching the nose. Although the activity was performed at a slow pace, an increased velocity was observed during the movement initiation with a Y-axis maximum value of 0.28 (±0.08).

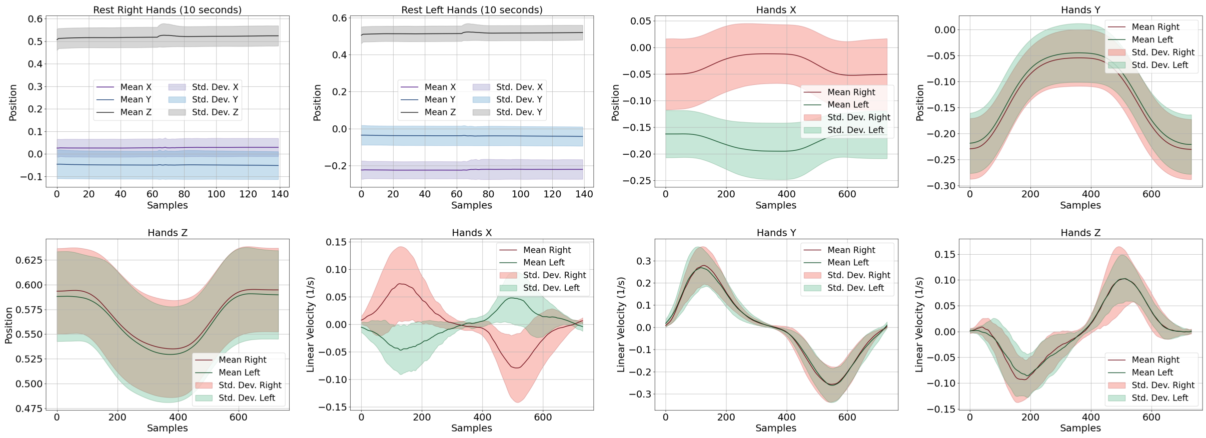


Figure 9: Mean (line) and standard deviation (shaded area) of the hands' position and linear velocity (1/s), along the ZXY axes, across all participants for activity of touching the nose. The first two plots depict the hands resting at shoulder height for 10 seconds.

3.7 Conclusions

The three MDS-UPDRS activities selected provided valuable biomechanical insights that can serve as reference learning data for technological interventions aimed at rehabilitation and assistance. In the leg-lifting activity, the data showed healthy symmetry between the left and right limbs, with minimal variation, demonstrating coordinated lower limb function. The smooth transition in foot position and velocity during the lifting phase indicated the absence of bradykinesia in healthy individuals, establishing a reliable baseline for comparison with motor impairments such as those found in PD. The activity of arising from a chair revealed a coordinated shift of the AP and ML COM, with minimal side-to-side movement, reflecting balanced postural control while standing up. This coordinated movement is essential to detect postural instability in individuals with movement disorders. In the nose-touching activity, the results indicated nearly symmetrical hand movements, with more variation in position and linear velocity along the Y-axis, which was expected given the nature of the exercise. The low standard deviations across the X, Y, and Z axes, combined with the almost zero velocity at the start and end points of movement, suggest precise hand coordination, providing a reference to assess potential tremors in clinical populations. The results identified consistent movement patterns and minimal variability across the twelve healthy subjects, establishing a strong foundation for guiding movement performance and real-time feedback mechanisms, to help users compare their movements to these healthy standards and adapt their training to match these targets.

4 Solution Implementation: VR-based Tool for Parkinson's Rehabilitation

The main focus of this dissertation is developing a wearable VR-based tool aimed at improving motor function in individuals diagnosed with PD, using a VRMT training program. This chapter describes in detail the proposed VRMT solution, including the VR devices and sensors used, and the strategies developed to create animations for the avatar to instruct participants in performing the motor activities, and to provide real-time feedback during the execution of these activities.

4.1 Equipment

The VRMT training is enabled by the fully immersive commercial VR setup device HTC Vive Pro Full Kit (HTC VIVE Pro, HTC, Taiwan, ROC). As shown in Figure 10, this setup device consists of a VR headset, two hand controllers and two base stations. The play area, where users interact with the VRE, is configured by the base stations via the "Room Setup" routine embedded in the SteamVR software, requiring a room-scale of up to 7m x 7m. This routine also calibrates the motion tracking for the VR headset and hand controllers, both of which are equipped with infrared (IR) sensors that detect the IR pulses emitted by the base stations to determine their current spatial position.

Figure 10: HTC Vive Pro Full Kit, including a VR headset, two controllers and two base stations.

Table 5 indicates some specifications of the HTC Vive Pro system, including features such as visual and auditory cues used to provide real-time feedback during the execution of the motor activities.

Table 5: Specifications of HTC Vive Pro headset and controllers

Headset Specifications			
Resolution	1440 x 1600 pixels per eye (2880 x 1600 pixels combined)	Sensors	SteamVR Tracking G-sensor Gyroscope Proximity Eye Comfort Setting (IPD)
Refresh rate	90 Hz		
Field of view	110 degrees		
Connections	Bluetooth, USB-C port for peripherals		
Audio	Hi-Res certificate headphones (removable) Hi-Res certificate headset High impedance headphones support	Ergonomics	Eye relief with lens distance adjustment Adjustable Eye Comfort Setting (IPD) Adjustable headphones Adjustable headstrap
Input	Integrated microphones		
Controllers Specifications			
Sensors	SteamVR Tracking 2.0	Input	Multifunction trackpad, Grip buttons dual-stage trigger, System button, Menu button
Connections	Micro-USB charging port		
Use per charge	Approximately 6 hours		

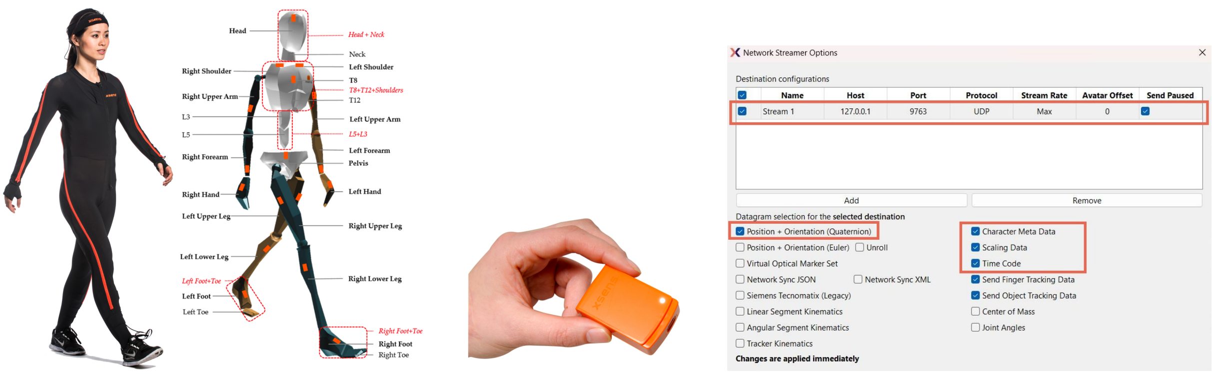
Moreover, HTC Vive Pro imposes some system requirements, as presented in Table 6, which must be met by the host computer to ensure an optimal VIVE experience. Failure to meet these requirements may result in a less fluid and realistic rendering of the virtual world, diminishing the overall user experience.

Table 6: Recommended system requirements for HTC Vive Pro

Component	**Recommended System Requirements**
Graphics	NVIDIA® GeForce® GTX1060 or AMD Radeon™ RX480, equivalent or better
Processor	Intel® Core™ i5-4590 or AMD FX™ 8350, equivalent or better
Memory	4 GB RAM or more
Video output	DisplayPort 1.2 or newer
USB ports	1x USB 3.0 or newer port
Operating system	Windows® 7, Windows® 8.1 or later, Windows® 10, Windows® 11 Upgrade to Windows® 10 for the best results with the dual front facing cameras

This dissertation integrates biomechanical data acquisition technologies to assess the accuracy of activity performance before and after VRMT. The Xsens MVN Awinda, an inertial measurement unit (IMU)-based motion capture system (Xsens, Enschede, The Netherlands), consists of a full-body suit equipped with 17 wireless motion tracker (MTw) sensors (Figure 11b). These MTw sensors are attached to body segments using adjustable straps (Figure 11a), and feature inertial and magnetic measurement units comprising 3D linear accelerometers, 3D gyroscopes, 3D magnetometers, and a barometer, which capture 3D acceleration, 3D angular velocity, 3D geomagnetic field, atmospheric pressure, and drift-free orientation data. Despite this, the system can experience a positional error of approximately 1% in traveled distance due to reliance on internal sensors and factors like sensor calibration [62].

The MVN Awinda software integrates data from individual MTw using StrapDown Integration (SDI) algorithms, and a biomechanical model that enables the extraction of additional data, such as joint angles and COM. Kinematic quantities for each body segment are expressed within a local coordinate frame, defined by a right-handed Cartesian system: X denotes forward movement in the horizontal plane, Y signifies lateral direction orthogonal to X and Z, and Z represents vertical orientation with positive values indicating upward direction. Position and orientation relationships between segments (${}^{L}p_B$ and ${}^{LB}q$) and their corresponding sensors (${}^{L}p_S$ and ${}^{LS}q$) are established through a sensor-to-segment calibration procedure to the orientation ${}^{LB}q = {}^{LS}q \otimes {}^{BS}q$, and the position ${}^{L}p_B = {}^{L}p_S + {}^{LB}q \otimes {}^{B}r_{BS} \otimes {}^{LB}q^{*}$, where ${}^{BS}q$ represents the sensor's orientation relative to the body, while ${}^{B}r_{BS}$ indicates the sensor's position relative to the segment origin within the segment frame. The symbol $\otimes$ denotes quaternion multiplication, and $*$ signifies the complex conjugate operation applied to the quaternion [63]. The software ensures real-time recording and streaming options for data transmission to external applications via the User Datagram Protocol (UDP) at 100 Hz (Figure 11c). This facilitates seamless integration of real-time data into Unity, where the VRMT solution will be implemented. The MVN Awinda kit includes an Awinda Station, which controls the reception of synchronized wireless data from all MTw sensors and enables the continuous tracking and recording of biomechanical data [62]. The SteamVR is utilized in the Unity project to control the HTC Vive Pro Full Kit.



(a) Xsens MVN link system [64] **(b)** IMU (XSens) **(c)** Xsens Network Streamer

Figure 11: Xsens MVN Awinda capture system.

4.2 Software Application

The VRE was built using the real-time 3D development platform Unity, created by Unity Technologies (Copenhagen, Denmark), with Editor version 2022.3.13f1 and Unity Hub version 3.8.0. The environment balances realism and minimalism to maintain participants' concentration, consisting of three interconnected rooms, each designed for a specific MT task, and containing office-like virtual objects downloaded from the Unity Asset Store. Each room also includes an avatar that physically resembles the participant for a personalized learning experience. The room displayed switches by altering the camera display linked to a specific activity, allowing for different observational perspectives. Figure 12 presents the VRE from a top-down perspective to clearly visualize the spatial arrangement and connectivity between the rooms.

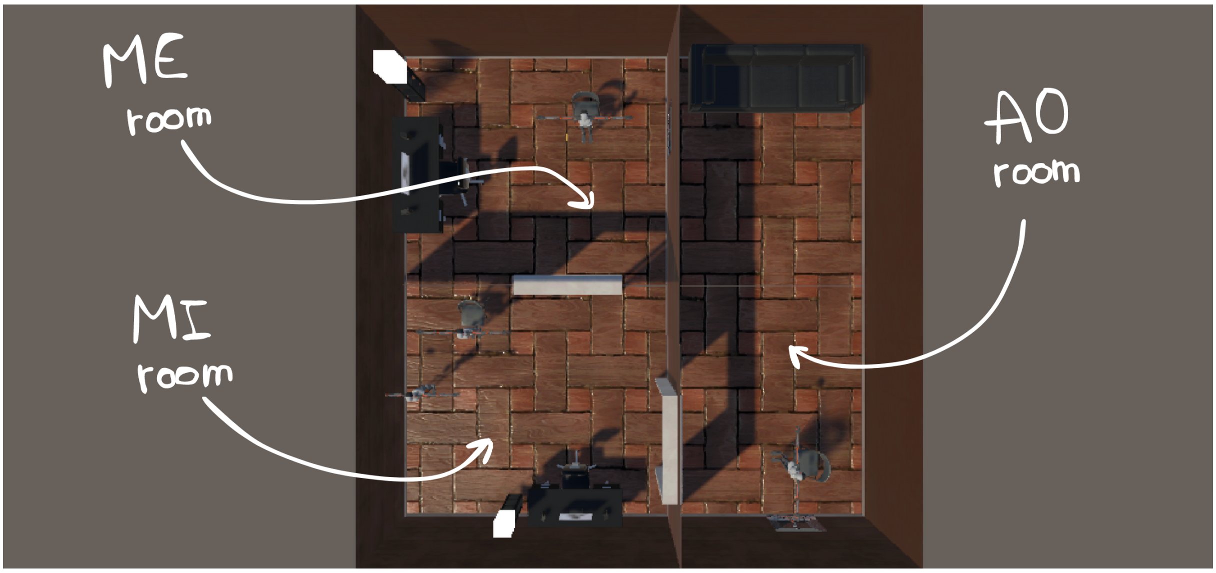


Figure 12: Overview of the VRE consisting of three interconnected rooms, from a top-down perspective.

This dissertation developed strategies to establish a dynamic VRE aimed at creating animation clips for the AO avatar and providing real-time feedback during the execution of motor activities. The VRMT solution offers real-time visual and auditory feedback to help participants stay motivated, understand whether the exercises are being performed correctly, and fix any mistakes. Moreover, while the MI avatars are controlled by animation controllers that maintain static poses, the AO avatar is managed by an animation controlled connected to dynamic animation clips that visually demonstrate the activities, enabling participants to learn and accurately execute the activities. In contrast, the ME avatar operates with real-time data streaming from the Xsens MVN Awinda system. Figure 13 presents a flowchart illustrating that, for AO and MI, the avatars are controlled by an animation controller linked to an animation clip, whereas for ME, the avatar receives real-time data streaming from the Xsens MVN Awinda system.

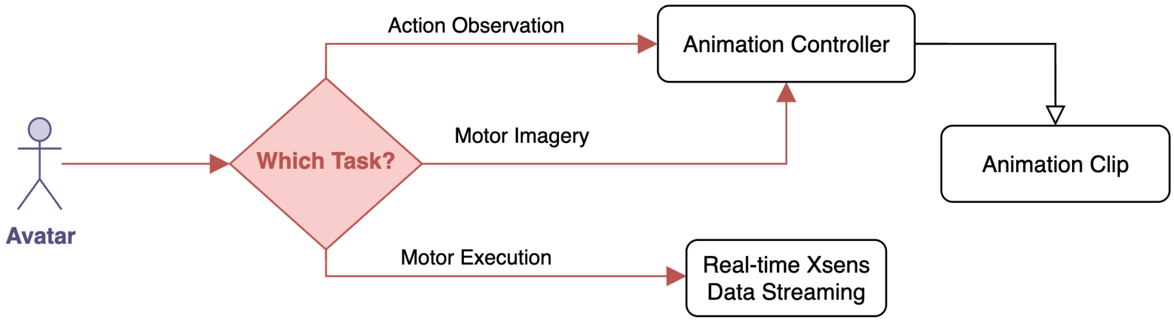


Figure 13: Flowchart illustrating the motion control of an avatar based on the proposed MT tasks.

The avatars initially presented in the VRE were provided by the public asset MVN Live Animation. However, to significantly enhance the realism and personalization of avatars, Ready Player Me (RPM) was incorporated, a renowned platform for creating customizable 3D avatars (Figures 14, 15 and 16). This platform allows users to generate avatars that are compatible across various virtual worlds, games and VR experiences, providing a more immersive and individualized experience. To integrate RPM avatars into Unity, the Unity SDK available on their GitHub page was imported, specifically accessing the release version 7.1.0. A key advantage of RPM is its capability to generate avatars from user photographs, which not only improves visual accuracy but also expedites the customization process.

(a) Lifting the leg **(b)** Arising from chair **(c)** Touching the nose

Figure 14: AO room with a personalized avatar, animated to demonstrate the activities' execution.

(a) Lifting the leg **(b)** Arising from chair **(c)** Touching the nose

Figure 15: ME room with an avatar moving in real-time, and an emoji indicating correct performance.

(a) Lifting the leg **(b)** Arising from chair **(c)** Touching the nose

Figure 16: MI room with two static avatars, indicating the activities' initial and final positions.

4.2.1 Action Observation

In the AO room, the avatar uses an animation controller linked to the animation clip of the observed activity to guide activities and prevent misunderstandings. The manipulation of animation clips used the reference learning data, employing the C# programming language along with namespaces from the .NET framework, Unity's API, and the Movella.Xsens namespace provided by the MVN Live Animation asset. Unity's API supports two types of animations: generic and humanoid. For this project, humanoid animations were created as they are suited to the avatar objects used, which are configured with an FBX file that maps each bone to a transform and defines muscle settings for those bones (Figure 17).

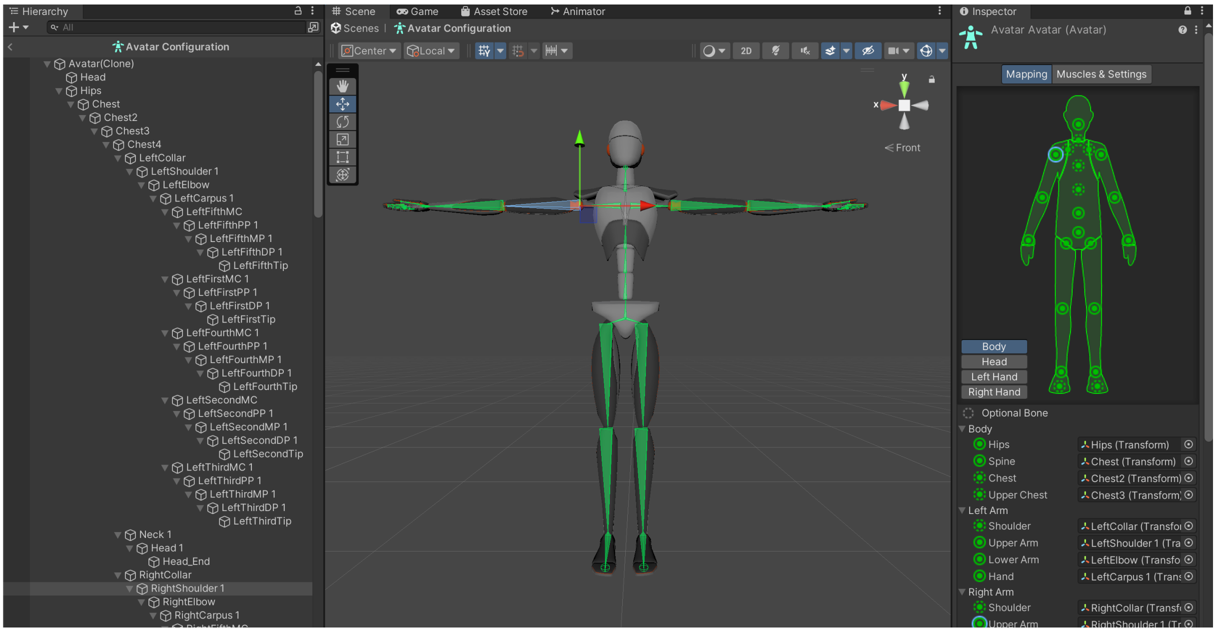


Figure 17: Avatar Configuration inspector, displaying the bone structure hierarchy of the Xsens MVN FBX model on the left and the corresponding bone mappings on the right.

Consequently, each joint angle parameter from the reference learning data was mapped to the corresponding parameter of type `HumanBodyBones` in the Animator to accurately represent the motor activities on the Xsens MVN avatar. Moreover, the Xsens MVN Awinda system considers a right-handed Cartesian Z-up coordinate system [62], whereas Unity uses a left-handed Cartesian Y-up system. Therefore, this discrepancy also required an axis conversion. Terms like "RLeft" and "LRight" were introduced: "RLeft" refers to the left-side parameters being inactive when the right-side bones move, while "LRight" indicates the reverse situation. These terms are only relevant for the activities of lifting the leg and touching the nose, where each side performs repetitions sequentially: first the right side, then the left.

In the muscle settings, each bone is associated with default range limits that can be adjusted to control movement stiffness; for example, Unity assigns a default range of -80 (variable `minRange`) to 80 (variable `maxRange`) degrees to the "Right Forearm Stretch". An adjustment (variable `offset`) is added to the respective reference learning data to ensure correct activity execution, and the axis direction (variable `scale`) is inverted if negative because the Y-axis pointing forward in the Xsens MVN Awinda corresponds to the X-axis pointing backward in Unity. To establish a precise reproduction of the reference learning data in the animation clips, each value is initially multiplied by the variable `scale`. If the result is negative, it is divided by the absolute value of `minRange`; if positive, it is divided by `maxRange`. Subsequently, the variable `offset` is added to this result, as expressed by the formula (3.1).

$$\text{adjustedValue} = (\text{value} \times \text{scale} < 0)?\left(\frac{\text{value} \times \text{scale}}{-\text{minRange}} + \text{offset}\right) : \left(\frac{\text{value} \times \text{scale}}{\text{maxRange}} + \text{offset}\right) \tag{4.1}$$

For the “Root” parameters in the `TraitPropMap` dictionary, where both `minRange` and `maxRange` are equal to zero due to the lack of joint angle representation, the division step is bypassed. Each adjusted value is then added to the animation curve at 17-millisecond intervals, aligning with the Xsens MVN Awinda’s sampling rate [62]. For the activities of lifting the leg and touching the nose, the time calculation for keyframes related to the left side of the body accounts for the prior execution of the right side. Therefore, for the keyframes related to the right side, the time in seconds is calculated by:

$$\text{timeInSeconds} = (j \times \text{valuesCount} + i) \times 0.017 \tag{4.2}$$

where 0.017 represents the 17-millisecond interval, `j` is the current repetition index (totaling 10 repetitions), and `i` is the current value index (out of `valuesCount`). For the left side, guaranteeing accurate spacing and sequencing of keyframes within the animation curve, the time for each keyframe is computed by adding the total duration of the right-side keyframes to the calculated time:

$$\text{timeInSeconds} = (9 \times \text{valuesCount} + (\text{valuesCount} - 1)) \times 0.017 + (j \times \text{valuesCount} + i) \times 0.017 \tag{4.3}$$

4.2.2 Motor Imagery

The MI room stands out because it features two static avatars: one in the initial position of an activity and the other in the final position (Figure 16). These avatars are controlled by the animation controllers ‘MI Avatar Init” and MI Avatar Final,” which are each linked to specific animation clips tailored to the imagined activity. Unlike the animation clips used in AO, these clips consist of single keyframes for each animator parameter, creating static poses for the avatars as their poses are unchanged over time.

4.2.3 Real-Time Feedback

In the ME room, the avatar replicates the participant’s movements in real-time, providing a realistic self-observation experience and a strong sense of presence during feedback, and thus is not connected to any animation controller. The VRMT solution offers users real-time visual and auditory feedback as they perform the proposed activities, in alignment with the principles of Reinforcement Theory. According to this theory, which is based on the “law of effect”, behaviors with positive outcomes are more likely to be repeated, while those with negative outcomes are less likely to recur [65]. In our implementation, auditory feedback serves as positive punishment by delivering an informative sound following an undesired behavior, thereby reducing the probability of its recurrence. This message acts as a reprimand whenever the user makes a mistake, encouraging the avoidance of repeating the error. Conversely, visual feedback functions as positive reinforcement by providing a rewarding stimulus following a desired behavior, thus increasing the probability of its repetition. Specifically, an emoji appears as a reward when the user correctly performs the motor activities (Figure 15), reinforcing the desirable behavior and motivating the user to continue learning. This dual approach recognizes that individuals learn effectively both from correcting their mistakes and from receiving motivational stimuli when they succeed. By combining positive punishment and positive reinforcement, the system ensures a balanced feedback mechanism that fixes errors and recompenses success, fostering a more efficient and engaging learning environment.

Depending on the activity, feedback is provided at intervals of 10 seconds or less, with real-time data reset to evaluate error conditions according to specific parameters, as detailed in Table 4.2.3. In the activity of lifting the leg, the foot must be raised as high and fast as possible. If the foot height during the ME task is below the mean height from the reference learning data, an audio prompt saying “raise your feet more” will play, and the smiling emoji will disappear. If the absolute values of the extreme foot velocities are below those from the reference values, the sound “speed up the movement” will be played, as long as the foot height is correct but the speed is insufficient.

In the activity of arising from a chair, the error conditions are assessed for the ML and AP COM. To maintain balance, the ML COM must stay within the reference mean value and the respective standard deviation; otherwise, the sound “don’t lean to the sides” will be played. Similarly, if the AP COM is less than the reference mean, an audio saying “don’t lean forward” will be heard.

For the activities that target tremors, the maximum and minimum peaks of the hand position in the up-down axis are recorded. If the difference between these two peaks exceeds the standard deviation, an auditory prompt saying “don’t tremble your hands” will be heard. During the nose-touching activity, similar to the leg-lifting exercise, if the absolute values of the extreme hand velocities are above the reference values and no hand tremor is detected, the sound “slow down the movement” will be played.

Table 7: Error conditions for each activity that trigger real-time feedback. The terms “meanMax”, “meanMin”, and “std” refer to the means and standard deviations from reference learning data. “Height” corresponds to participant’s height, while the other values are those measured in real-time

Activity ID	**Parameter**	**Error Condition**	
Activity 1	Position Foot Up-Down	**ERROR IF**	positionMax $<$ (meanMax $-$ std) $\times$ height
	Velocity Foot Up-Down	**ERROR IF**	velocityMax $<$ (meanMax $-$ std) $\times$ height || velocityMin $>$ (meanMin $+$ std) $\times$ height

(Table 7 continues on next page)

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Activity ID	Parameter	Error Condition
		AND IF no position error
Activity 2	Mediolateral COM	**ERROR IF** positionMin $<$ (mean $-$ std) $\times$ height || positionMax $>$ (mean $+$ std) $\times$ height
	Anteroposterior COM	**ERROR IF** positionMin $<$ (meanMin $-$ std) $\times$ height
Activity 3.1	Position Hand Up-Down	**ERROR IF** positionMax $-$ positionMin $>$ std
Activity 3.2	Position Hand Up-Down	**ERROR IF** positionMax $-$ positionMin $>$ std
	Velocity Hand Front-Back	**ERROR IF** velocityMax $>$ (meanMax $+$ std) $\times$ height || velocityMin $<$ (meanMin $-$ std) $\times$ height **AND IF** no position error

The QR code shown in Figure 18 links to videos demonstrating different feedback responses. A PD patient struggled with the leg-lifting activity, receiving auditory cues as negative feedback. In contrast, a healthy participant completed the movement successfully, receiving a positive feedback emoji.

Figure 18: QR code linking to video demonstrations of feedback responses.

To accurately detect tremors during the activity of touching the nose, a second-order high-pass filter was applied to the real-time data recorded every 12 seconds. This filtering step is essential for isolating high-frequency tremor signals from the low-frequency motion inherent in the hand's front-to-back movement, which is irrelevant to our analysis and could interfere with the tremor measurements. Therefore, the filter was designed to attenuate these low-frequency components while preserving the high-frequency tremors, which generally manifest above 5 Hz in PD [66]. For this purpose, an empirical cutoff frequency of 10.0 Hz was selected for the filter, based on the frequency range where tremors are most likely to be observed. The sampling frequency used was approximately 58.8 Hz, corresponding to a sample interval of 17 milliseconds, selected to provide sufficient temporal resolution for capturing the high-frequency tremor signals. The implementation of the second-order high-pass filter is demonstrated in the code below. The filter parameters include a quality factor (Q) set to 2.0, which controls the sharpness of the filter's frequency response. A higher Q factor results in a steeper cutoff, enhancing the filter's ability to distinguish between the tremor signals and low-frequency motion artifacts.

To enable real-time feedback, the implementation resorted to the code from the MVN Live Animation asset. Initially, this code could only handle a single data packet of 32 bytes, containing position and quaternion data for all body segments. However, the code was updated because, for certain activities, additional data packets providing the linear velocity of each segment (40 bytes) and the COM position (16 bytes) are required. First, the frame data structure was modified to include two new arrays, each containing vectors of three coordinates: one array for the linear velocities and the other for the COM positions.

Each data packet requires different processing due to variations in size and content, with each value taking up 4 bytes. Unlike the position and quaternion data packet, which is used to update the avatar's position in real-time, not all data in other packets are necessary. For the COM data packet, only the first three values, representing the COM position in the three axes (12 bytes), are stored in an array of vectors, reordered to match Unity's Cartesian system. Similarly, for the data packet containing linear velocities for each segment, the first 16 bytes are ignored, and only the next three values, related to the linear velocities in the three axes (12 bytes), are stored in an array of vectors after conversion to Unity's Cartesian system. When a COM position data packet is received, the frame data structure populates these values in the array for the COM positions, while the arrays for the velocities and for the positions and quaternions remain empty. This approach distinguishes which type of feedback is provided based on the data packet received. The same process applies to the other data packets, where only the corresponding arrays are populated.

4.3 Conclusions

The system's architecture combines the commercial HTC Vive Pro headset with the Xsens MVN Awinda motion capture system, creating an immersive and personalized rehabilitation experience that promotes a strong sense of presence and realism. The VRMT system provides dynamic animations for AO and static poses for MI, as well as real-time biomechanical representation for ME, allowing participants to observe themselves practice the activities and receive immediate feedback. Developed on Unity's platform, the software facilitates the creation of a minimalist yet realistic VRE, while seamlessly integrating the motion capture data to ensure accurate and responsive avatar movements. The ability to detect and respond to errors in real ime further underscores its potential as a powerful rehabilitation tool, particularly for patients with motor impairments like PD. The visual and auditory feedback is based on reinforcement theory, guiding participants toward correct performance and keeping them motivated throughout their exercises. Furthermore, the use of high-pass filtering for tremor detection and the transmission of multiple data packets, including COM data and body segment linear kinematics, are key features that contribute to the system's precision in monitoring rehabilitation progress.

5 Validation Protocol

This chapter outlines the protocol implemented to validate the VRMT system for PD rehabilitation through a pre-post randomized experimental design involving healthy subjects and PD patients. It begins by detailing the participants' characteristics and the inclusion and exclusion criteria for their selection. The experimental procedure is then thoroughly explained, describing the data acquisition and processing methods used to prepare the data for outcome assessment.

5.1 Participants

Data collection involved eight healthy subjects (five females and three males), approved by the ethical committee CEICVS 006/2020 at the University of Minho, with a mean age of 23 (±2) years and a height of 1.70 (±0.09) meters. Data were also collected from a 67-year-old male PD patient, recruited from Campus Neurológico in Braga, with approval from the ethical committee CES CNS 04_2024. The patient had a H&Y stage of 1.5 and a score of 25 on the MDS-UPDRS III. Eligibility criteria for healthy participants included the absence of significant medical, psychiatric, or neurological disorders, whereas PD patients were required to have H&Y scores between 1 to 3, indicating mild to moderate PD severity. All participants needed to be able to walk independently, be medically stable, free from the influence of drugs or psychotropic substances, and have no visual or auditory impairments, or any other conditions that could impede cognitive comprehension or mobility. Subjects signed an informed consent form to participate in this protocol, following the Declaration of Helsinki and the Oviedo Convention. Table 8 presents demographic information about the participants, including their gender, age, height (meters), and for PD patients, the H&Y stage and the MDS-UPDRS III score.

Table 8: Demographic details of participants, gender, age, and height, along with H&Y and UPDRS scores for the PD patient, with the term HP referring to healthy participants

Participant	Gender	Age (years)	Height (m)	H&Y Score[1]	UPDRS III Score[1]
HP1	Female	28	1.53	-	-
HP2	Male	21	1.74	-	-
HP3	Male	23	1.80	-	-

(Table 8 continues on next page)

(Table 8 continued from previous page)

Participant	Gender	Age (years)	Height (m)	H&Y Score[1]	UPDRS III Score[1]
HP4	Male	20	1.79	-	-
HP5	Female	20	1.63	-	-
HP6	Female	23	1.72	-	-
HP7	Female	23	1.72	-	-
HP8	Female	23	1.63	-	-
PD9	Male	67	1.70	1.5	25

[1] Applicable only to participants diagnosed with PD.

5.2 Experimental Protocol

Before the experimental protocol began, the play area was configured using the "Room Setup" routine to prepare for the user's interaction with the VRE. The HTC Vive Pro headset was also calibrated to recenter the user's starting position inside the virtual world, ensuring an optimal user experience. The protocol started with the participant's anthropometric measurements and the attachment of Xsens MVN Awinda's IMUs to their body, followed by calibrating the biomechanical model using the "Npose + Walk" routine in the MVN Analyze Pro software. The experimental setup features the participant wearing the HTC Vive Pro headset and Xsens wireless sensors. The Xsens base station is connected to a computer on a nearby desk, with a monitor to control the VRMT intervention and to keep an eye on the view inside the headset.

The protocol consists of three sessions conducted on separate days in a randomized order for each healthy participant to prevent order effects from influencing the results and ensure unbiased findings (Section 3.1). Each possible order was followed by at least one participant: `A-B-C` was completed by participants 5 and 7, `A-C-B` by participant 8, `B-A-C` by participant 6, `B-C-A` by participants 1 and 2, `C-A-B` by participant 4, and `C-B-A` by participant 3. All sessions include pre- and post-VRMT assessments of the motor activities detailed in Section 3.3, with instructions given beforehand to ensure familiarization before recording. The VRMT intervention has a 30-minute duration and a 24-hour wash-out period between sessions to prevent cross-session influence. Considering the sensor placement, the pre- and post-VRMT data acquisition, and the questionnaire completion, the total estimated time for the protocol was approximately 1 hour. The sequence and duration of the MT tasks for each session are outlined in Table 9. In case of discomfort during the virtual experience, the session is immediately paused, regardless of whether the scheduled rest time was reached.

Session A involves observing each motor activity inside the VRE for 8 minutes, followed by a 3-minute rest outside of the VRE between activities (Figure 20a). This rest period is based on Meta Quest 3's health and safety guidelines, which recommend a 15-minute break after every 30 minutes of continuous use [67]. In Session B, participants observe each activity for 4 minutes and then imagine it for another 4 minutes, all within the VRE (Figure 20b), with the same 3-minute rest period. Session C requires participants to observe each activity for 2.5 minutes, imagine it for 2.5 minutes, and then perform it with real-time feedback for 2.5 minutes, also within the VRE (Figure 20c), with a 3-minute rest between activities.

Table 9: Sequence and duration of the AO, MI, and ME tasks for each activity across different sessions, along with the corresponding rest periods

Session	Lifting the leg			Rest	Arising from chair			Rest	Extending arms			Touching the nose		
	AO	MI	ME		AO	MI	ME		AO	MI	ME	AO	MI	ME
A	8 min	x	x	3 min	8 min	x	x	3 min	1 min	x	x	7 min	x	x
B	4 min	4 min	x	3 min	4 min	4 min	x	3 min	30 sec	30 sec	x	3.5 min	3.5 min	x
C	2.5 min	2.5 min	2.5 min	3 min	2.5 min	2.5 min	2.5 min	3 min	20 sec	20 sec	20 sec	2.5 min	2.5 min	2.5 min

(a) Observing (AO) **(b)** Imagining (MI) **(c)** Performing (ME) with feedback

Figure 19: VRMT intervention: (a) Participant 3 observing an avatar resembling themselves executing the nose-touching activity; (b) Participant 6 imagining the sit-to-stand activity; (c) Participant 4 performing the leg-lifting activity while receiving real-time feedback.

Unlike the healthy participants who completed all three sessions, the PD patient only participated in Session C, where he observed, imagined, and executed with real-time feedback a single activity to minimize the physical and cognitive demands (Figure 20). The activity of lifting the leg was the one selected as it targets one of his most affected symptoms, which is bradykinesia. Consequently, the experimental protocol for this patient was shortened to around 45 minutes, encompassing anthropometric measurements, sensor placement, pre- and post-VRMT assessments, and questionnaire completion. The session was immediately paused in case the patient experienced any discomfort inside the VRE.

(a) Observing (AO) **(b)** Right foot ME with feedback **(c)** Left foot ME with feedback

Figure 20: VRMT intervention for PD patient during leg-lifting activity in session C: (a) observing a personalized avatar; (b) lifting the right foot; (c)lifting the left foot.

5.3 Data Acquisition

All eight healthy individuals and the PD patient concluded the entire protocol without any unscheduled interruptions. Before the pre-VRMT assessment, the PD patient completed the MDS-UPDRS Part III, a well-known self-report and clinical observation tool commonly used to monitor the progression of motor symptoms in PD [34]. Each item is scored on a scale from 0 (normal) to 4 (severe), and the symptom with the highest total score is identified as the most affected motor domain. If multiple symptoms had the same score, clinicians assess the impact on daily activities and quality of life to determine the most critical one. According to Skorvanek *et al.* [68], motor symptoms as in our study most strongly correlated with reduced health-related quality of life were tremor, postural instability, and bradykinesia, in that order, targeted by the activities of touching the nose, arising from a chair and lifting the leg, respectively. The MDS-UPDRS III results helped determine the specific activity the patient would perform during the VRMT intervention based on the most affected symptom.

For all nine participants, sensor-based assessment was conducted using MTw sensors from the Xsens MVN Awinda IMU-based motion capture system in a full-body configuration. Biomechanical data was collected at a frequency of 60 Hz during pre- and post-VRMT assessments and, in the case of Session C, during the ME task with real-time feedback. In general, the outcomes measured were consistent with those used to evaluate conditions that might trigger feedback: (1) for the activity of lifting the leg, the position and the linear velocity of both feet; (2) for the activity of arising from a chair, the ML and AP positions of the COM; (3.1) for the activity of extending your arms, the position of both hands; and (3.2) for the activity of touching the nose, the position and linear velocity of both hands.

Furthermore, two widely recognized VR questionnaires, the IPQ and IMI, were completed by all nine participants following the conclusion of the VRMT intervention. The IPQ is a questionnaire designed to evaluate the user's sense of presence within a VRE, comprising 14 questions rated on a scale from 0 (strongly disagree) to 6 (strongly agree). These questions are grouped into three subscales: (i) "spatial presence", which assesses the sense of being physically present; (ii) "involvement", which measures the level of immersion in the virtual experience; and (iii) "experienced realism", which gauges how subjectively realistic the VRE felt [57]. Unrelated to any subscale, an additional general item evaluates the overall sense of presence as a culmination of the three dimensions. The IMI offers another reliable assessment, focusing on participants' subjective experiences after the VRMT intervention. Among its seven subscales, five were relevant in this study: "interest/enjoyment", "perceived competence", "effort/importance", "pressure/tension", and "value/usefulness". The inventory contains 30 items, scored on a scale of 1 (completely disagree) to 7 (completely agree), with seven of these items being reverse-scored, i.e. a lower score indicates better outcomes, while for the remaining items, higher scores correspond to more favorable results [58]. The final questionnaire answered was the KVIQ, which evaluates both visual and kinesthetic imagery abilities from a first-person perspective during the MI task. For each activity, participants were asked to rate the visual imagery clarity and the sensation intensity, on a scale from 1 ("no image/sensation") to 5 ("image as clear as seeing/as intense as executing the action") [27].

5.4 Data Processing

The data processing was performed using Python 3.11.0, leveraging the `Numpy`, `pandas`, `matplotlib`, `seaborn`, and `scipy.interpolate` libraries. Biomechanical data from a single participant generated twenty four datasets, distributed across three sessions: eight datasets for each session, considering that each activity produced two datasets (one related to before VRMT and one after VRMT). Within each dataset, position and velocity parameters were reprocessed to set the right-foot as the origin, and a specific position parameter was then used to identify the indices that segmented the data from each activity into movement cycles. Before segmentation, the second-order high-pass filter used for real-time feedback during ME in session C was also applied to the position data resulting from the activities that target tremors.

For the activities of lifting the leg and touching the nose, segmentation was based on the Z-axis (up-down) right-foot position and the Y-axis (front-back) right-hand position, respectively, for the right side of the body, with analogous left-side parameters segmenting the left-side data. In the activity of standing up from a chair, segmentation relied on the COM position along the Y-axis (AP), after which each segment from the ML COM was reset to the origin to prevent any unintended displacement. The remaining parameters in each dataset were segmented using the indices derived from the segmentation, and all position and velocity parameters were normalized to the participant's height. Each segment corresponds to a single execution, with exercises repeated 10 times. However, the position data from the activity of extending arms forward during 10 seconds was normalized but not segmented, as this exercise involved no repetitions. The lack of body movement produced minimal temporal variation, resulting in a nearly constant function.

Interpolation was applied to each segment based on the participant's maximum sample count for a given activity across all sessions, generating equal-length curves to calculate the mean curve and standard deviation for each parameter across all participants. From the resulting mean curves, several features were extracted: (1) for the activity of lifting the leg, the maximum foot position and the minimum and maximum foot velocity; (2) for the activity of arising from a chair, the ML and AP COM displacement from the seated to standing position; (3.1) for the activity of extending the arms forward, the hand position amplitude, calculated as the difference between the minimum and maximum values; and (3.2) for the activity of touching the nose, both the hand position amplitude and the minimum and maximum hand velocity. Figure 21 provides an overview of the data processing workflow described.

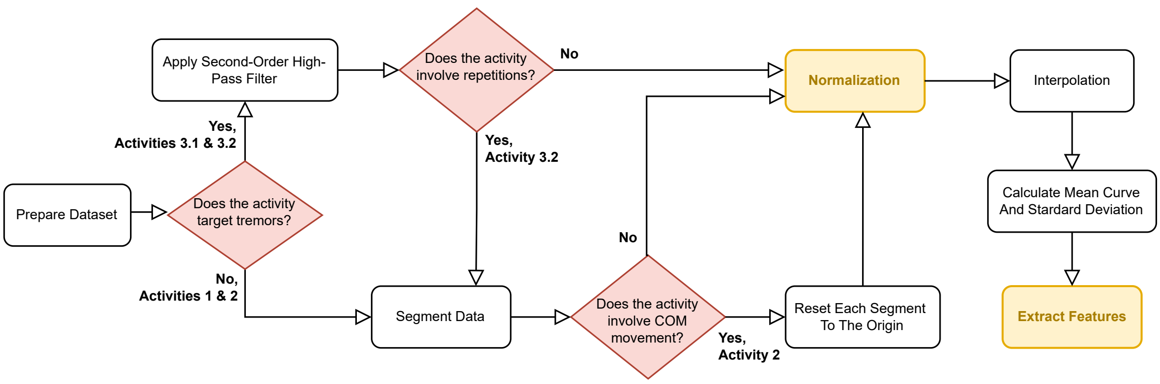

Figure 21: Flowchart depicting the data processing workflow, outlining key decisions and processes for data segmentation, normalization, and feature extraction from activity-based datasets.

5.5 Statistical Analysis

The statistical analysis was conducted using IBM SPSS software version 29.0.2.0 for macOS (IBM Corporation, Armonk, NY, USA). The null hypothesis states that there are no statistically significant differences in the pre-post results between sessions A, B, and C (p-value > 0.05). To test this hypothesis, the non-parametric Friedman test was applied to each activity data to evaluate pre- and post-intervention differences across sessions A, B, and C for all healthy participants. For the leg-lifting activity, the input values for the test were derived by subtracting pre-results from post-results, as higher values were expected after the intervention. For the other activities, the input values were computed by subtracting post-results from pre-results, anticipating lower values after the intervention. In either case, a negative pre-post difference indicates a decrease in performance from the pre- to the post-VRMT assessment. Following a significant Friedman test result (p-value below 0.05), Dunn's post-hoc test was performed using Python's `scikit-posthocs` library to identify specific pairs of sessions (A versus B, A versus C, B versus C) with significant differences. To control for the increased risk of familywise errors due to multiple comparisons, p-values from Dunn's test were adjusted using the Bonferroni correction method [69].

5.6 Conclusions

All eight healthy participants and the PD patient completed the randomized VRMT intervention protocol successfully and safely, with data collected at two distinct time points: before and after the VRMT intervention. Healthy participants undertook three 30-minute sessions, each with a 6-minute rest period, across different days. In contrast, the PD patient engaged in a single 15-minute session, after assessing the MDS-UPDRS Part III to determine the most affected motor domain. Considering the sensor placement, the data acquisition, and the questionnaire completion, the total estimated time for the protocol was approximately 1 hour for healthy and 30 minutes for PD patients. Data processing involved the segmentation, normalization, interpolation, and mean curve calculation of biomechanical parameters, enabling the extraction of important features: (1) maximum foot position, and minimum and maximum foot velocities; (2) ML and AP COM displacements during the sit-to-stand transition; (3.1 and 3.2) hand position amplitude; and (3.2) minimum and maximum hand velocities. After the VRMT intervention, all participants completed the IMI, IPQ, and KVIQ questionnaires. This methodology ensured that the data were prepared for statistical analysis, including the Friedman test to compare results across sessions and the Dunn's post-hoc test to determine significant differences between session pairs.

6 Results and Discussion

This chapter discusses the results from the validation protocol designed to evaluate the VRMT system for PD rehabilitation. It provides an analysis of the biomechanical data collected before and after the VRMT intervention, and the responses from the usability and imagery assessments.

6.1 Biomechanical Outcomes

Activity of Lifting The Leg Figure 22 presents the normalized foot position and linear velocity (1/s) along the Z-axis across the three sessions. The red and green lines depict the mean data from all healthy participants during the pre- and post-VRMT assessments, respectively, with the shaded areas indicating the standard deviation ranges. The black dashed line represents the reference learning data used to create the animations for the AO avatars and to implement the real-time feedback mechanisms.

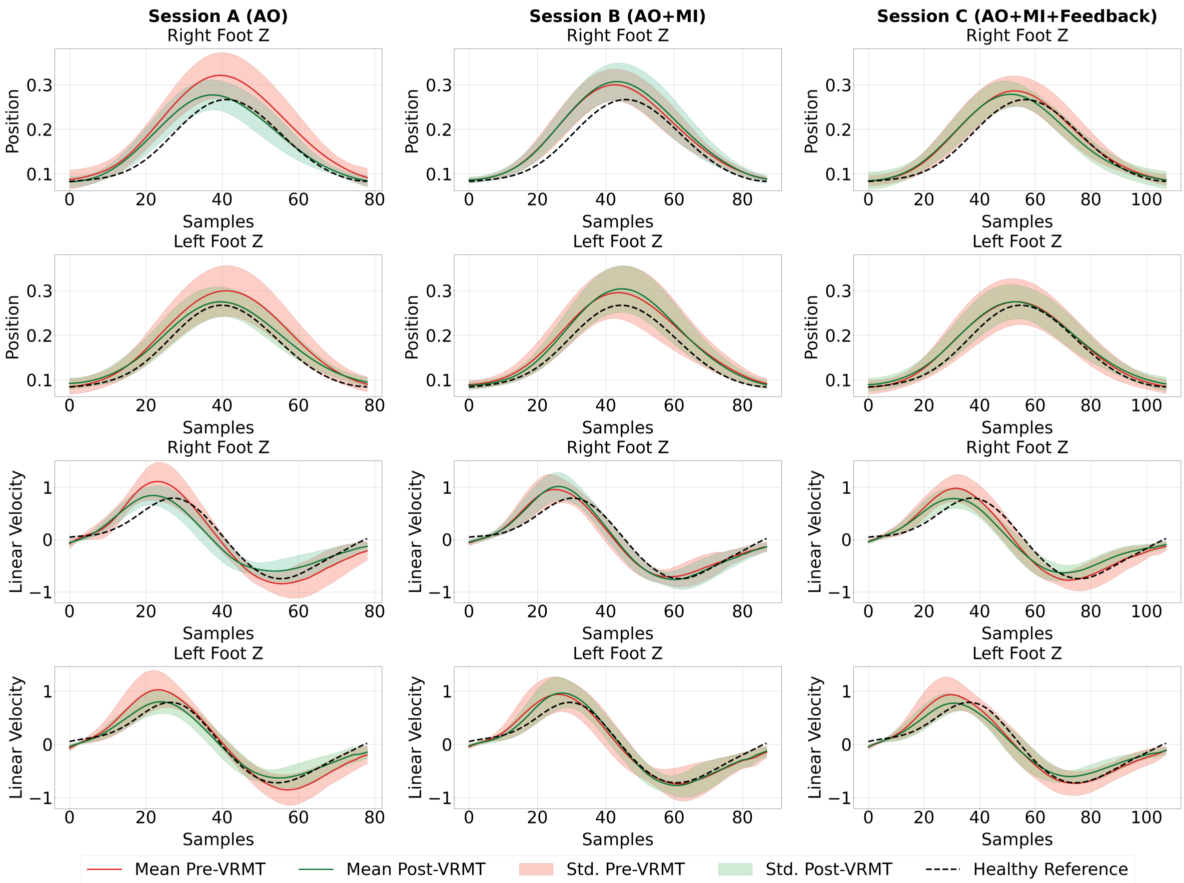

Figure 22: Mean (line) and standard deviation (shaded area) of foot position and linear velocity (1/s) in the Z-axis, recorded before and after VRMT in each session across all healthy participants, for activity of lifting the leg. The black dashed line represents the reference learning data.

After processing and extracting the key features from each participant's data, which are detailed in Table 21 in Appendix A, the data were statistically analyzed using the Friedman test. This analysis compared the outcomes of each parameter, calculated by subtracting pre-results from post-results, across sessions A, B, and C. Table 10 lists the features extracted from the pre- and post-VRMT assessments related to the activity of lifting the leg for all healthy participants, along with the statistical results from the Friedman test. Given that the *p*-value was below 0.001, Dunn's post-hoc test was conducted to identify specific pairs of sessions with significant differences, with these results shown in Table 11.

Table 10: Normalized mean maximum foot position, along with mean minimum and maximum foot linear velocities (± standard deviation), recorded during pre- and post-VRMT assessments in each session across healthy participants, and the results from the Friedman test, for leg-lifting activity. The term "REF" refers to the reference learning data

Healthy | Activity of Lifting The Leg (1)								
Limb	**Session**	**Max Position (Z-axis)**		**Min Velocity (Z-axis)**		**Max Velocity (Z-axis)**		**Friedman**
		Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**	**p-value**
Right Foot	A	0.32 (±0.05)	0.28 (±0.03)	-0.84 (±0.25)	-0.6 (±0.2)	1.11 (±0.37)	0.84 (±0.18)	<.001
	B	0.3 (±0.04)	0.31 (±0.04)	-0.71 (±0.15)	-0.76 (±0.17)	0.96 (±0.28)	1.02 (±0.27)	
	C	0.29 (±0.03)	0.28 (±0.03)	-0.77 (±0.17)	-0.64 (±0.15)	0.98 (±0.26)	0.78 (±0.19)	
	REF	0.27 (±0.04)		-0.75 (±0.21)		0.79 (±0.26)		
Left Foot	A	0.3 (±0.06)	0.27 (±0.03)	-0.86 (±0.29)	-0.63 (±0.17)	1.03 (±0.36)	0.8 (±0.22)	.004
	B	0.3 (±0.06)	0.3 (±0.05)	-0.74 (±0.31)	-0.77 (±0.2)	0.94 (±0.33)	0.96 (±0.3)	
	C	0.28 (±0.05)	0.28 (±0.04)	-0.73 (±0.23)	-0.6 (±0.11)	0.93 (±0.31)	0.77 (±0.16)	
	REF	0.27 (±0.05)		-0.72 (±0.18)		0.79 (±0.23)		

Table 11: Dunn's post-hoc test results with Bonferroni correction, comparing session pairs for right (R) and left (L) foot position (Pos), and maximum (Max) and minimum (Min) velocities (Vel). The most representative results ($p < 0.05$) are highlighted in grey

	RPos_A	**RPos_B**	**RPos_C**		**LPos_A**	**LPos_B**	**LPos_C**
RPos_A	1.0	**0.003**	0.121	**LPos_A**	1.0	0.29	0.25
RPos_B	**0.003**	1.0	0.688	**LPos_B**	0.29	1.0	1.0
RPos_C	0.121	0.688	1.0	**LPos_C**	0.25	1.0	1.0

(Table 11 continues on next page)

(Table 11 continued from previous page)

	RMaxVel_A	RMaxVel_B	RMaxVel_C		LMaxVel_A	LMaxVel_B	LMaxVel_C
RMaxVel_A	1.0	**0.008**	1.0	**LMaxVel_A**	1.0	0.097	1.0
RMaxVel_B	**0.008**	1.0	**0.014**	**LMaxVel_B**	0.097	1.0	0.279
RMaxVel_C	1.0	**0.014**	1.0	**LMaxVel_C**	1.0	0.279	1.0
	RMinVel_A	**RMinVel_B**	**RMinVel_C**		**LMinVel_A**	**LMinVel_B**	**LMinVel_C**
RMinVel_A	1.0	**0.001**	1.0	**LMinVel_A**	1.0	0.085	1.0
RMinVel_B	**0.001**	1.0	**0.01**	**LMinVel_B**	0.085	1.0	0.312
RMinVel_C	1.0	**0.01**	1.0	**LMinVel_C**	1.0	0.312	1.0

The statistical analysis of the leg-lifting activity revealed significant differences between sessions for the right foot ($\chi^2(8, N = 8) = 53.9, p < 0.001$), rejecting the null hypothesis. Post-hoc analysis showed that session B produced significantly better pre-post results for the right foot compared to sessions A and C. The right-foot position in session A improved significantly after VRMT compared to session B (p = 0.003) since it aligned more closely with the reference data after the intervention. In session A, the right-foot position decreased from a pre-maximum of 0.32 (±0.05) to post-maximum of 0.28 (±0.03), while in session B, it increased from 0.3 (±0.04) to 0.31 (±0.04). For comparison, the right-foot position recorded a maximum of 0.27 (±0.04) in the reference learning data. Additionally, session B demonstrated faster right-foot velocities after VRMT compared to session A (p = 0.001 for minimum and p = 0.008 for maximum) and session C (p = 0.01 for minimum and p = 0.014 for maximum). Session B saw an increase in maximum velocity (1/s) from 0.96 (±0.28) pre-intervention to 1.02 (±0.27) post-intervention. In contrast, session A showed a decrease from 1.11 (±0.37) to 0.84 (±0.18), and in session C, it dropped from 0.98 (±0.26) to 0.78 (±0.19). Similarly, session B recorded a decrease in minimum right-foot velocity (1/s) from -0.71 (±0.15) pre-intervention to -0.76 (±0.17) post-intervention, whereas session A saw an increase from -0.84 (±0.25) to -0.6 (±0.2), and session C improved from -0.77 (±0.17) to -0.64 (±0.15). For comparison, the right-foot velocity (1/s) recorded a minimum of -0.75 (±0.21) and a maximum of 0.79 (±0.26) in the reference learning data. Even though significant differences were observed for the left foot ($\chi^2(8, N = 8) = 22.3, p = 0.004$), there were no significant differences in the pairwise comparisons, which aligns with most participants being right-foot dominant.

Figure 23 presents the normalized foot position and velocity (1/s) along the Z-axis for the PD patient during the leg-lifting activity in session C. The purple, red and green lines depict the mean data in the during-, pre- and post-VRMT assessments, with the shaded areas indicating the standard deviation ranges.

The black dashed line represents the reference learning data. Table 12 presents the features extracted from the pre- and post-VRMT assessments of the PD patient during the leg-lifting activity.

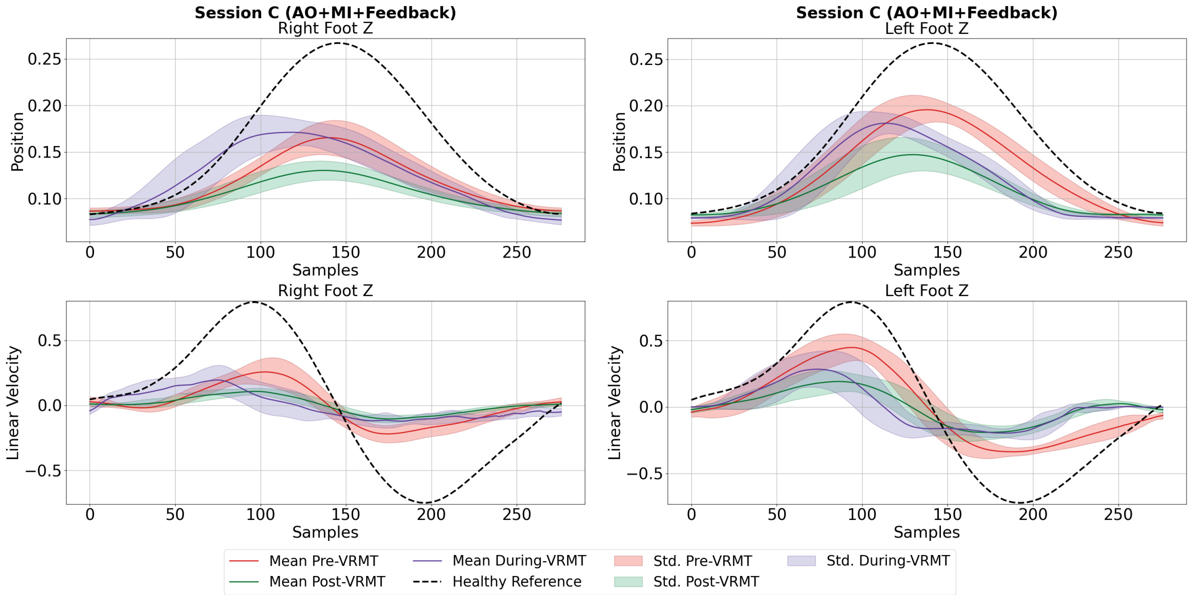

Figure 23: Mean (line) and standard deviation (shaded area) of foot position and linear velocity (1/s) in the Z-axis for the PD patient, measured before and after VRMT in session C, while performing the leg-lifting activity. The black dashed line represents the reference learning data.

Table 12: Normalized mean maximum foot position, along with mean minimum and maximum foot linear velocities (± standard deviation) for the PD patient, measured during pre- and post-VRMT assessments in session C while performing the leg-lifting activity

Parkinson | Activity of Lifting The Leg (1)						
Limb	**Max Position (Z-axis)**		**Min Velocity (Z-axis)**		**Max Velocity (Z-axis)**	
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**
Right Foot	0.17 (±0.02)	0.13 (±0.01)	-0.22 (±0.07)	-0.1 (±0.03)	0.26 (±0.11)	0.11 (±0.03)
Left Foot	0.2 (±0.01)	0.15 (±0.02)	-0.34 (±0.03)	-0.19 (±0.06)	0.45 (±0.1)	0.19 (±0.08)

Compared to the healthy reference data, where the right-foot position peaks at 0.27 (±0.04), the PD patient was only able to lift it to 0.17 (±0.02) before VRMT, which further decreased to 0.13 (±0.01) post-intervention. A similar pattern was observed for velocity (1/s): the reference data showed a maximum of 0.79 (±0.26) and a minimum of -0.75 (±0.21), while the patient's pre-intervention values were 0.26 (±0.11) and -0.22 (±0.07), dropping to 0.11 (±0.03) and -0.1 (±0.03) afterward. Interestingly, despite exhibiting more Parkinson's symptoms, particularly tremors, on the left side of the body, the left foot performed slightly better than the right. The pre- and post-maximum left-foot positions were 0.2 (±0.01) and 0.15 (±0.02), with pre- and post-intervention velocities (1/s) of 0.45 (±0.1) and 0.19 (±0.08), respectively.

Activity of Arising From a Chair Figure 24 presents the normalized ML and AP COM position across the three sessions. The red and green lines depict the mean data from all healthy participants during the pre- and post-VRMT assessments, and the black dashed line the reference learning data.

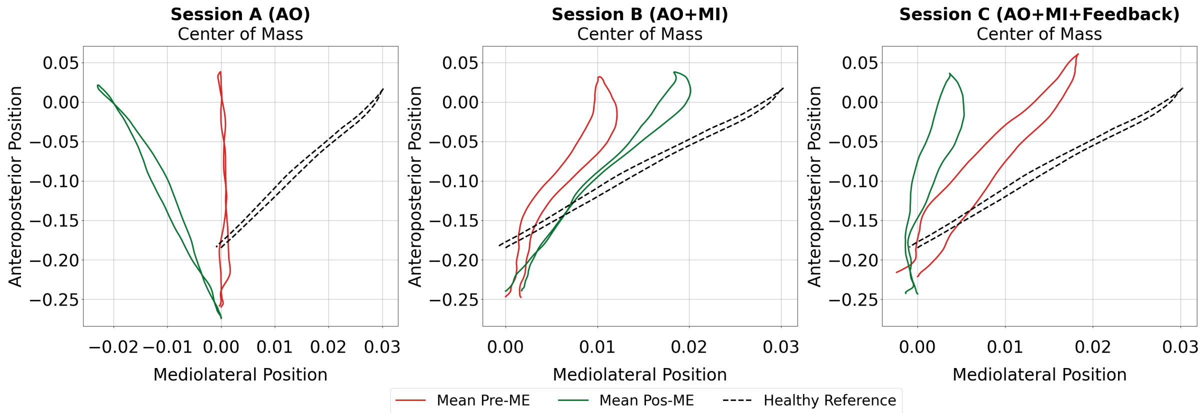

Figure 24: Mean (line) of the AP COM position along the ML COM position, recorded during the pre- and post-VRMT assessments in each session across all healthy participants, for activity of arising from a chair. The black dashed line represents the reference learning data.

Table 13 lists the features extracted from the pre- and post-VRMT assessments of all healthy participants during the activity of arising from a chair, along with the statistical results from the Friedman test. To perform this statistical analysis, the outcomes of each participant, presented in Table 22 in Appendix A, were calculated by subtracting post-results from pre-results across all sessions.

Table 13: Mean ML and AP COM displacement (± standard deviation) from the seated to the standing position, recorded during pre- and post-VRMT assessments in each session across all healthy participants, and the results from the Friedman test, for activity of arising from a chair. The term "REF" refers to the reference learning data

Healthy | Activity of Arising From Chair (2)					
Session	**ML COM Displacement**		**AP COM Displacement**		**Friedman**
	Pre	**Post**	**Pre**	**Post**	**p-value**
A	0.00 (±0.03)	0.02 (±0.03)	0.3 (±0.04)	0.3 (±0.04)	0.489
B	0.01 (±0.02)	0.02 (±0.01)	0.28 (±0.02)	0.28 (±0.04)	
C	0.02 (±0.05)	0.01 (±0.02)	0.28 (±0.05)	0.28 (±0.06)	
REF	0.03 (±0.09)		0.2 (±0.01)		

Although no significant differences were found in the pre-post results between sessions ($\chi^2(5, N = 8) = 4.43$, $p = 0.489$), the pre-post difference of ML COM displacement during the sit-to-stand movement decreased in session C. In session A, it shifted from 0.00 (±0.03) to 0.02 (±0.03); in session B, from 0.01 (±0.02) to 0.02 (±0.01); and in session C, from 0.02 (±0.05) to 0.01 (±0.02). For comparison, the ML COM displacement reported in the reference learning data was 0.03 (±0.09).

Activity of Extending Arms Forward Figure 25 shows the normalized hand position across all sessions. The red and green lines depict the mean data from healthy participants before and after VRMT intervention, with the shaded areas indicating the standard deviation ranges.

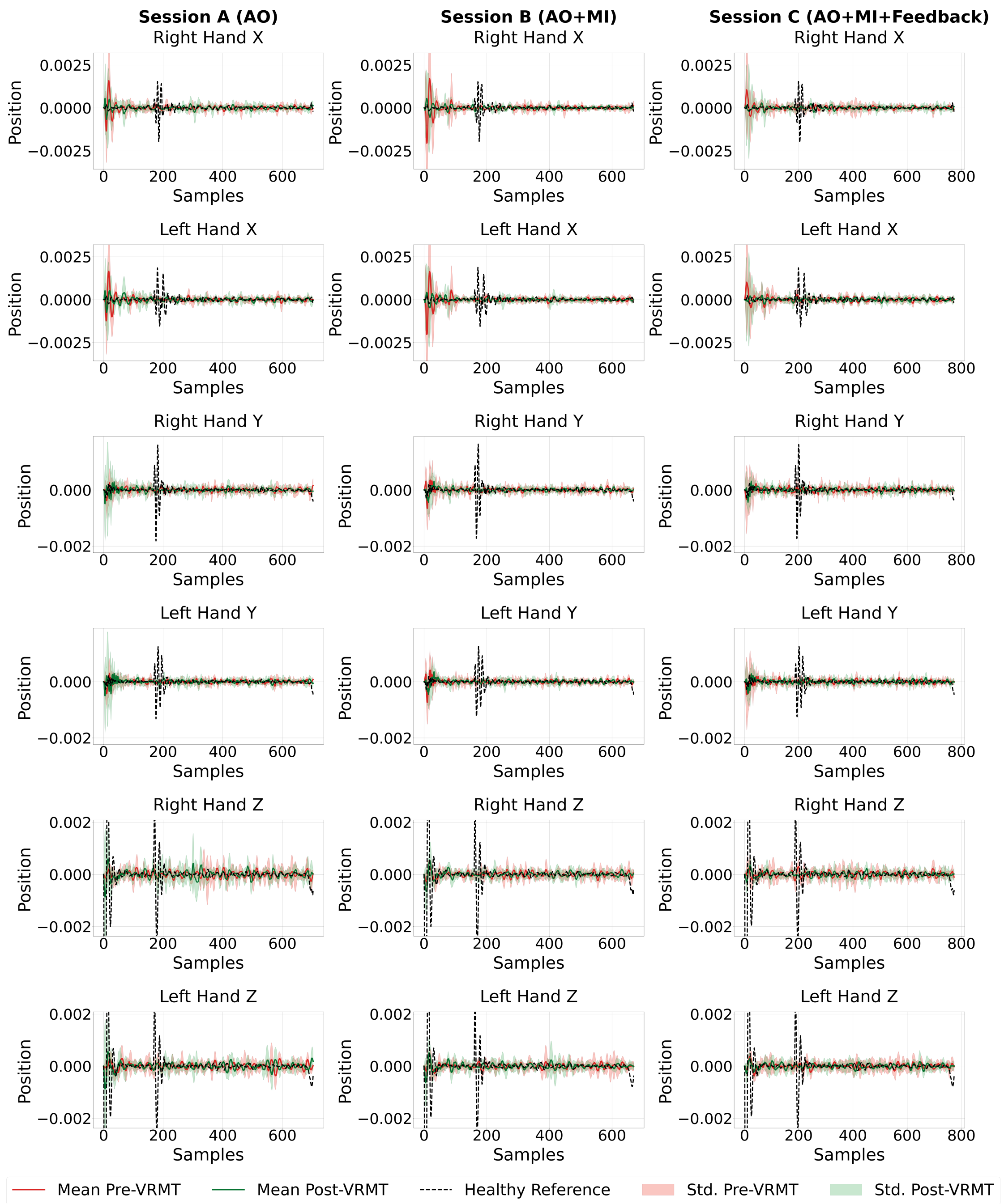

Figure 25: Mean (line) and standard deviation (shaded area) of hand position along the ZXY axes, recorded during the pre- and post-VRMT assessments in each session across all healthy participants, for activity of extending the arms forward for 10 seconds.

Table 14 presents the features obtained before and after VRMT during the arm-extension activity for all healthy participants, along with the statistical results from the Friedman test. The statistical analysis was conducted using the outcomes of each participant, detailed in Table 23 in Appendix A, which were calculated by subtracting post-results from pre-results across all sessions.

Table 14: Normalized mean hand position amplitude (±standard deviation), recorded during pre- and post-VRMT assessments in each session across all healthy participants, and the results from the Friedman test, for activity of extending arms forward. "REF" refers to the reference learning data

Healthy | Activity of Extending Arms Forward (3.1)								
Limb	**Session**	**Position Amplitude (X-axis)**		**Position Amplitude (Y-axis)**		**Position Amplitude (Z-axis)**		**Friedman**
		Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**	**p-value**
Right Hand	A	.003 (±.003)	.001 (±.002)	.001 (±.001)	.001 (±.001)	.001 (±.001)	.001 (±.003)	0.983
	B	.004 (±.005)	.001 (±.002)	.001 (±.001)	.001 (±.001)	.001 (±0.0)	.001 (±.001)	
	C	.002 (±.003)	.001 (±.001)	.001 (±.001)	.001 (±.001)	.001 (±0.0)	.001 (±.001)	
	REF	0.004 (±0.009)		0.003 (±0.008)		0.016 (±0.015)		
Left Hand	A	.003 (±.003)	.001 (±.001)	.001 (±.001)	.001 (±.001)	.001 (±.001)	.001 (±.003)	0.741
	B	.004 (±.005)	.001 (±.003)	.001 (±.001)	.001 (±.001)	.001 (±0.0)	.001 (±.001)	
	C	.001 (±.003)	.001 (±.001)	.001 (±.002)	.001 (±.001)	.001 (±0.0)	.001 (±0.0)	
	REF	0.004 (±0.008)		0.003 (±0.006)		0.016 (±0.015)		

The statistical analysis of the arm-extension activity showed minimal differences in the pre-post results between sessions either for both the right side ($\chi^2(8, N = 8) = 1.93, p = 0.983$) or the left side ($\chi^2(8, N = 8) = 5.16, p = 0.741$). Hand amplitudes in the Y and Z axes measured before the VRMT intervention were either unchanged or slightly higher compared to afterward, with the most notable variation in the X-axis. In session A, the right-hand amplitude in the X-axis decreased from 0.003 (±0.003) pre-intervention to 0.001 (±0.002) post-intervention. Similarly, in session B, it dropped from 0.004 (±0.005) to 0.001 (±0.002), and in session C, from 0.002 (±.003) to 0.001 (±0.001). Conversely, both hand amplitudes in the ZX axes remained consistently unchanged across all sessions, maintaining a value of 0.001. For comparison, the right-hand amplitude in the reference learning data was 0.004 (±0.009) on the X-axis, 0.003 (±0.008) on the Y-axis, and 0.016 (±0.015) on the Z-axis.

Activity of Touching The Nose Figure 26 displays the normalized hand position along the Z-axis and linear velocity (1/s) along the Y-axis across sessions. The red and green lines depict the mean data from all healthy participants recorded before and after VRMT, with the shaded areas indicating the standard deviation ranges and the black dashed line representing the reference learning data.

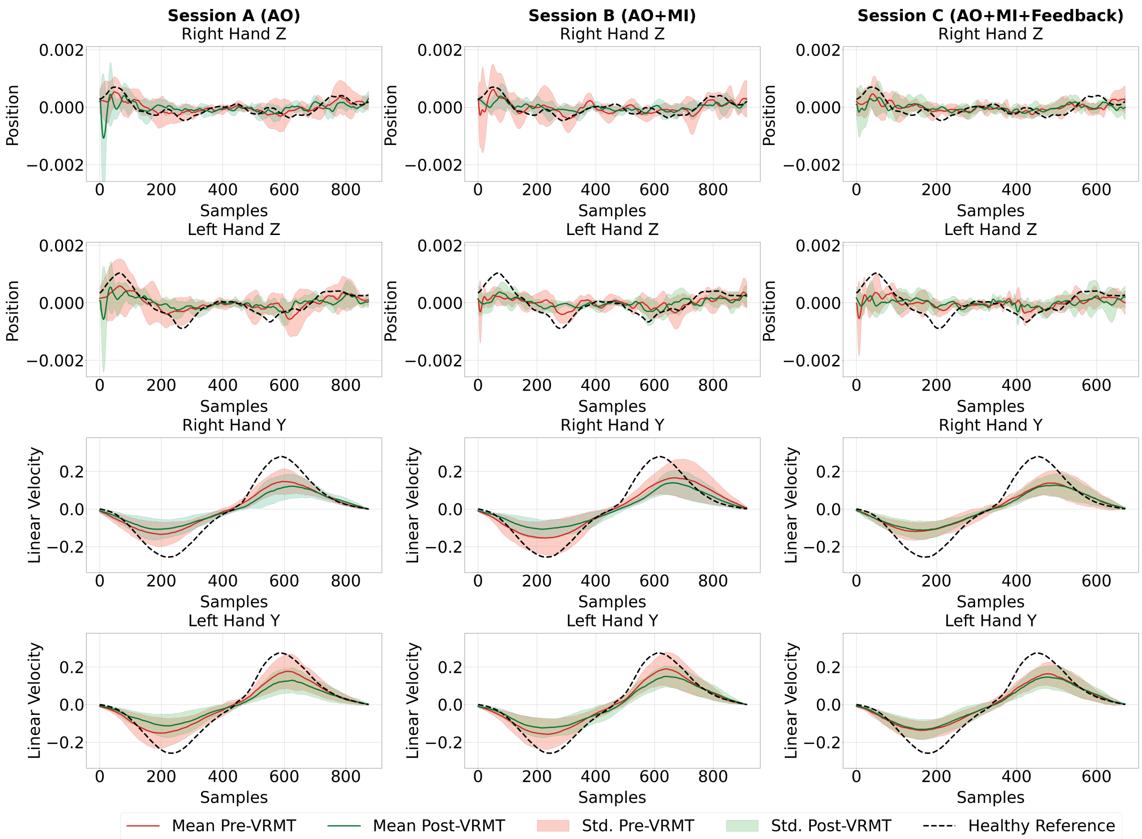

Figure 26: Mean (line) and standard deviation (shaded area) of hand position in the Z-axis and linear velocity (1/s) in the Y-axis, before and after VRMT in each session across all healthy participants, for activity of touching the nose. The black dashed line represents the reference learning data.

Table 15 lists the pre- and post-VRMT features of all healthy participants during the activity of touching the nose, along with the corresponding results from the Friedman test. The term "REF" refers to the reference learning data. The statistical analysis was based on individual participant data, outlined in Table 24 in Appendix A, with each outcome calculated by subtracting the post-intervention results from the pre-intervention results for all sessions.

Table 15: Normalized mean hand position amplitude, along with mean minimum and maximum hand linear velocities (± standard deviation), recorded during pre- and post-VRMT assessments in each session across all healthy participants, and the results from the Friedman test, for activity of touching the nose

Healthy | Activity of Touching The Nose (3.2)								
Limb	**Session**	**Position Amplitude (Z-axis)**		**Min Velocity (Y-axis)**		**Max Velocity (Y-axis)**		**Friedman**
		Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**	**p-value**
Right Hand	A	.001 (±.001)	.002 (±.002)	-0.14 (±0.06)	-0.11 (±0.06)	0.15 (±0.07)	0.12 (±0.06)	0.153
	B	.001 (±.001)	.001 (±0.0)	-0.15 (±0.09)	-0.11 (±0.05)	0.17 (±0.1)	0.14 (±0.07)	
	C	.001 (±.001)	.001 (±.001)	-0.12 (±0.05)	-0.11 (±0.05)	0.14 (±0.07)	0.13 (±0.06)	
	REF	0.001 (±0.001)		-0.24 (±0.08)		0.28 (±0.08)		
Left Hand	A	.001 (±.001)	.001 (±.002)	-0.15 (±0.08)	-0.11 (±0.06)	0.18 (±0.09)	0.13 (±0.07)	0.519
	B	.001 (±.001)	.001 (±0.0)	-0.16 (±0.08)	-0.12 (±0.05)	0.19 (±0.09)	0.15 (±0.06)	
	C	.001 (±.001)	.001 (±.001)	-0.14 (±0.05)	-0.13 (±0.05)	0.16 (±0.06)	0.15 (±0.06)	
	REF	0.002 (±0.001)		-0.24 (±0.08)		0.24 (±0.09)		

Although no significant differences were observed in the pre-post results between sessions for either the right side ($\chi^2(8, N = 8) = 12.0, p = 0.153$) or the left side ($\chi^2(8, N = 8) = 7.17, p = 0.519$), both hand amplitudes along the Z-axis remained consistently stable across all sessions, with a mean value of 0.001 and a standard deviation of less than 0.002. For comparison, the hand amplitude recorded in the reference learning data was 0.001 (±0.001) in the right side and 0.002 (±0.001) in the left side. In contrast, hand velocities showed a consistent decline after the intervention, with both post-minimum and post-maximum velocities being lower than their pre-intervention counterparts. For example, in session A, the right-hand pre-maximum velocity (1/s) dropped from 0.15 (±0.07) to 0.12 (±0.06) post-intervention. Similarly, session B saw a reduction from 0.17 (±0.1) to 0.14 (±0.07) and session C from 0.14 (±0.07) to 0.13 (±0.06). For comparison, the right-hand velocity (1/s) recorded a minimum of -0.24 (±0.08) and a maximum of 0.28 (±0.08) in the reference learning data.

6.2 Usability and Imagery Assessments

The usability tests were designed to evaluate the VRMT system's realism by asessing the participants' engagement (IPQ) and the user experience during the virtual intervention (IMI). The KVIQ imagery test measured participants' visual and kinesthetic sensations during the MI task for each activity.

Igroup Presence Questionnaire Figure 27 illustrates the mean scores for the IPQ subscales – Spatial Presence, Involvement, Experienced Realism, and General Presence – across all participants. The chart highlights differences between sessions, with separate data for healthy participants and the PD patient. Table 16 summarizes the mean scores for each subscale, from 0 to 6, their standard deviations, and the *p*-values from the Friedman test. Table 25 in Appendix B provides the mean and maximum scores for each IPQ subscale per participant. Given the significant differences found between sessions for the subscale Spatial Presence ($\chi^2(2, N = 8) = 6.28$, $p = 0.043$), Dunn's post-hoc test with Bonferroni correction was applied to conduct pairwise comparisons across healthy individuals (Table 17).

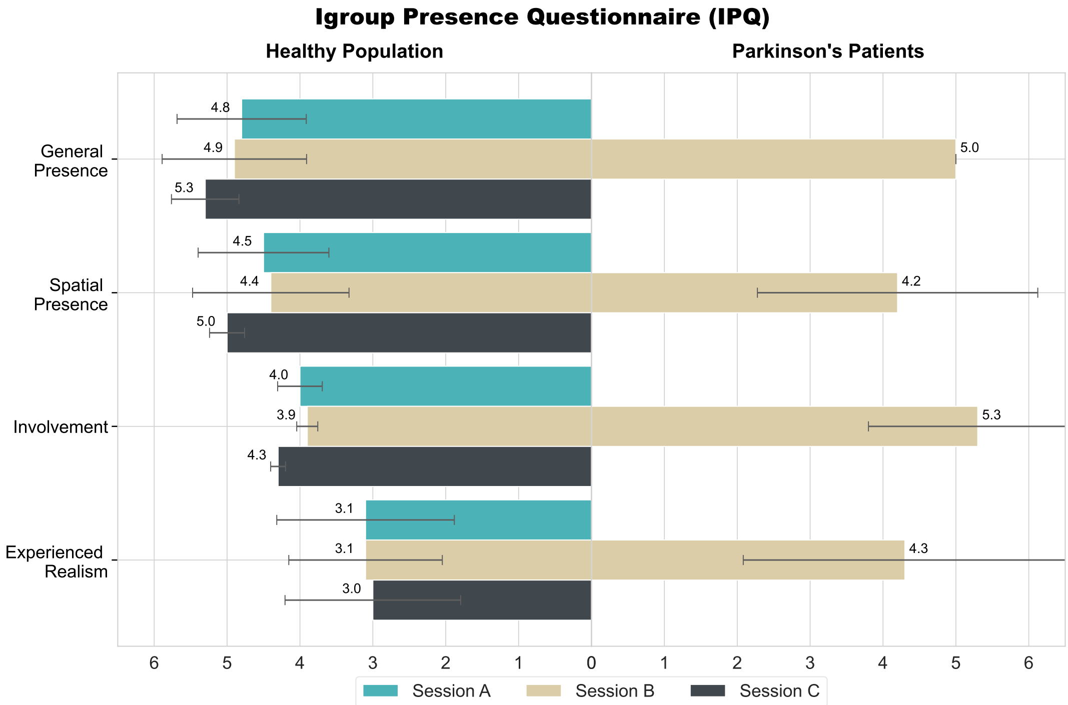

Figure 27: Mean scores for the IPQ subscales, Spatial Presence, Involvement, Experienced Realism, and General Presence, collected from all participants across the three sessions.

Table 16: Mean (± standard deviation) scores, ranging from 0 to 6, for each IPQ's subscale of all healthy and PD participants across sessions A, B, and C, and the Friedman test's *p*-values. The most representative results ($p < 0.05$) are highlighted in grey

Igroup Presence Questionnaire (IPQ)				
Healthy Population				
	General Presence	**Spatial Presence**	**Involvement**	**Experienced Realism**
Session A	4.8 (±0.9)	4.5 (±0.9)	4.0 (±0.3)	3.1 (±1.2)
Session B	4.9 (±1.0)	4.4 (±1.1)	3.9 (±0.1)	3.1 (±1.1)

(Table 16 continues on next page)

(Table 16 continued from previous page)

	General Presence	Spatial Presence	Involvement	Experienced Realism
Session C	5.3 (±0.5)	5.0 (±0.2)	4.3 (±0.1)	3.0 (±1.2)
p-value	0.156	**0.043**	0.356	0.862
		PD Patients		
Session C	5.0 (±0.0)	4.2 (±1.9)	5.3 (±1.5)	4.3 (±2.2)

Table 17: Dunn's post-hoc test results with Bonferroni correction for pairwise session comparisons of the IPQ subscale Spatial Presence across all healthy participants

	SpatialPresence_A	SpatialPresence_B	SpatialPresence_C
SpatialPresence_A	1.0	1.0	0.369
SpatialPresence_B	1.0	1.0	0.078
SpatialPresence_C	0.369	0.078	1.0

The post-hoc analysis revealed minimal differences between sessions A and B, while session C stood out with more distinct IPQ responses, particularly in comparison to session B (p = 0.078). Among the healthy participants, General Presence had the highest scores in session C, with a mean of 5.3 (±0.5), a consistently strong sense of presence during the VRMT intervention. Spatial Presence followed closely with a mean of 5.0 (±0.2), reflecting a high sense of transportation, Involvement scored 4.3 (±0.1) in session C, and Experienced Realism was notably lower, with a mean of 3.1 (±1.2) in session A.

In contrast, the PD patient reported a strong sense of Involvement, with a score of 5.3 (±1.5). General Presence was rated at 5.0 (±0.0), and Spatial Presence at 4.2 (±1.9), suggesting strong feelings of presence and transportation. Unlike the healthy participants, the patient also experienced a notably higher level of Experienced Realism, scoring 4.3 (±2.2).

Intrinsic Motivation Inventory Figure 28 displays the mean scores for the IMI subscales — Interest/Enjoyment, Perceived Competence, Effort/Importance, Pressure/Tension, and Value/Usefulness — across all participants. The chart differentiates between healthy participants and the PD patient, highlighting session-specific variations. Table 18 summarizes the mean scores for each subscale, from 1 to 7, along with their standard deviations and the p-values from the Friedman test. Detailed individual scores for each IMI subscale, including the means and maximums per participant, are listed in Table 26 in Appendix B. Due to the significant differences observed between sessions for the IMI subscale Pressure/Tension

($\chi^2(2, N = 8) = 7.19$, $p = 0.028$), Dunn's post-hoc test with Bonferroni correction was conducted for pairwise session comparisons across healthy population (Table 19).

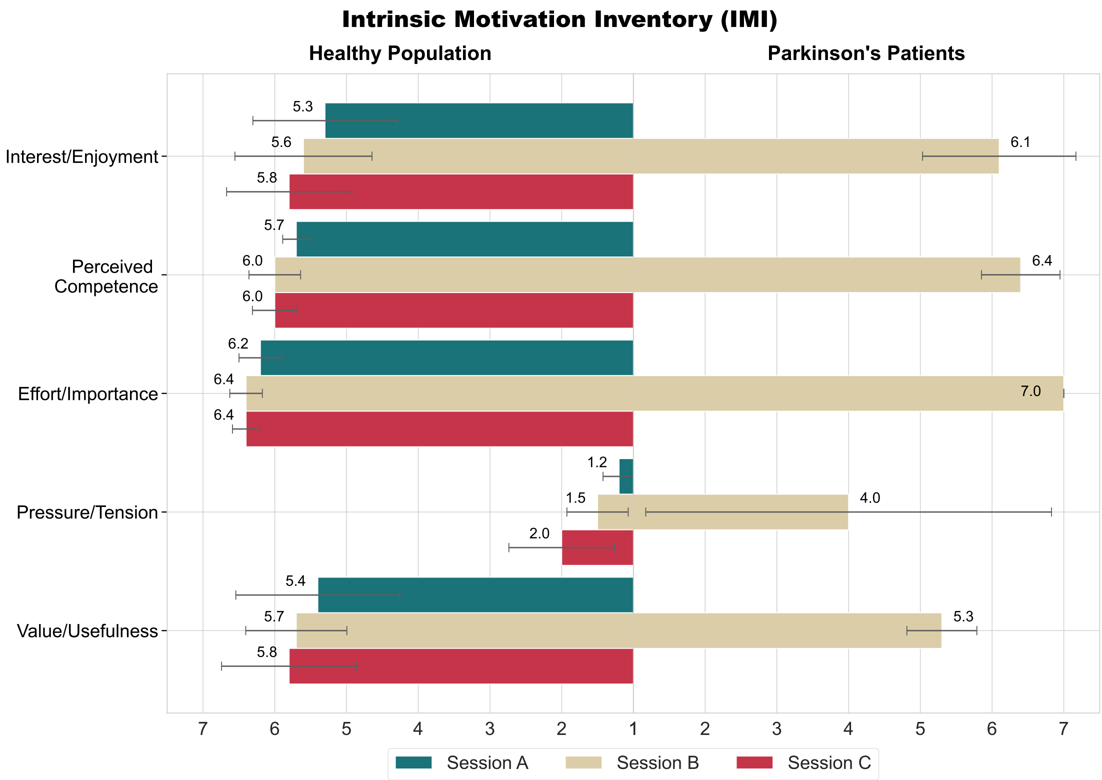

Figure 28: Mean scores for the IMI subscales, Interest/Enjoyment, Perceived Competence, Effort/Importance, Pressure/Tension, and Value/Usefulness, from all participants across sessions.

Table 18: Mean (± standard deviation) scores, ranging from 1 to 7, for each IMI's subscale of all healthy and PD participants across sessions A, B, and C, and the Friedman test's *p*-values. The most representative results ($p < 0.05$) are highlighted in grey

Intrinsic Motivation Inventory (IMI)					
Healthy Population					
	Interest/ Enjoyment	**Perceived Competence**	**Effort/ Importance**	**Pressure/ Tension**	**Value/ Usefulness**
Session A	5.3 (±1.0)	5.7 (±0.2)	6.2 (±0.3)	1.2 (±0.2)	5.4 (±1.1)
Session B	5.6 (±1.0)	6.0 (±0.4)	6.4 (±0.2)	1.5 (±0.4)	5.7 (±0.7)
Session C	5.8 (±0.9)	6.0 (±0.3)	6.4 (±0.2)	2.0 (±0.7)	5.8 (±0.9)
p-value	0.131	0.727	0.582	**0.028**	0.519
PD Patients					
Session C	6.1 (±1.1)	6.4 (±0.5)	7.0 (±0.0)	4.0 (±2.8)	5.3 (±0.5)

Table 19: Dunn's post-hoc test results with Bonferroni correction for pairwise session comparisons of the IMI subscale Pressure/Tension across all healthy participants

	PressureTension_A	**PressureTension_B**	**PressureTension_C**
PressureTension_A	1.0	0.67	0.052
PressureTension_B	0.67	1.0	0.734
PressureTension_C	0.052	0.734	1.0

The post-hoc analysis indicated nearly significant differences between sessions A and C ($p = 0.052$), with session A showing lower scores which suggests that healthy participants experienced less pressure and tension compared to session C. Effort/Importance received the highest scores in session C, with a mean of 6.4 (±0.2), accompanied by a notable increase in Pressure/Tension (mean of 2.0 ±0.7). This population felt that the VRMT system had substantial Value/Usefulness for motor rehabilitation, reflected by a mean score of 5.8 (±0.9), and expressed high Interest/Enjoyment (mean of 5.8 ±0.9), proving the system's strong acceptability. Additionally, they reported high levels of Perceived Competence (mean of 6.0 ±0.3) while performing the motor activities in session C.

For the PD patient, Effort/Importance also emerged as the highest-rated subscale with a perfect score of 7.0 (±0.0), followed by Perceived Competence at 6.4 (±0.5). Despite not excelling in the leg-lifting task, the patient gave maximum effort in attempting to do so. Additionally, the patient expressed a strong Interest/Enjoyment in the VRMT intervention, rating it at 6.1 (±1.1), and recognized significant Value/Usefulness for motor rehabilitation, scoring 5.3 (±0.5). However, the individual experienced a high level of Pressure/Tension (4.0 ±2.8), even exceeding the levels of the healthy participants.

Kinesthetic and Visual Imagery Questionnaire Figure 29 shows mean scores for the KVIQ's visual and kinesthetic components for each activity across all participants. The chart distinguishes between healthy subjects and the PD patient, emphasizing session-specific variations. Table 20 summarizes the mean scores for each component, from 1 to 5, and their respective standard deviations. Since only sessions B and C integrated MI, the Wilcoxon's signed rank test was applied for statistical analysis. Individual participant scores for each activity's imagery component are presented in Table 27 in Appendix B.

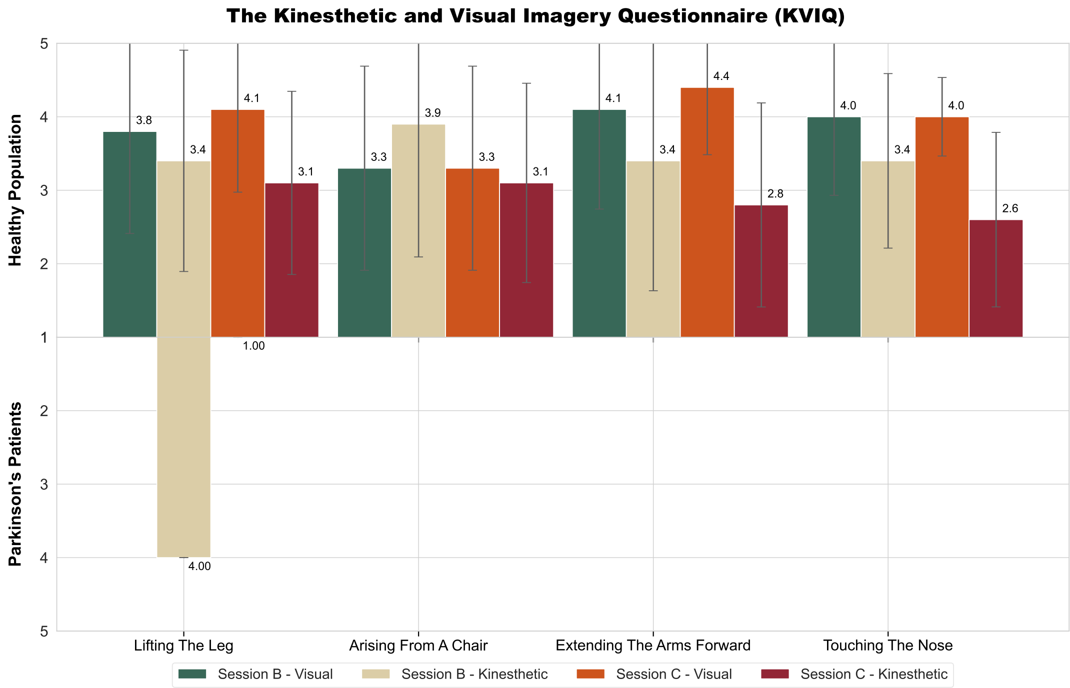

Figure 29: Mean scores for the KVIQ's visual and kinesthetic imagery components, recorded for each activity across all participants over the three sessions.

Table 20: Mean (± standard deviation) scores, ranging from 1 to 5, for the visual (V) and kinesthetic (K) components of the KVIQ for each activity (Act), collected from healthy and PD participants across sessions (S) B and C, along with *p*-values from Wilcoxon's signed-rank test. The most representative results ($p < 0.05$) are highlighted in grey

Kinesthetic and Visual Imagery Questionnaire (KVIQ)								
Healthy Population								
	Act1V	**Act1K**	**Act2V**	**Act2K**	**Act3.1V**	**Act3.1K**	**Act3.2V**	**Act3.2K**
Session B	3.8 (±1.4)	3.4 (±1.5)	3.3 (±1.4)	3.9 (±1.8)	4.1 (±1.4)	3.4 (±1.8)	4.0 (±1.1)	3.4 (±1.2)
Session C	4.1 (±1.1)	3.1 (±1.2)	3.3 (±1.4)	3.1 (±1.4)	4.4 (±0.9)	2.8 (±1.4)	4.0 (±0.5)	2.6 (±1.2)
p-value	0.083	0.480	0.891	0.340	0.705	0.129	0.705	**0.034**
PD Patients								
Session C	4.0 (±0.0)	1.0 (±0.0)	-	-	-	-	-	-

For the healthy population, the statistical analysis identified significant differences in kinesthetic imagery of the nose-touching activity ($Z = -2.121$, $p = 0.034$), with session B showing higher scores. In terms of visual imagery, the leg-lifting activity achieved a mean score of 4.1 (±1.1) in session C, while the kinesthetic component was rated 3.4 (±1.5) in session B. The activity of arising from a chair excelled in the kinesthetic component, with a mean score of 3.9 (±1.8) in session B, whereas the visual component reached 3.3 (±1.4). For arm-extension activity, visual imagery dominated with a mean of 4.4 (±0.9) in session C, in contrast to kinesthetic imagery which scored 3.4 (±1.8) in session B. Finally, the nose-touching activity scored 4.0 (±1.1) in the visual component and 3.4 (±1.2) in kinesthetic imagery in session B. Meanwhile, the PD patient scored 4 in the visual component and 1 in the kinesthetic component for the activity of lifting the leg, despite unclear if the individual understood the task and how to rate these KVIQ components when asked to imagine the movement.

6.3 Discussion

Healthy Individuals The activity of lifting the leg was designed to target the PD symptom of bradykinesia, instructing participants to perform the movement as high and as quickly as possible. Statistical analysis indicated significant differences in performance across sessions for the right foot ($p < 0.001$), with session A proving to outperform session B (Table 11) since results in session A aligned more closely with the reference data after the intervention. Session A showed a decrease in the post-assessment results compared to the pre-assessment results (Figure 22), suggesting that participants lifted their legs more slowly and lower after the VRMT intervention. However, Table 10 reveals that the right foot's post-intervention maximum height of 0.28 (±0.03) and velocity of 0.84 (±0.18), dropping from 0.32 (±0.05) and 1.11 (±0.37) pre-intervention, aligned more closely with the reference learning data, which recorded a maximum height of 0.27 (±0.04) and velocity of 0.79 (±0.26). This outcome may be explained by the post-VRMT instructions, where participants were asked to replicate each activity solely based on what they had observed, imagined, and executed with real-time feedback. In session A, they exclusively learned the exercise by observing the AO avatar, animated with the reference learning data, for 8 minutes straight. This emphasizes the effective role of AO in facilitating motor learning [13, 31], whereas the contribution of imagery-based approaches remains a subject for further exploration [31]. Conversely, despite minimal variation between the two evaluation points, the outcomes from session C were also satisfactory, as they remained consistently close to the reference learning data both before and after VRMT. The right foot achieved pre- and post-assessment heights of 0.29 (±0.03) and 0.28 (±0.03), respectively, with corresponding velocities of 0.98 (±0.26) and 0.78 (±0.19). Significant differences were observed between sessions for the left foot as well ($p = 0.004$). However, unlike the right foot, there were no significant differences in the pairwise comparisons, probably due to most participants being right-side dominant or because the right foot was always trained first. Additionally, no notable discrepancies between limbs were detected, as the extreme measurements remained nearly identical across sessions, which aligns with the expected symmetry in healthy individuals [59].

In the activity of arising from a chair, no statistically significant differences were detected in the ML and AP COM displacement across sessions ($p = 0.489$). However, session A revealed a decrease in the ML COM position during the sit-to-stand transition (Figure 24), with a mean displacement of 0.02 (±0.03) after the intervention (Table 13), still lower than the reference learning data of 0.03 (±0.09). This shift occurred because most participants predominantly relied on their left side to stand. In contrast, before VRMT, the mean displacement was nearly unchanged at 0.0 (±0.01), as participants were evenly split between relying on their left and right sides, leading to a consistent mean variation close to zero. While session B once again demonstrated no improvements between the two evaluation points, session C exhibited the most favorable post-VRMT results, with a mean ML COM displacement of 0.01 (±0.02). This linear progress in the AP COM relative to the ML COM indicates a low coordinated shift of the COM both front-to-back and side-to-side, contributing to effective weight distribution while standing up [60]. Although this displacement was notably lower than the reference data, the pre-post findings were encouraging because a smaller side-to-side movement correlates with improved balance [60], meaning that participants demonstrated enhanced stability after the intervention in session C. Despite being from a healthy population, these results are consistent with some studies in the literature, which concluded that the combination of VR, AO, MI, and ME can lead to clinically significant improvements in balance [34], as well as specific functional reorganization of brain regions associated with motor control [17].

The activity of extending the arms forward for 10 seconds aimed at addressing tremors, as well as the nose-touching activity. In the arm-extension exercise, there were no statistically significant differences in pre-post hand amplitude across sessions for either the right side ($p = 0.983$) or the left side ($p = 0.741$). After applying a second-order high-pass filter to the hand position data, low-frequency components were filtered out, leaving only high-frequency tremor data. Table 14 reveals a common pattern across sessions, with hand amplitude remaining nearly unchanged between pre- and post-assessments in the Y and Z axes. However, more pre-post variation was observed in the X-axis, indicating more lateral hand amplitude, on contrary to the reference learning data, which showed greater vertical movement, with a mean of 0.016 and a standard deviation of 0.015 (Figure 25). All sessions positively reduced lateral movement in both hands, resulting in a post-intervention mean amplitude of 0.002 (±0.004). Similarly, in the nose-touching activity, no significant pre-post differences were observed across sessions for either the right side ($p = 0.153$) or the left side ($p = 0.519$). The hand amplitude in the Z-axis showed minimal variation pre- to post-assessment, often measuring a mean of 0.001 (±0.001), in alignment with the reference learning data (Table 15). Since healthy participants exhibited no vertical tremors, the VRMT intervention did not significantly impact the motor performance. On the other hand, Figure 26 shows that VRMT played a positive role in decreasing hand velocity and led to a slower nose-touching movement post-intervention compared to pre-assessment. Sessions A and B displayed greater reductions, while ME with real-time feedback contributed less to this decrease. In session A, maximum right-hand velocity in the Y-axis dropped from 0.15 (±0.07) pre-assessment to 0.12 (±0.06) post-assessment, in session B from 0.17 (±0.1) to 0.14 (±0.07), and in session C from 0.14 (±0.07) to 0.13 (±0.06). Both left- and right-hand features mirrored each other, reflecting the expected healthy symmetry between limbs [59].

Healthy participants reported high scores on the IPQ and IMI subscales, with session C presenting slightly higher ratings (Figures 27 and 28). This proposes that the integration of ME with real-time feedback may intensify the user's engagement and motivation by enabling for greater interaction with the VRMT system. Nonetheless, statistically significant differences between sessions were only observed in the IPQ's Spatial Presence subscale ($p = 0.043$) and the IMI's Pressure/Tension subscale ($p = 0.028$). As shown in Table 16, during session C, healthy participants felt a strong sense of presence (5.3 ±0.5), transportation (5.0 ±0.2) and involvement (4.3 ±0.1) within the VRE. However, their perception of realism was vaguely lower compared to other sessions (3.0 ±1.2 in session C and 3.1 ±1.1 in other sessions), which could be attributed to data transmission delays or inaccurate negative feedback during the ME task experienced by a few participants. In Table 18, healthy subjects found the experiment highly interesting (5.8 ±0.9) and valuable for motor function improvement (5.8 ±0.9), thus demonstrating considerable effort and dedication to the exercises (6.4 ±0.2) and feeling more competent after completing them (6.0 ±0.3). However, they also experienced slightly more pressure during session C (2.0 ±0.7), likely due to the increased interaction required for responding to real-time feedback while performing the activities. Interestingly, session B scores on the IMI subscales were either consistent with or lower than session C, but always higher than session A. This suggests that the introduction of MI and/or ME with real-time feedback could have more impact on the user's engagement and experience than AO alone, where participants only passively observed visual stimuli without any system interaction or active involvement.

For the KVIQ scores, even though there were no significant differences between sessions, except for the kinesthetic imagery of the nose-touching activity ($p = 0.034$), session C generally showed equal or higher scores than session B in the visual component, while session B consistently outperformed session C in the kinesthetic component (Figure 29). This difference may be assigned to the shorter MI duration in session C (2.5 minutes) compared to session B (4 minutes). Kinesthetic imagery tends to be more challenging and less intuitive, especially for individuals with greater motor difficulties [70], often requiring more time and preparation to reach comparable performance levels. In general, these responses are less assertive than the other questionnaires, indicating that the role of imagery modalities still requires extensive exploration [31]. This is largely due to the inherent difficulty in ensuring that participants fully understand the concept of imagining a movement, particularly regarding visual and kinesthetic imagery [34].

Although the healthy participants demonstrated proficiency in motor performance throughout the three experimental sessions, a range of operational issues and usability suggestions were reported. Despite their interest in the VRMT intervention, participants noted delays in the real-time feedback during the sit-to-stand activity, attributed to the transmission of multiple data packets between the MVN Awinda System and Unity. Additionally, smoother upper-body animation was recommended to make the movement appear more natural. Two participants also experienced inaccurate negative feedback while arising from a chair, caused by shifts in the avatar position from the Xsens MVN Awinda system and calibration disorientation. This misalignment resulted in incorrect feedback when the avatar was not perpendicular to the origin and the ML and AP COM positions exceeded the predefined learning data.

Another challenge participants faced was a lack of self-recognition in some activities, particularly in the AO task when the seated user observes an animated avatar. However, the diagonal perspective was appreciated during the sit-to-stand activity. Suggestions included a first-person [40, 41, 48–50] or, for the tremor-targeted activities, a mirrored view for better self-association, as the literature supported that anatomical perspectives could lead to more errors [48]. On the other hand, the VRE was praised for being a comfortable, secure, and immersive setting, which could become even more realistic with improved computational performance, such as greater RAM capacity.

Despite its importance for the learning process, the 8-minute duration of the AO task in session A was considered excessive, making this session less engaging compared to shorter observation times in other sessions. Session C, which combined AO, MI, and ME with real-time feedback, stood out as the most beneficial, with feedback being crucial to the success of the ME task. Opinions on the MI task were not consensual, with most participants preferring to close their eyes and imagine the exercises in the first person, though the MI avatars were particularly useful for more complex tasks, such as nose-touching. Some participants also found the sit-to-stand activity more difficult to imagine since it requires a full-body movement and, in the remaining activities, the dominant limb is chosen to imagine the movement.

Parkinson's Patient The PD patient, primarily affected on the left side, only observed, imagined, and executed the leg-lifting activity, targeting one of his most prominent symptoms. He had taken his medication four hours prior to the experimental protocol and was due for his next dose in another four hours, indicating that he was still under partial medication influence, though symptoms were beginning to reemerge. Despite the left side being more afflicted, the right foot underperformed: its height decreased from 0.17 (±0.02) pre-assessment to 0.13 (±0.01) post-assessment, whereas the left-foot height dropped from 0.2 (±0.01) to 0.15 (±0.02). This could be attributed to the patient putting more effort into the left leg due to its greater impairment. The left foot was also faster, but post-intervention results were suboptimal. Before the intervention, the maximum velocity (1/s) of the right and left feet was 0.26 (±0.11) and 0.45 (±0.1), respectively, which dropped to 0.11 (±0.03) and 0.19 (±0.08) afterward. Both results were significantly lower than the reference learning data, which measured 0.79 (±0.26).

A key factor for these outcomes could be the feedback threshold, which was set to 5 seconds for this activity based on the healthy execution duration per repetition. As a result, the patient frequently heard auditory messages warning him to lift his leg higher or speed up his movement since his foot was not reaching the reference height or velocity. The repetitive nature of these messages over a short period made the patient increasingly nervous, evidenced by increased tremors in his left hand. Nonetheless, the real-time feedback proved effective and useful, as he interacted with the system and adjusted his performance, eventually lifting his left foot more and hearing fewer corrective prompts. This underscores the need for personalized feedback timing, tailored to each subject's execution speed, along with varying difficulty levels to make tasks more achievable compared to the reference learning data. Since most PD patients are over 60, some motor deficits may be attributed to age-related physiological changes rather than the disease itself [71]. Giannakopoulos *et al.* [13] similarly recommended adapting interventions to meet the specific needs of individuals without overwhelming them.

There was uncertainty regarding the patient's understanding of the MI task, despite his claim that he focused on the avatars and imagined lifting the leg. In Table 20, his self-reported scores of 4 for the visual component and 1 for the kinesthetic component on the KVIQ may have been inaccurately assigned, possibly due to confusion over the definitions of visual and sensory imagery or the natural decline in imagery ability that often accompanies aging [72]. Additionally, the subject stated that he could not recall what he had learned from the three MT tasks, suggesting that any learning may have been unconscious. A potential solution would be to administer a cognitive assessment, such as the MMSE [17, 24, 26, 28–30, 32–34, 37], before the experiment to enhance the reliability of responses on other questionnaires. According to the IPQ scores, he reported a strong sense of presence (5.0 ±0.0), transportation (4.2 ±1.9), and involvement (5.3 ±1.5) during the virtual experience. Despite feeling somewhat claustrophobic over time and becoming nervous due to the feedback (4.0 ±2.8), the PD patient classified the intervention as enjoyable (6.1 ±1.1) in the IMI and recognized its potential value in Parkinson's rehabilitation (5.3 ±0.5). The patient also rated the VRE as highly realistic (4.3 ±2.2), contrasting with the rating from healthy participants. Although his motor performance did not improve significantly, he considered himself competent during the experiment (6.4 ±0.5), expressing that he dedicated maximum effort to it (7.0 ±0.0).

6.4 Conclusions

The biomechanical outcomes revealed that sessions A and C produced superior results compared to session B, which reinforces that visual stimuli and real-time feedback can effectively facilitate motor improvements, particularly in the leg-lifting activity, though the participant sample collected is not enough to represent an entire population. Imagery pratice, on the other hand, yielded less robust and conclusive results, highlighting the need for further investigation in this area. The PD patient's outcomes after the intervention were worse than before, likely due to the overwhelming effect of real-time feedback provided during ME, indicating that this approach requires adjustments to be more beneficial for this population.

Among healthy participants, during the leg-lifting activity, session A showed a significant difference in pre- and post-assessment results compared to session B, with post-assessment outcomes aligning more closely with the reference learning data. Session B failed to meet expectations, with results remaining further from the healthy reference at both evaluation points. Session C presented intermediate results, exhibiting no significant changes before and after VRMT, yet both evaluation points were closer to the reference learning data. For the sit-to-stand activity, session A demonstrated a lower ML COM displacement relative to the reference learning data. In session B, post-intervention results were inferior to pre-intervention outcomes, while session C revealed post-VRMT results notably lower than both pre-VRMT and the reference learning data. In the exercises targeting tremors, minimal differences in hand position amplitude were observed across sessions. However, during the arm-extension activity, increased lateral hand movement was noted, contrasting with the more vertical amplitude seen in the reference data. In the nose-touching activity, hand velocity displayed minimal pre- to post-session differences, remaining consistently lower than the reference values at both evaluation points.

Regarding questionnaire responses, session C outperformed the others, suggesting that increased interaction with the system, driven by immediate reaction to real-time feedback, enhanced user engagement. Overall,the VRMT system was well received by both healthy participants and the PD patient, who reported enjoying the intervention and finding it valuable, experiencing a sense of presence, involvement, and realism through the implemented VRE. With further adaptations, this intervention seems promising for motor rehabilitation, particularly for individuals with PD, in contrast to traditional therapeutic strategies.

7 Conclusions

PD is a prevalent neurodegenerative disorder, affecting millions of cases worldwide, primarily among older men. Characterized by progressive motor impairments, including tremors, balance issues, and bradykinesia, this disease also leads to non-motor symptoms, such as depression and sleep disturbances. While current treatments like medication and deep brain stimulation can alleviate symptoms, they fail to stop disease progression and may raise further health concerns. As research advances, MT techniques, such as AO, MI, and ME, have shown promise in promoting motor function recovery by inducing brain plasticity. These approaches gain further efficacy when integrated with VR-based interventions, such as VRMT, in which users engage within an immersive VRE that offers a 3D perspective of their limbs, augmenting body ownership and actively involving them in the rehabilitation process. Despite its potential, the use of VRMT in PD rehabilitation remains underexplored, introducing a promising area for further research to address the physical and cognitive challenges faced by patients. In this context, the present dissertation designed, implemented, and conducted preliminary validation of a fully immersive VRMT system, aimed at improving motor function in individuals diagnosed with PD. The system was carefully developed to not only maximize motor recovery but also to prioritize user acceptability and engagement, following a user-centered approach. These objectives were outlined and accomplished in Chapter 1.

In the state-of-the-art exploration, AO (without ME) therapy has shown significant positive outcomes for PD, particularly in improving balance, FoG, disease severity, and non-motor abilities. While MI has also demonstrated potential in dual-task gait and balance training, its results underperformed AO, highlighting the need for further investigation to establish more conclusive results and confirm its efficacy. The combination of AO, MI, and ME in rehabilitation can produce synergistic effects, as these techniques work together to activate the MNS, promoting motor learning and brain plasticity. Integrating VR into MT adds another layer of effectiveness, especially when providing visual feedback and real-time performance observation, enhancing motor function. VR-based rehabilitation introduces greater immersion and motivational benefits, but caution is necessary due to potential side effects like dizziness and nausea. With further advancements, VRMT stands as a promising avenue for future PD rehabilitation research, requiring long-term studies to evaluate its sustained benefits and the combined impact of AO, MI, and ME on motor recovery. These findings were thoroughly discussed in Chapter 2.

The developed VRMT system combines the HTC Vive Pro virtual headset with the Xsens MVN Awinda motion capture system to deliver an immersive and personalized rehabilitation experience that enhances realism and presence. Ensuring relevant observational perspectives for each motor activity, it supports dynamic avatar animations for AO, static poses for MI, and provides real-time visual and auditory feedback during ME. The avatars, designed to resemble the participants, ensure a more personalized learning experience across all three MT tasks. By utilizing Xsens data and finite state machine algorithms, the system allows participants to observe themselves and immediately correct their performance. The design and implementation of the VRMT system, detailed in Chapter 4, aim to strike a balance between realism and minimalism to maintain participant concentration.

Biomechanical reference data for VRMT rehabilitation interventions was collected from twelve healthy participants performing three MDS-UPDRS activities: lifting the leg, arising from a chair, and touching the nose. The leg-lifting activity, aimed at addressing bradykinesia, demonstrated healthy symmetry and coordinated lower limb function. The activity of arising from a chair showed a low shift in the ML compared with AP COM, reflecting balanced postural control. In the nose-touching activity, nearly symmetrical hand movements were observed, with low standard deviations across the axes suggesting an absence of tremors. The biomechanical characterization of these consistent movement patterns, using inertial sensors, creates a solid foundation for guiding movement performance and enabling AO, MI and real-time feedback, helping users align their exercises with healthy standards. These findings are covered in Chapter 3.

The validation protocol was successfully completed by eight healthy participants and one PD patient, with data collected before and after the VRMT intervention. Healthy participants underwent three 30-minute sessions with a 3-minute rest period between activities, while the PD patient underwent a single 15-minute session, followed by H&Y and MDS-UPDRS III assessments. Data processing included segmentation, normalization, interpolation, and mean curve calculations of key biomechanical parameters for each activity. After the intervention, all participants completed the IMI, IPQ, and KVIQ questionnaires to evaluate their subjective experience and their sense of presence in the VRE, as well as their imagery abilities. The details of the experimental protocol validation are discussed in Chapter 5.

The biomechanical analysis indicated that sessions A and C produced superior outcomes than session B, particularly in the leg-lifting activity, emphasizing the advantages of incorporating visual stimuli and real-time feedback for motor rehabilitation. In contrast, imagery practice yielded less consistent improvements, suggesting the need for additional research in this area. The patient with PD showed suboptimal performance, likely due to the overwhelming nature of the feedback while performing. However, the patient remained highly responsive, adjusting immediately to improve performance based on the feedback. Regarding the questionnaires, session C outperformed the remaining sessions, which indicates that greater interaction with real-time feedback fosters higher engagement. Healthy participants and the PD patient reported positive experiences with the VRMT system, highlighting its potential for motor rehabilitation, particularly with further refinements, such as personalizing the level of difficulty, to better suit PD patients. The results and discussion of these findings are presented in Chapter 6.

This dissertation provides answers to the research questions established in Chapter 1:

- **Research Question 1: How are MT strategies applied and what effects are reported in the literature for PD's victims?**

  Chapter 2 answered that MT interventions for PD rehabilitation commonly combine AO, MI, and ME, with 2-3 sessions per week, over 4.5 weeks, lasting around 60 minutes each. These approaches aim to improve motor functions such as balance, gait, and movement coordination. AO therapy is particularly effective in stimulating spontaneous movements, especially when paired with ME without feedback, while MI alone shows limited efficacy unless paired with other techniques. When tailored to the specific needs of individuals and incorporated into dual-task training, these combined techniques can enhance both motor and cognitive functions, promoting brain reorganization and providing long-term benefits, especially in early-stage PD.

- **Research Question 2: What are the VRMT strategies described in the literature that have a positive impact on motor effects?**

  Chapter 2 identified several VRMT strategies in the literature that positively impact motor rehabilitation, though not yet focused specifically on PD. The integration of immersive and realistic VRE, and VR-based AO, combined with visual and kinesthetic MI and real-time feedback, has proven more effective than traditional MT techniques in stimulating participant engagement, facilitating motor learning and enhancing brain activity, particularly through increased contralateral alpha ERD. Moreover, visual feedback using avatar embodiment and manipulating movement perspectives in VR can also contribute to motor improvement.

- **Research Question 3: How does incorporating AO, MI, and real-time feedback into VRMT influence biomechanical adjustments in healthy population and a PD case study?**

  Chapter 6 revealed that, for healthy participants, incorporating AO and real-time feedback into VRMT resulted in significant performance improvements in the leg-lifting activity (right foot: p-value < 0.001; left foot: p-value $= 0.004$), by enhancing participant engagement and motor learning. Additionally, real-time feedback contributed to improved stability, as evidenced by a slight reduction in the ML COM displacement during the sit-to-stand transition (before VRMT: 0.02 ± 0.05; after VRMT 0.01 ± 0.02). Since healthy participants had no hand tremors, no significant changes were noted in the activities targeting this symptom, aside from learning to moderate their movement velocity. In contrast, the PD patient struggled with motor performance and exhibited increased tremors under pressure from auditory real-time performance. Nevertheless, real-time feedback enabled the patient to make motor adjustments while performing, suggesting that such interventions can facilitate learning even when immediate improvements are not evident.

7.1 Future Work

Considering the overwhelming experience reported by the PD patient due to the repetitive auditory feedback during ME, future work will include personalizing the feedback threshold according to each participant's motor performance. This adjustment will foster a more dynamic interaction, providing participants adequate time to process the information and react by correcting their performance. The second-order high-pass filter, applied to the biomechanical data in real-time for the activities targeting hand tremors, will be fine-tuned to each participant's performance as well. As these activities involve slow-paced movements, the cutoff frequency must be appropriately adjusted to accurately attenuate low-frequency signals specific to each participant. The reference learning data for these tremor-related activities will be recollected to better support feedback mechanisms. Additionally, a tiered feedback system will be established, progressively increasing the complexity of exercises as participants improve, to make the activities more accessible to a wider range of individuals.

Prior to the VRMT intervention, assessments will encompass not only the H&Y scale and the MDS-UPDRS III but also the patient's cognitive abilities and educational background. This multi-faceted evaluation will assist in identifying whether any suboptimal outcomes stem from the VRMT inefficacy or from the patient's mental state and educational limitations. Additionally, the experimental protocol will require participants to undergo the three-session training regimen multiple times, on separate days, to assess whether repeated exposure leads to improved outcomes.

To address the less significant results observed in the MI task, future work will also comprise developing customized feedback mechanisms for the imagery modality. Participants will use EEG equipment to monitor their brain activity during MI exercises, and reference data from highly skilled individuals proficient in imagery techniques will be employed to train a specialized deep learning algorithm. Participants will then receive real-time feedback based on their brain signals transmitted through the EEG, aiming to facilitate a more impactful and effective learning experience.

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A Biomechanical Data

Tables 21 to 24 present the normalized pre- and post-VRMT results of every activity for each participant across sessions: (1) for the leg-lifting activity, the maximum foot position, and minimum and maximum foot velocity (1/s) along the Z-axis; (2) for the sit-to-stand activity, the ML and AP COM displacements; (3.1) for the arm-extension activity, the hand amplitude across the ZXY axes; and (3.2) for the nose-touching activity, the hand amplitude in the Z-axis and minimum and maximum hand velocity (1/s) along the Y-axis.

Table 21: Mean maximum foot position, and minimum and maximum foot velocity (± standard deviation), recorded for each healthy participant during pre- and post-VRMT of the leg-lifting activity

Activity of Lifting The Leg (1)								
Participant	**Limb**	**Session**	**Max Position (Z-axis)**		**Min Velocity (Z-axis)**		**Max Velocity (Z-axis)**	
			Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**
P1	Right Foot	A	0.3 (±0.01)	0.29 (±0.01)	-0.81 (±0.09)	-0.72 (±0.05)	0.88 (±0.1)	0.81 (±0.07)
		B	0.25 (±0.02)	0.25 (±0.01)	-0.58 (±0.09)	-0.61 (±0.05)	0.66 (±0.08)	0.69 (±0.07)
		C	0.25 (±0.01)	0.26 (±0.01)	-0.7 (±0.04)	-0.59 (±0.08)	0.78 (±0.05)	0.62 (±0.12)
	Left Foot	A	0.27 (±0.01)	0.26 (±0.01)	-0.84 (±0.05)	-0.7 (±0.08)	0.87 (±0.06)	0.74 (±0.06)
		B	0.23 (±0.01)	0.25 (±0.01)	-0.67 (±0.07)	-0.61 (±0.03)	0.7 (±0.1)	0.65 (±0.05)
		C	0.21 (±0.01)	0.25 (±0.01)	-0.62 (±0.06)	-0.63 (±0.03)	0.62 (±0.07)	0.66 (±0.03)
P2	Right Foot	A	0.37 (±0.02)	0.32 (±0.01)	-0.99 (±0.08)	-0.78 (±0.05)	1.13 (±0.1)	0.87 (±0.07)
		B	0.36 (±0.02)	0.35 (±0.02)	-0.89 (±0.04)	-0.86 (±0.06)	1.04 (±0.1)	0.96 (±0.07)
		C	0.32 (±0.01)	0.31 (±0.09)	-0.89 (±0.04)	-0.74 (±0.15)	0.95 (±0.11)	0.81 (±0.07)
	Left Foot	A	0.34 (±0.01)	0.31 (±0.01)	-1.0 (±0.24)	-0.88 (±0.05)	1.34 (±0.12)	1.04 (±0.1)
		B	0.34 (±0.01)	0.32 (±0.02)	-0.87 (±0.04)	-0.85 (±0.05)	0.95 (±0.07)	0.95 (±0.07)
		C	0.36 (±0.01)	0.34 (±0.01)	-0.93 (±0.11)	-0.77 (±0.13)	1.14 (±0.1)	0.85 (±0.07)
P3	Right Foot	A	0.27 (±0.02)	0.23 (±0.01)	-0.63 (±0.12)	-0.48 (±0.06)	0.69 (±0.1)	0.62 (±0.09)
		B	0.28 (±0.03)	0.28 (±0.01)	-0.62 (±0.13)	-0.64 (±0.13)	0.77 (±0.16)	0.73 (±0.15)
		C	0.29 (±0.02)	0.27 (±0.01)	-0.63 (±0.07)	-0.43 (±0.1)	0.8 (±0.1)	0.55 (±0.08)

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Participant	Limb	Session	Max Position (Z-axis)		Min Velocity (Z-axis)		Max Velocity (Z-axis)	
			Pre	Post	Pre	Post	Pre	Post
	Left Foot	A	0.26 (±0.01)	0.25 (±0.01)	-0.45 (±0.05)	-0.5 (±0.05)	0.57 (±0.06)	0.55 (±0.15)
		B	0.3 (±0.01)	0.3 (±0.01)	-0.61 (±0.1)	-0.56 (±0.06)	0.74 (±0.09)	0.71 (±0.11)
		C	0.22 (±0.02)	0.26 (±0.01)	-0.41 (±0.07)	-0.42 (±0.03)	0.56 (±0.07)	0.55 (±0.09)
P4	Right Foot	A	0.34 (±0.01)	0.29 (±0.01)	-1.4 (±0.16)	-0.92 (±0.05)	1.91 (±0.16)	1.29 (±0.15)
		B	0.32 (±0.02)	0.32 (±0.02)	-1.08 (±0.22)	-1.1 (±0.09)	1.57 (±0.13)	1.56 (±0.08)
		C	0.34 (±0.03)	0.31 (±0.01)	-1.22 (±0.13)	-0.97 (±0.07)	1.54 (±0.15)	1.24 (±0.09)
	Left Foot	A	0.34 (±0.03)	0.28 (±0.02)	-1.4 (±0.09)	-0.93 (±0.1)	1.71 (±0.27)	1.2 (±0.14)
		B	0.34 (±0.03)	0.33 (±0.02)	-1.27 (±0.35)	-1.17 (±0.14)	1.63 (±0.17)	1.53 (±0.12)
		C	0.35 (±0.0)	0.34 (±0.02)	-1.22 (±0.12)	-0.89 (±0.17)	1.55 (±0.17)	1.17 (±0.13)
P5	Right Foot	A	0.41 (±0.01)	0.33 (±0.08)	-1.05 (±0.23)	-0.7 (±0.09)	1.34 (±0.06)	0.99 (±0.08)
		B	0.34 (±0.02)	0.33 (±0.01)	-0.88 (±0.27)	-0.87 (±0.14)	1.29 (±0.23)	1.15 (±0.16)
		C	0.33 (±0.04)	0.31 (±0.01)	-0.88 (±0.17)	-0.71 (±0.11)	1.22 (±0.2)	0.83 (±0.15)
	Left Foot	A	0.36 (±0.02)	0.33 (±0.01)	-1.03 (±0.2)	-0.75 (±0.08)	1.2 (±0.23)	0.86 (±0.11)
		B	0.3 (±0.01)	0.32 (±0.02)	-0.84 (±0.07)	-0.92 (±0.14)	1.0 (±0.12)	1.13 (±0.14)
		C	0.3 (±0.02)	0.29 (±0.01)	-0.82 (±0.13)	-0.68 (±0.07)	1.18 (±0.26)	0.84 (±0.06)
P6	Right Foot	A	0.35 (±0.01)	0.29 (±0.01)	-1.12 (±0.06)	-0.82 (±0.04)	1.28 (±0.11)	0.93 (±0.06)
		B	0.3 (±0.01)	0.38 (±0.01)	-0.74 (±0.09)	-0.86 (±0.1)	0.89 (±0.08)	1.0 (±0.11)
		C	0.3 (±0.01)	0.3 (±0.02)	-0.97 (±0.06)	-0.78 (±0.08)	1.12 (±0.05)	0.9 (±0.09)
	Left Foot	A	0.37 (±0.02)	0.3 (±0.02)	-0.98 (±0.08)	-0.75 (±0.09)	1.23 (±0.05)	0.81 (±0.11)
		B	0.3 (±0.02)	0.37 (±0.03)	-0.78 (±0.09)	-0.91 (±0.1)	0.85 (±0.1)	1.0 (±0.11)
		C	0.3 (±0.02)	0.29 (±0.01)	-0.79 (±0.13)	-0.66 (±0.03)	0.95 (±0.12)	0.75 (±0.06)
P7	Right Foot	A	0.28 (±0.01)	0.27 (±0.02)	-0.57 (±0.09)	-0.55 (±0.11)	0.8 (±0.07)	0.76 (±0.16)
		B	0.33 (±0.02)	0.32 (±0.01)	-0.83 (±0.08)	-0.93 (±0.07)	1.04 (±0.3)	1.37 (±0.11)
		C	0.25 (±0.01)	0.28 (±0.01)	-0.71 (±0.08)	-0.65 (±0.05)	0.86 (±0.11)	0.81 (±0.06)
	Left Foot	A	0.22 (±0.01)	0.29 (±0.0)	-0.56 (±0.05)	-0.6 (±0.03)	0.72 (±0.15)	0.88 (±0.04)

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Participant	Limb	Session	Max Position (Z-axis)		Min Velocity (Z-axis)		Max Velocity (Z-axis)	
			Pre	Post	Pre	Post	Pre	Post
		B	0.4 (±0.03)	0.37 (±0.01)	-1.05 (±0.09)	-0.98 (±0.05)	1.45 (±0.09)	1.3 (±0.09)
		C	0.26 (±0.01)	0.22 (±0.01)	-0.73 (±0.1)	-0.63 (±0.02)	0.93 (±0.09)	0.87 (±0.04)
P8	Right Foot	A	0.26 (±0.01)	0.23 (±0.01)	-0.83 (±0.07)	-0.62 (±0.07)	0.96 (±0.04)	0.7 (±0.07)
		B	0.24 (±0.01)	0.25 (±0.01)	-0.59 (±0.05)	-0.68 (±0.09)	0.79 (±0.06)	0.86 (±0.08)
		C	0.25 (±0.01)	0.22 (±0.0)	-0.73 (±0.03)	-0.67 (±0.03)	0.97 (±0.11)	0.75 (±0.04)
	Left Foot	A	0.23 (±0.03)	0.21 (±0.01)	-0.68 (±0.22)	-0.48 (±0.08)	0.79 (±0.17)	0.56 (±0.03)
		B	0.22 (±0.0)	0.21 (±0.01)	-0.63 (±0.07)	-0.63 (±0.14)	0.8 (±0.04)	0.73 (±0.04)
		C	0.24 (±0.01)	0.24 (±0.01)	-0.73 (±0.11)	-0.69 (±0.05)	0.95 (±0.07)	0.79 (±0.06)

Table 22: Mean ML and AP COM displacement (± standard deviation) recorded for each healthy participant during pre- and post-VRMT assessments of the activity of arising from a chair

Activity of Arising From Chair (2)					
Participant	Session	ML COM Displacement		AP COM Displacement	
		Pre	Post	Pre	Post
P1	A	0.03 (±0.01)	0.02 (±0.01)	0.27 (±0.01)	0.26 (±0.01)
	B	0.02 (±0.01)	0.01 (±0.0)	0.23 (±0.01)	0.25 (±0.01)
	C	0.02 (±0.01)	0.01 (±0.0)	0.22 (±0.02)	0.24 (±0.01)
P2	A	0.06 (±0.03)	0.03 (±0.02)	0.23 (±0.1)	0.3 (±0.01)
	B	0.02 (±0.01)	0.02 (±0.01)	0.29 (±0.02)	0.27 (±0.01)
	C	0.04 (±0.01)	0.04 (±0.01)	0.22 (±0.01)	0.22 (±0.01)
P3	A	0.05 (±0.01)	0.01 (±0.01)	0.3 (±0.03)	0.3 (±0.02)
	B	0.01 (±0.01)	0.03 (±0.01)	0.31 (±0.01)	0.31 (±0.01)
	C	0.03 (±0.01)	0.02 (±0.01)	0.34 (±0.03)	0.32 (±0.03)
P4	A	0.04 (±0.01)	0.04 (±0.01)	0.3 (±0.02)	0.29 (±0.01)
	B	0.03 (±0.01)	0.04 (±0.0)	0.3 (±0.01)	0.28 (±0.01)

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Participant	Session	ML COM Displacement		AP COM Displacement	
		Pre	Post	Pre	Post
	C	0.1 (±0.01)	0.02 (±0.01)	0.24 (±0.02)	0.26 (±0.01)
P5	A	0.02 (±0.01)	0.02 (±0.01)	0.34 (±0.05)	0.32 (±0.02)
	B	0.03 (±0.01)	0.04 (±0.03)	0.3 (±0.02)	0.3 (±0.03)
	C	0.08 (±0.01)	0.02 (±0.02)	0.35 (±0.08)	0.3 (±0.01)
P6	A	0.02 (±0.01)	0.03 (±0.0)	0.34 (±0.02)	0.33 (±0.0)
	B	0.03 (±0.02)	0.01 (±0.01)	0.29 (±0.02)	0.3 (±0.02)
	C	0.05 (±0.01)	0.04 (±0.01)	0.26 (±0.01)	0.28 (±0.01)
P7	A	0.02 (±0.03)	0.06 (±0.01)	0.35 (±0.01)	0.33 (±0.01)
	B	0.05 (±0.01)	0.04 (±0.01)	0.26 (±0.01)	0.28 (±0.01)
	C	0.04 (±0.01)	0.02 (±0.0)	0.31 (±0.02)	0.3 (±0.01)
P8	A	0.05 (±0.01)	0.06 (±0.01)	0.28 (±0.01)	0.26 (±0.01)
	B	0.05 (±0.01)	0.02 (±0.01)	0.28 (±0.01)	0.24 (±0.01)
	C	0.06 (±0.01)	0.04 (±0.01)	0.33 (±0.01)	0.31 (±0.01)

Table 23: Mean hand position amplitude (± standard deviation), recorded for each healthy participant during pre- and post-VRMT assessments of the activity of extending the arms forward

Activity of Extending Arms Forward (3.1)								
Participant	Limb	Session	Position Amplitude (X-axis)		Position Amplitude (Y-axis)		Position Amplitude (Z-axis)	
			Pre	Post	Pre	Post	Pre	Post
P1	Right Hand	A	0.018	0.003	0.002	0.002	0.001	0.012
		B	0.001	0.001	0.0	0.0	0.001	0.001
		C	0.001	0.001	0.0	0.0	0.001	0.001
	Left Hand	A	0.018	0.003	0.002	0.002	0.002	0.012
		B	0.001	0.001	0.0	0.0	0.001	0.001
		C	0.001	0.001	0.0	0.0	0.001	0.001

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Participant	Limb	Session	Position Amplitude (X-axis)		Position Amplitude (Y-axis)		Position Amplitude (Z-axis)	
			Pre	Post	Pre	Post	Pre	Post
P2	Right Hand	A	0.001	0.017	0.002	0.014	0.001	0.002
		B	0.001	0.006	0.001	0.004	0.001	0.001
		C	0.002	0.009	0.002	0.004	0.001	0.001
	Left Hand	A	0.001	0.017	0.002	0.014	0.001	0.002
		B	0.001	0.007	0.0	0.004	0.001	0.001
		C	0.008	0.008	0.004	0.004	0.002	0.002
P3	Right Hand	A	0.01	0.009	0.002	0.001	0.001	0.001
		B	0.021	0.008	0.003	0.005	0.001	0.001
		C	0.009	0.005	0.002	0.003	0.001	0.002
	Left Hand	A	0.011	0.009	0.003	0.002	0.001	0.002
		B	0.019	0.008	0.003	0.005	0.001	0.002
		C	0.009	0.004	0.002	0.003	0.002	0.002
P4	Right Hand	A	0.007	0.009	0.006	0.006	0.002	0.002
		B	0.015	0.017	0.008	0.005	0.003	0.002
		C	0.022	0.003	0.01	0.004	0.004	0.002
	Left Hand	A	0.007	0.009	0.005	0.006	0.001	0.001
		B	0.015	0.017	0.008	0.005	0.002	0.002
		C	0.025	0.002	0.011	0.005	0.002	0.001
P5	Right Hand	A	0.005	0.007	0.003	0.003	0.005	0.006
		B	0.004	0.009	0.004	0.004	0.003	0.005
		C	0.005	0.012	0.002	0.003	0.003	0.002
	Left Hand	A	0.007	0.008	0.002	0.003	0.004	0.004
		B	0.004	0.011	0.003	0.004	0.003	0.005
		C	0.006	0.012	0.003	0.002	0.002	0.002
P6	Right Hand	A	0.007	0.012	0.003	0.002	0.001	0.001

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Participant	Limb	Session	Position Amplitude (X-axis)		Position Amplitude (Y-axis)		Position Amplitude (Z-axis)	
			Pre	Post	Pre	Post	Pre	Post
		B	0.003	0.012	0.002	0.003	0.002	0.002
		C	0.004	0.001	0.004	0.003	0.001	0.001
	Left Hand	A	0.007	0.012	0.003	0.002	0.001	0.001
		B	0.003	0.012	0.002	0.003	0.001	0.002
		C	0.004	0.002	0.004	0.003	0.002	0.001
P7	Right Hand	A	0.001	0.005	0.002	0.005	0.001	0.001
		B	0.034	0.012	0.009	0.004	0.002	0.003
		C	0.004	0.022	0.006	0.003	0.002	0.002
	Left Hand	A	0.002	0.004	0.001	0.005	0.001	0.001
		B	0.035	0.012	0.009	0.003	0.002	0.002
		C	0.004	0.021	0.006	0.003	0.002	0.001
P8	Right Hand	A	0.011	0.001	0.004	0.002	0.001	0.001
		B	0.002	0.001	0.002	0.001	0.001	0.001
		C	0.002	0.002	0.001	0.002	0.001	0.001
	Left Hand	A	0.012	0.002	0.005	0.002	0.001	0.001
		B	0.002	0.001	0.002	0.002	0.001	0.001
		C	0.002	0.002	0.001	0.002	0.001	0.001

Table 24: Mean hand position amplitude and mean minimum and maximum hand velocity (± standard deviation), recorded for each healthy participant during pre- and post-VRMT of the nose-touching activity

Activity of Touching The Nose (3.2)								
Participant	Limb	Session	Position Amplitude (Z-axis)		Min Velocity (Y-axis)		Max Velocity (Y-axis)	
			Pre	Post	Pre	Post	Pre	Post
P1	Right Hand	A	.002 (±.002)	.001 (±.001)	-0.17 (±0.04)	-0.15 (±0.03)	0.15 (±0.02)	0.13 (±0.02)

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Participant	Limb	Session	Position Amplitude (Z-axis)		Min Velocity (Y-axis)		Max Velocity (Y-axis)	
			Pre	Post	Pre	Post	Pre	Post
		B	.002 (±.001)	.001 (±.001)	-0.27 (±0.04)	-0.19 (±0.04)	0.21 (±0.03)	0.18 (±0.03)
		C	.001 (±.001)	.001 (±.001)	-0.17 (±0.02)	-0.13 (±0.03)	0.16 (±0.03)	0.14 (±0.02)
	Left Hand	A	.002 (±.002)	.001 (±.001)	-0.19 (±0.03)	-0.09 (±0.02)	0.14 (±0.03)	0.1 (±0.02)
		B	.001 (±.001)	.001 (±.001)	-0.23 (±0.02)	-0.17 (±0.05)	0.18 (±0.04)	0.15 (±0.03)
		C	.001 (±.001)	.001 (±.001)	-0.21 (±0.03)	-0.15 (±0.03)	0.16 (±0.03)	0.14 (±0.02)
P2	Right Hand	A	.002 (±.001)	.001 (±0.0)	-0.18 (±0.03)	-0.11 (±0.02)	0.17 (±0.04)	0.12 (±0.03)
		B	.004 (±.001)	.001 (±.001)	-0.33 (±0.03)	-0.12 (±0.04)	0.35 (±0.09)	0.15 (±0.03)
		C	.002 (±.001)	.002 (±.001)	-0.18 (±0.03)	-0.19 (±0.05)	0.23 (±0.04)	0.21 (±0.06)
	Left Hand	A	.003 (±.001)	.002 (±.001)	-0.22 (±0.04)	-0.14 (±0.03)	0.24 (±0.06)	0.15 (±0.03)
		B	.002 (±.002)	.001 (±.001)	-0.28 (±0.05)	-0.15 (±0.02)	0.36 (±0.08)	0.19 (±0.03)
		C	.001 (±.001)	.002 (±.002)	-0.19 (±0.06)	-0.23 (±0.05)	0.19 (±0.05)	0.25 (±0.05)
P3	Right Hand	A	.001 (±.001)	.007 (±.014)	-0.11 (±0.03)	-0.1 (±0.01)	0.12 (±0.02)	0.11 (±0.03)
		B	.006 (±.013)	.001 (±.001)	-0.11 (±0.01)	-0.12 (±0.04)	0.13 (±0.03)	0.15 (±0.03)
		C	.001 (±.001)	.001 (±.001)	-0.12 (±0.02)	-0.11 (±0.02)	0.13 (±0.04)	0.14 (±0.03)
	Left Hand	A	.001 (±.001)	.001 (±.001)	-0.1 (±0.03)	-0.11 (±0.02)	0.13 (±0.02)	0.14 (±0.03)
		B	.002 (±.002)	.002 (±.001)	-0.11 (±0.03)	-0.14 (±0.02)	0.12 (±0.04)	0.18 (±0.03)
		C	.002 (±.002)	.001 (±.002)	-0.14 (±0.03)	-0.14 (±0.03)	0.2 (±0.04)	0.16 (±0.04)
P4	Right Hand	A	.001 (±.001)	.007 (±.016)	-0.09 (±0.02)	-0.1 (±0.02)	0.09 (±0.03)	0.09 (±0.02)
		B	.002 (±.001)	.001 (±.001)	-0.08 (±0.01)	-0.08 (±0.01)	0.08 (±0.02)	0.08 (±0.01)
		C	.001 (±.001)	.003 (±.007)	-0.08 (±0.02)	-0.11 (±0.02)	0.11 (±0.03)	0.13 (±0.02)
	Left Hand	A	.001 (±0.0)	.008 (±.016)	-0.09 (±0.02)	-0.11 (±0.03)	0.11 (±0.02)	0.11 (±0.03)
		B	.001 (±.001)	.001 (±0.0)	-0.11 (±0.03)	-0.1 (±0.01)	0.13 (±0.03)	0.1 (±0.01)
		C	.001 (±.001)	.002 (±.002)	-0.13 (±0.03)	-0.13 (±0.04)	0.13 (±0.04)	0.13 (±0.03)
P5	Right Hand	A	.003 (±.003)	.003 (±.008)	-0.27 (±0.05)	-0.18 (±0.03)	0.29 (±0.08)	0.23 (±0.04)
		B	.004 (±.002)	.002 (±.002)	-0.27 (±0.04)	-0.2 (±0.06)	0.3 (±0.04)	0.28 (±0.08)

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Participant	Limb	Session	Position Amplitude (Z-axis)		Min Velocity (Y-axis)		Max Velocity (Y-axis)	
			Pre	Post	Pre	Post	Pre	Post
		C	.002 (±.002)	.003 (±.008)	-0.19 (±0.02)	-0.19 (±0.03)	0.29 (±0.05)	0.23 (±0.03)
	Left Hand	A	.005 (±.002)	.002 (±.002)	-0.28 (±0.06)	-0.23 (±0.05)	0.37 (±0.1)	0.25 (±0.05)
		B	.002 (±.002)	.003 (±.002)	-0.25 (±0.05)	-0.22 (±0.07)	0.25 (±0.06)	0.26 (±0.06)
		C	.003 (±.001)	.003 (±.002)	-0.23 (±0.04)	-0.19 (±0.05)	0.3 (±0.03)	0.25 (±0.05)
P6	Right Hand	A	.001 (±.001)	.001 (±.001)	-0.09 (±0.02)	-0.04 (±0.01)	0.1 (±0.03)	0.05 (±0.02)
		B	.001 (±.001)	.001 (±.001)	-0.16 (±0.03)	-0.07 (±0.01)	0.18 (±0.03)	0.09 (±0.03)
		C	.003 (±.002)	.002 (±.003)	-0.11 (±0.02)	-0.07 (±0.01)	0.09 (±0.03)	0.06 (±0.01)
	Left Hand	A	.001 (±.001)	.001 (±.001)	-0.11 (±0.04)	-0.05 (±0.02)	0.13 (±0.02)	0.06 (±0.03)
		B	.002 (±.001)	.001 (±.001)	-0.2 (±0.06)	-0.09 (±0.03)	0.27 (±0.07)	0.13 (±0.03)
		C	.003 (±.004)	.002 (±.004)	-0.12 (±0.03)	-0.08 (±0.02)	0.15 (±0.03)	0.07 (±0.02)
P7	Right Hand	A	.001 (±.001)	.002 (±.001)	-0.15 (±0.03)	-0.21 (±0.05)	0.2 (±0.02)	0.23 (±0.03)
		B	.001 (±.001)	.001 (±.002)	-0.09 (±0.03)	-0.13 (±0.02)	0.15 (±0.02)	0.19 (±0.06)
		C	.001 (±.001)	.001 (±.001)	-0.12 (±0.04)	-0.12 (±0.03)	0.14 (±0.06)	0.16 (±0.04)
	Left Hand	A	.003 (±.002)	.003 (±.002)	-0.27 (±0.02)	-0.19 (±0.04)	0.28 (±0.06)	0.24 (±0.07)
		B	.001 (±.001)	.002 (±.001)	-0.14 (±0.04)	-0.17 (±0.03)	0.2 (±0.06)	0.19 (±0.06)
		C	.002 (±.002)	.002 (±.001)	-0.14 (±0.03)	-0.18 (±0.02)	0.19 (±0.05)	0.21 (±0.05)
P8	Right Hand	A	.001 (±0.0)	.001 (±0.0)	-0.07 (±0.02)	-0.04 (±0.02)	0.09 (±0.01)	0.06 (±0.01)
		B	.004 (±.009)	0.0 (±0.0)	-0.04 (±0.01)	-0.05 (±0.01)	0.05 (±0.01)	0.05 (±0.01)
		C	.001 (±0.0)	.002 (±.005)	-0.06 (±0.01)	-0.09 (±0.02)	0.07 (±0.02)	0.11 (±0.02)
	Left Hand	A	.001 (±.001)	.001 (±.001)	-0.07 (±0.02)	-0.04 (±0.01)	0.07 (±0.01)	0.05 (±0.01)
		B	.004 (±.01)	.001 (±.001)	-0.05 (±0.01)	-0.05 (±0.01)	0.04 (±0.01)	0.07 (±0.02)
		C	.006 (±.013)	.001 (±.001)	-0.06 (±0.01)	-0.06 (±0.01)	0.07 (±0.02)	0.07 (±0.02)

B Usability and Imagery Assessments

Table 25 shows the mean and maximum scores, ranging from 0 to 6, for each IPQ subscale – General Presence, Spatial Presence, Involvement and Experienced Realism –, per participant across the three sessions. Similarly, Table 26 presents the mean and maximum scores, from 1 to 7, for each IMI subscale – Interest/Enjoyment, Perceived Competence, Effort/Importance, Pressure/Tension, and Value/Usefulness –, per participant across every session. Lastly, Table 27 provides the scores, ranging from 1 to 5, for the visual and kinesthetic components of each activity, per participant, across sessions B and C.

Table 25: Mean (± standard deviation) and maximum scores, ranging from 0 to 6, for each IPQ's subscale by each healthy participant across sessions A, B, and C

Igroup Presence Questionnaire (IPQ)									
Participant	**Session**	**General Presence**		**Spatial Presence**		**Involvement**		**Experienced Realism**	
		Mean	**Max**	**Mean**	**Max**	**Mean**	**Max**	**Mean**	**Max**
P1	A	6.0 (±0.0)	6	4.8 (±1.6)	6	5.0 (±0.0)	5	3.5 (±1.7)	5
	B	5.0 (±0.0)	5	4.6 (±1.7)	6	4.8 (±0.5)	5	3.5 (±1.0)	4
	C	6.0 (±0.0)	6	4.8 (±1.3)	6	5.3 (±0.5)	6	3.0 (±2.0)	4
P2	A	5.0 (±0.0)	5	4.4 (±2.5)	6	4.3 (±1.0)	5	3.3 (±2.2)	5
	B	6.0 (±0.0)	6	4.0 (±2.3)	6	4.0 (±0.0)	4	3.0 (±1.4)	4
	C	5.0 (±0.0)	5	5.0 (±1.0)	6	4.0 (±0.0)	4	3.0 (±2.0)	4
P3	A	5.0 (±0.0)	5	4.8 (±0.4)	5	4.0 (±0.8)	5	2.5 (±1.3)	4
	B	6.0 (±0.0)	6	5.6 (±0.5)	6	4.0 (±0.8)	5	3.5 (±0.6)	4
	C	5.0 (±0.0)	5	4.8 (±0.4)	5	5.5 (±0.6)	6	2.8 (±1.0)	4
P4	A	4.0 (±0.0)	4	4.8 (±0.8)	6	3.3 (±0.5)	4	3.3 (±1.0)	4
	B	4.0 (±0.0)	4	4.2 (±1.1)	6	2.8 (±0.5)	3	2.5 (±1.0)	3
	C	5.0 (±0.0)	5	4.6 (±0.5)	5	5.0 (±0.5)	5	2.5 (±1.0)	3
P5	A	4.0 (±0.0)	4	4.2 (±1.5)	6	4.0 (±0.0)	4	2.8 (±1.3)	4
	B	4.0 (±0.0)	4	4.2 (±2.0)	6	3.0 (±0.0)	3	2.3 (±1.7)	4
	C	5.0 (±0.0)	5	5.2 (±0.4)	6	2.8 (±0.5)	3	2.3 (±2.1)	5

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Participant	Session	General Presence		Spatial Presence		Involvement		Experienced Realism	
		Mean	**Max**	**Mean**	**Max**	**Mean**	**Max**	**Mean**	**Max**
P6	A	4.0 (±0.0)	4	3.6 (±0.5)	4	4.3 (±0.5)	5	3.3 (±1.0)	4
	B	4.0 (±0.0)	4	3.8 (±0.4)	4	4.0 (±0.0)	4	3.0 (±1.4)	4
	C	5.0 (±0.0)	5	4.6 (±0.5)	5	4.5 (±0.6)	5	3.3 (±1.0)	4
P7	A	4.0 (±0.0)	4	4.0 (±0.7)	5	3.3 (±1.3)	5	3.0 (±1.4)	4
	B	4.0 (±0.0)	4	3.6 (±0.5)	4	3.5 (±0.6)	4	3.3 (±1.0)	4
	C	5.0 (±0.0)	5	4.8 (±0.8)	6	3.8 (±1.0)	5	3.5 (±1.3)	5
P8	A	6.0 (±0.0)	6	5.4 (±1.3)	6	4.0 (±0.8)	5	3.0 (±0.8)	4
	B	6.0 (±0.0)	6	4.8 (±2.2)	6	5.0 (±0.0)	5	3.5 (±1.0)	4
	C	6.0 (±0.0)	6	6.0 (±0.0)	6	3.3 (±0.5)	4	4.0 (±0.8)	5

Table 26: Mean (± standard deviation) and maximum scores, ranging from 1 to 7, for each IMI's subscale by each healthy participant, across sessions A, B, and C. The subscales evaluated include "Interest/Enjoyment" (INT/ENJ), "Perceived Competence" (COMP), "Effort/Importance" (EFF/IMP), "Pressure/Tension" (PRE/TEN) and "Value/Usefulness" (VALUE)

		Intrinsic Motivation Inventory (IMI)									
Participant	Session	INT/ENJ		COMP		EFF/IMP		PRE/TEN		VALUE	
		Mean	**Max**	**Mean**	**Max**	**Mean**	**Max**	**Mean**	**Max**	**Mean**	**Max**
P1	A	6.3 (±0.8)	7	6.2 (±0.4)	7	7.0 (±0.0)	7	1.2 (±0.4)	2	5.4 (±1.5)	7
	B	5.4 (±1.8)	7	6.2 (±1.1)	7	7.0 (±0.0)	7	1.6 (±1.3)	4	6.0 (±0.6)	7
	C	6.6 (±0.8)	7	6.2 (±0.4)	7	6.6 (±0.5)	7	1.2 (±0.4)	2	5.1 (±1.5)	7
P2	A	4.0 (±1.4)	5	4.8 (±0.4)	5	5.6 (±1.1)	7	1.0 (±0.0)	1	5.1 (±1.7)	7
	B	4.3 (±1.0)	6	5.8 (±0.4)	6	7.0 (±0.0)	7	1.0 (±0.0)	1	5.0 (±1.2)	6
	C	4.7 (±1.6)	7	5.8 (±0.8)	7	6.4 (±0.5)	7	1.6 (±1.3)	4	5.0 (±2.2)	7
P3	A	5.0 (±1.2)	6	4.8 (±0.8)	6	6.4 (±0.9)	7	2.4 (±1.5)	4	6.6 (±0.5)	7
	B	5.9 (±1.1)	7	6.6 (±0.5)	7	6.6 (±0.6)	7	2.4 (±1.1)	4	7.0 (±0.0)	7
	C	5.0 (±0.8)	6	5.6 (±0.5)	6	6.2 (±0.4)	7	3.4 (±1.5)	5	6.3 (±0.8)	7

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Participant	Session	INT/ENJ		COMP		EFF/IMP		PRE/TEN		VALUE	
		Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max
P4	A	5.7 (±1.1)	7	5.0 (±0.7)	6	6.2 (±0.8)	7	1.0 (±0.0)	1	5.0 (±1.9)	7
	B	6.4 (±0.8)	7	6.0 (±0.0)	6	6.6 (±0.5)	7	1.2 (±0.4)	2	5.3 (±1.4)	7
	C	5.7 (±1.8)	7	5.2 (±0.4)	6	6.8 (±0.4)	7	3.0 (±1.4)	4	4.9 (±1.2)	6
P5	A	4.7 (±1.4)	6	6.2 (±0.4)	7	6.2 (±0.8)	7	1.0 (±0.0)	1	5.7 (±1.9)	7
	B	4.9 (±1.7)	7	6.2 (±0.4)	7	6.2 (±1.3)	7	1.2 (±0.4)	2	5.0 (±2.2)	7
	C	5.0 (±1.7)	7	6.0 (±0.0)	6	6.0 (±1.7)	7	1.0 (±0.0)	1	5.0 (±2.1)	7
P6	A	6.7 (±0.8)	7	5.4 (±1.1)	7	6.0 (±0.0)	6	1.0 (±0.0)	1	6.9 (±0.4)	7
	B	6.4 (±0.8)	7	4.6 (±0.9)	6	5.8 (±0.4)	6	1.2 (±0.4)	2	7.0 (±0.0)	7
	C	6.7 (±0.8)	7	6.4 (±0.5)	7	5.8 (±0.4)	6	1.6 (±0.9)	3	7.0 (±0.0)	7
P7	A	5.0 (±1.2)	6	6.2 (±0.8)	7	5.4 (±1.9)	7	1.2 (±0.4)	2	4.1 (±0.9)	5
	B	5.0 (±1.2)	6	5.2 (±0.8)	6	5.4 (±0.5)	6	2.2 (±1.1)	4	4.6 (±0.8)	6
	C	6.1 (±0.4)	7	6.0 (±0.0)	6	5.8 (±0.4)	6	1.8 (±1.3)	4	6.4 (±0.5)	7
P8	A	4.6 (±1.6)	7	7.0 (±0.0)	7	7.0 (±0.0)	7	1.0 (±0.0)	1	4.6 (±2.4)	7
	B	6.9 (±0.4)	7	7.0 (±0.0)	7	7.0 (±0.0)	7	1.0 (±0.0)	1	6.0 (±1.0)	7
	C	6.7 (±0.8)	7	7.0 (±0.0)	7	7.0 (±0.0)	7	2.2 (±1.1)	4	6.4 (±0.5)	7

Table 27: Scores ranging from 1 to 5 for each KVIQ's subscale by each healthy participant, across sessions B and C. The subscales include "Activity 1 Visual" (1V), "Activity 1 Kinesthetic" (1K), "Activity 2 Visual" (2V), "Activity 2 Kinesthetic" (2K), "Activity 3.1 Visual" (3.1V), "Activity 3.1 Kinesthetic" (3.1K) and "Activity 3.2 Visual" (3.2V), "Activity 3.2 Kinesthetic" (3.2K)

Kinesthetic and Visual Imagery Questionnaire (KVIQ)									
Participant	Session	1V	1K	2V	2K	3.1V	3.1K	3.2V	3.2K
P1	B	4	2	4	1	5	1	3	3
	C	4	3	4	3	5	1	3	1
P2	B	3	4	3	4	4	2	5	3
	C	3	3	2	4	3	2	4	2

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Participant	Session	1V	1K	2V	2K	3.1V	3.1K	3.2V	3.2K
P3	B	1	4	1	5	1	5	2	4
	C	2	4	2	2	4	4	4	3
P4	B	3	4	5	5	5	5	4	4
	C	4	2	2	1	5	3	4	3
P5	B	5	5	5	5	5	4	4	4
	C	5	5	5	4	5	5	4	4
P6	B	5	1	2	5	5	1	5	1
	C	5	1	2	4	5	1	5	1
P7	B	4	2	3	1	4	4	4	3
	C	5	3	4	2	5	3	4	3
P8	B	5	5	3	5	4	5	5	5
	C	5	4	5	5	3	3	4	4