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UNIVERSITÉ DE LORRAINE

École doctorale IAEM Lorraine

# Development of a new methodology for quantitative analysis of rigidity in Parkinson's disease

## THÈSE

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**(Automatique, Traitement du signal et des images, Génie informatique)**

par

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CAMILLE MARQUES ALVES

# DEVELOPMENT OF A NEW METHODOLOGY FOR QUANTITATIVE ANALYSIS OF RIGIDITY IN PARKINSON'S DISEASE

Thesis developed under a cotutelle programme between the Federal University of Uberlândia (UFU) and the University of Lorraine (UL). The thesis was submitted to both institutions as part of the requirements for obtaining the degree of PhD.

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2024

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*"Rien dans la vie n'est à craindre, tout doit être compris. C'est maintenant le moment de comprendre davantage, afin de craindre moins."*

Marie Curie

ABSTRACT

**Introduction:** Parkinson's disease (PD) is a chronic neurodegenerative disorder that predominantly impairs motor function and affects millions of people worldwide. Rigidity is one of the main symptoms of PD and is present in around 89% of patients. This rigidity makes it difficult to move limbs, affecting the quality of life of these people. The assessment of rigidity is of great importance in clinical practice to monitor the rehabilitation process. Traditional methods for assessing rigidity, such as the Movement Disorder Society - Unified Parkinson's Disease Rating Scale (MDS-UPDRS) have limitations, leading to the exploration of novel approaches. However, there are still no standardised quantitative measures for this assessment. Therefore, there is great interest in implementing new methods that can adequately quantify this disorder. Methods that use surface Electromyography (sEMG) and joint amplitude sensors are very promising. **Objective:** The general objective of this research is to propose and evaluate a method for the quantitative assessment of wrist rigidity in patients with PD, using inertial sensors and sEMG. **Methods:** Initially, a literature review was conducted to identify the most suitable and consistent sensors for this purpose. Based on such review, an experimental protocol was developed that incorporates a variety of movements, including active, slow passive, and fast passive stretches, to capture different aspects of rigidity. The protocol also includes participant interaction with the RehaBEElitation, a Serious Game (SG) that aims to provide an engaging and accessible approach to assessing rigidity. For the study, 15 people with PD were evaluated, in the ON and OFF states of the medication and 15 healthy people, matched in sex and age. **Results and Discussion:** The main findings of this research highlight speed as a crucial determinant in the manifestation of rigidity in individuals with PD. It was observed that fast passive movements were the most effective in causing and highlighting rigidity, while slow passive movements showed less significant results. Furthermore, phase 4 of RehaBEElitation emerged as a highlight, proving to be crucial for identifying and evaluating rigidity. Features estimated from signals of accelerometers and gyroscopes were particularly notable, demonstrating strong correlation with MDS-UPDRS assessment, and offering valuable insights into the movement dynamics. On the other hand, sEMG proved to be more effective, in detecting rigidity, when movements were ordered, highlighting the importance of muscular coordination in assessing rigidity when using this method. These findings highlight the complexity of rigidity in PD and the need for multifaceted and sensitive approaches to its assessment and understanding. **Conclusion:** This study successfully developed and implemented a new method to quantify wrist rigidity in individuals with PD. The results demonstrated strong correlations between sensor data and clinical assessments, indicating the effectiveness of the developed method in accurately quantifying wrist rigidity in different disease states. These findings underscore the potential of the proposed approach to improve the clinical management of PD, offering valuable insights into motor symptoms and paving the way for personalized interventions tailored to address rigidity and improve quality of life for PD patients.

**Keywords:** Parkinson's disease; rigidity; objective evaluation; inertial sensors; electromyography; serious game.

RESUMÉ

## Introduction

La maladie de Parkinson (MP) est une maladie neurodégénérative chronique résultant de la perte progressive des neurones dopaminergiques de la substantia nigra du mésencéphale. Ces neurones sont normalement responsables de la production et du stockage de la dopamine, un neurotransmetteur crucial pour la régulation des mouvements. Le manque de dopamine affecte principalement la fonction motrice, entraînant des troubles du mouvement tels que la bradykinésie (lenteur des mouvements), le tremblement de repos, la rigidité musculaire et l'instabilité posturale.

En plus des symptômes moteurs, la MP présente également des symptômes non moteurs tels que les troubles du sommeil, la constipation, la douleur, l'hypotension orthostatique, les paresthésies, les troubles de l'érection, la dépression, la somnolence, l'anosmie (perte de l'odorat), les mouvements oculaires rapides et les changements de personnalité. Ces symptômes contribuent à l'altération de la qualité de vie et à l'augmentation du handicap chez les personnes atteintes de la maladie.

L'évaluation clinique de la MP repose largement sur l'utilisation de l'échelle MDS-UPDRS (Movement Disorders Society-Unified Parkinson's Disease Rating Scale). Cette échelle évalue les caractéristiques motrices et non motrices du patient en attribuant des scores basés sur l'observation visuelle de l'examinateur, ce qui peut être sujet à la subjectivité et à la dépendance à l'égard de l'expérience de l'examinateur.

Cependant, les avancées technologiques offrent de nouvelles possibilités d'évaluation plus objective du mouvement, en utilisant des dispositifs tels que les Serious Games (SG) intégrant des capteurs inertiels. Ces capteurs, tels que les électromyogrammes (EMG) et les unités de mesure inertielle (IMU), permettent d'obtenir des mesures précises et reproductibles du mouvement. L'intégration de ces technologies dans les jeux sérieux offre un potentiel prometteur dans le domaine de la réadaptation et de l'évaluation du mouvement chez les patients atteints de la maladie de Parkinson. En utilisant ces outils, il est possible d'évaluer de manière objective et reproductible la progression de la maladie et l'efficacité des interventions thérapeutiques, offrant ainsi une approche plus précise et moins subjective.

## Objectifs

L'objectif principal de cette étude était d'investiguer et d'évaluer la gravité de la rigidité chez les personnes diagnostiquées avec la maladie de Parkinson, à la fois avec et sans l'influence de médicaments, et de comparer les résultats à ceux des personnes sans la maladie. Les méthodes suivantes ont été utilisées pour l'évaluation objective de la rigidité

: (i) les signaux EMG et inertiel ; et (ii) un jeu sérieux (SG) développé pour évaluer les signes moteurs de la maladie de Parkinson.

Pour atteindre les objectifs de recherche, les buts suivants ont été définis :

- Effectuer une revue exhaustive de la littérature axée sur l'évaluation de la rigidité du poignet chez les personnes atteintes de la maladie de Parkinson
- Développer une méthode novatrice pour évaluer objectivement la rigidité chez les patients atteints de la maladie de Parkinson
- Établir un protocole de collecte de données impliquant des patients atteints de la maladie de Parkinson (états on" et off" des médicaments) et des individus en bonne santé, facilitant l'analyse comparative des résultats
- Évaluer objectivement la rigidité à travers deux protocoles distincts : (i) en utilisant l'EMG et l'IMU, et (ii) en employant une approche de jeu sérieux (SG)
- Obtenir des informations sur les mécanismes de la rigidité du poignet chez les patients atteints de la maladie de Parkinson grâce à des techniques de collecte de données et de traitement des signaux
- Comparer les résultats obtenus à partir de différents protocoles d'évaluation et déterminer la méthode la plus efficace pour évaluer la rigidité
- Corréler les données expérimentales pour discerner les différentes manifestations de la rigidité et leurs facteurs sous-jacents

**Méthodes**

Initialement, une revue de la littérature approfondie a été menée pour identifier les capteurs les plus adaptés et les plus cohérents pour l'évaluation de la rigidité du poignet chez les personnes atteintes de la maladie de Parkinson (MP). Cette revue a couvert divers aspects de la maladie de Parkinson et de la rigidité, ainsi que des méthodes actuelles d'évaluation, en mettant l'accent sur les signaux électromyographiques (EMG) et les unités de mesure inertielle (IMU).

Sur la base de cette revue, un protocole expérimental a été développé, intégrant une variété de mouvements pour capturer différents aspects de la rigidité. Les mouvements inclus étaient des étirements actifs, passifs lents et passifs rapides. Ce protocole a été conçu pour maximiser la sensibilité et la spécificité de la détection de la rigidité.

Le protocole comprend également l'interaction des participants avec RehaBEElitation, un jeu sérieux conçu pour fournir une approche engageante et accessible pour évaluer la rigidité. Le développement de ce jeu et de l'interface homme-machine associée est détaillé,

avec une validation de son efficacité pour évaluer objectivement la rigidité chez les patients atteints de MP.

Pour l'étude, 15 personnes atteintes de MP ont été évaluées, tant dans l'état ON (sous l'influence de la médication) que dans l'état OFF (sans médication). En parallèle, 15 personnes en bonne santé, appariées selon le sexe et l'âge, ont été incluses comme groupe de contrôle. Cette méthodologie permet de comparer les données entre les patients et les sujets sains, et d'évaluer l'impact de la médication sur la rigidité.

**Résultats et discussion**

Les principales conclusions de cette étude mettent en évidence plusieurs aspects cruciaux liés à la vitesse comme un déterminant essentiel dans la manifestation de la rigidité chez les individus atteints de la maladie de Parkinson. En particulier, il a été observé que les mouvements passifs rapides étaient les plus efficaces pour provoquer et mettre en évidence la rigidité, tandis que les mouvements passifs lents montraient des résultats moins significatifs. Cette observation est en accord avec d'autres études antérieures, qui ont également souligné l'importance de la vitesse dans l'évaluation de la rigidité parkinsonienne.

La phase 4 du programme RehaBEElitation a été identifiée comme un point culminant dans cette étude, se révélant cruciale pour identifier et évaluer la rigidité. Cette phase a permis de capturer des données précises et pertinentes sur la dynamique des mouvements, ce qui a été essentiel pour une évaluation précise. Les caractéristiques estimées à partir des signaux des accéléromètres et des gyroscopes, en particulier, ont démontré une forte corrélation avec l'évaluation de l'échelle MDS-UPDRS (Movement Disorder Society - Unified Parkinson's Disease Rating Scale). Ces dispositifs de mesure inertielle ont offert des perspectives précieuses sur la dynamique des mouvements, permettant une analyse plus fine des variations de la rigidité au cours des différentes phases de mouvement.

En outre, l'électromyographie (EMG) s'est révélée particulièrement efficace pour détecter la rigidité lorsque les mouvements étaient ordonnés. Cela souligne l'importance de la coordination musculaire dans l'évaluation de la rigidité, montrant que des schémas de mouvement spécifiques peuvent améliorer la sensibilité de la détection par EMG. De manière similaire, les accéléromètres et les gyroscopes ont également démontré leur utilité dans ce contexte, en fournissant des données précises sur les mouvements et les variations de vitesse et de direction. Ces capteurs inertiels, lorsqu'ils sont utilisés conjointement avec l'EMG, permettent une évaluation plus complète et multidimensionnelle de la rigidité. Cette découverte suggère que l'intégration de l'EMG, des accéléromètres et des gyroscopes dans des protocoles de mouvement structurés pourrait améliorer la précision des évaluations cliniques de la rigidité, en offrant une vue d'ensemble plus détaillée des aspects moteurs impliqués dans la maladie de Parkinson.

Ces conclusions mettent en lumière la complexité de la rigidité dans la maladie de

Parkinson et la nécessité d'approches multifacettes pour son évaluation et sa compréhension. L'utilisation combinée de technologies avancées, telles que les capteurs inertiels et l'EMG, avec des protocoles de mouvement spécifiques, offre une voie prometteuse pour une évaluation plus précise et objective de la rigidité. En outre, ces résultats soulignent l'importance de personnaliser les approches d'évaluation en fonction des caractéristiques individuelles des patients, afin d'optimiser les stratégies de traitement et d'amélioration de la qualité de vie des personnes atteintes de la maladie de Parkinson.

Enfin, ces avancées technologiques et méthodologiques ouvrent de nouvelles perspectives pour la recherche future. Elles permettent d'explorer plus en profondeur les mécanismes sous-jacents de la rigidité et de développer des interventions thérapeutiques mieux ciblées. L'intégration de ces outils dans la pratique clinique quotidienne pourrait transformer la manière dont la rigidité parkinsonienne est diagnostiquée, évaluée et traitée, offrant ainsi des bénéfices significatifs pour les patients.

**Conclusion**

En conclusion, cette étude a réussi à développer et à mettre en œuvre une nouvelle méthode pour quantifier la rigidité du poignet chez les individus atteints de la maladie de Parkinson. Les résultats ont démontré de fortes corrélations entre les données des capteurs et les évaluations cliniques, indiquant l'efficacité de la méthode développée pour quantifier avec précision la rigidité du poignet dans différents états de la maladie. Ces résultats soulignent le potentiel de l'approche proposée pour améliorer la prise en charge clinique de la MP, offrant des perspectives précieuses sur les symptômes moteurs et ouvrant la voie à des interventions personnalisées visant à traiter la rigidité et à améliorer la qualité de vie des patients atteints de la maladie de Parkinson.

Une des directions futures est l'intégration de données multimodales. Pour une évaluation plus complète et robuste de la rigidité, les recherches futures devraient se concentrer sur la fusion des données provenant de différents capteurs, EMG et IMU. Des techniques avancées de fusion de données, y compris des algorithmes d'apprentissage automatique, pourraient être utilisées pour intégrer ces signaux de manière efficace et extraire des informations significatives.

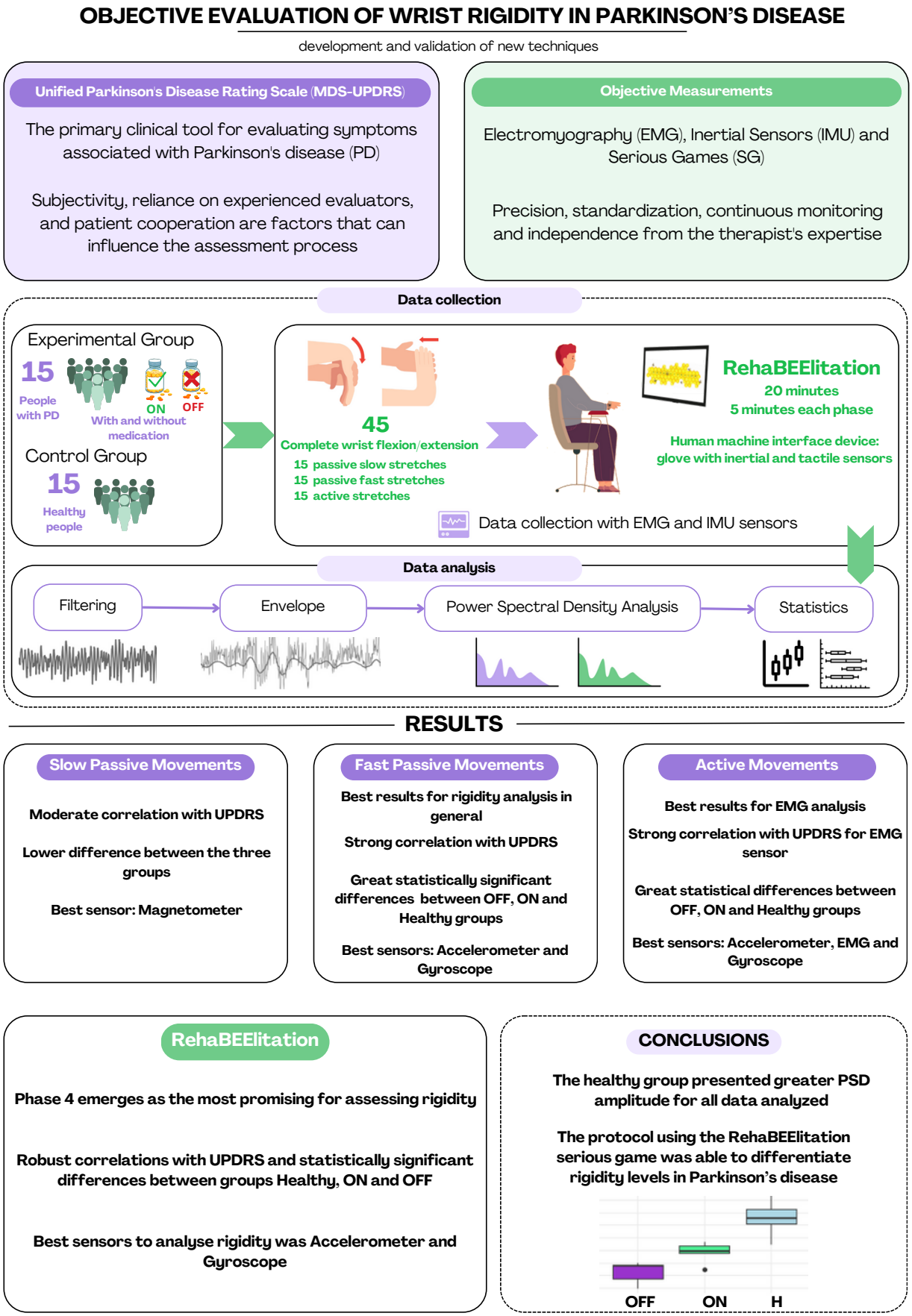
La réalisation d'études longitudinales pour surveiller la rigidité chez les patients atteints de MP sur de longues périodes est également importante. Cela aiderait à comprendre la progression de la maladie et les effets à long terme des traitements sur la rigidité. Une surveillance continue, utilisant des dispositifs portables équipés de capteurs inertiels, pourrait fournir des données précieuses sur la variabilité de la rigidité avec les activités quotidiennes et au fil du temps.

Améliorer l'expérience utilisateur du jeu sérieux RehaBEElitation pourrait également contribuer à un meilleur engagement et à une meilleure adhésion des patients. Incorporer des éléments tels que des niveaux de difficulté adaptatifs, des retours en temps réel et des

objectifs personnalisés rendrait le jeu plus motivant et agréable pour les patients, ce qui pourrait mener à une utilisation plus cohérente et à des données de meilleure qualité.

Les méthodologies développées dans ce travail pourraient être adaptées et appliquées à d'autres affections neurologiques où la rigidité et les symptômes moteurs sont fréquents. Étendre la recherche à des conditions telles que la sclérose en plaques, la paralysie cérébrale ou les accidents vasculaires cérébraux pourrait aider à développer des outils complets pour évaluer et gérer les déficits moteurs dans une population de patients plus large.

En conclusion, bien que cette thèse marque une avancée significative dans l'évaluation de la rigidité dans la MP, elle ouvre également plusieurs possibilités pour de futures recherches et développements. En suivant ces directions, nous pouvons aspirer à créer des outils plus précis, fiables et conviviaux pour surveiller et gérer la rigidité, améliorant ainsi la qualité de vie des personnes atteintes de MP.

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# List of Abbreviations and Acronyms

**CG** Control Group

**DBS** Deep Brain Stimulation

**EG** Experimental Group

**EMD** Empirical Mode Decomposition

**EMG** Electromyography

**HMI** Human Machine Interface

**IMU** Inertial Measurement Unit

**LDR** Light Dependent Resistor

**MDS-UPDRS** Movement Disorder Society - Unified Parkinson's Disease Rating Scale

**MMSE** Mini Mental State Examination

**MVC** Maximum Voluntary Contraction

**OSC** Open Sound Control

**PD** Parkinson's disease

**PSD** Power Spectral Density

**sEMG** surface Electromyography

**SG** Serious Game

**SGs** Serious Games

**SN** Substantia Nigra

**UDP** User Datagram Protocol

**UPDRS** Unified Parkinson's Disease Rating Scale

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# 1

# Introduction

## 1.1 Relevance of the Thesis

Parkinson's disease represents a significant public health challenge, being classified as the second most prevalent neurodegenerative disease in the world, after Alzheimer's disease (91). Its incidence has increased considerably, with rapid growth in terms of prevalence, disability and mortality (from 2.5 million patients in 1990 to 6.1 million in 2016) (41). It is estimated that the prevalence of PD is 0.3% in the general population, increasing to 1% in people over 60 years of age and to 3% in those aged 80 years and over. The incidence rate of PD ranges from 108 to 212 per 100.000 person-years (129). For instance, projections suggest that by 2030, China alone will have an estimated 4.94 million PD patients, comprising half of the global PD population (34). This rapid rise in PD cases imposes significant burdens on society, individuals, and healthcare systems.

In this sense, it is possible to notice an increase in the burden of chronic conditions, such as PD, which reinforces the demand for new therapies and innovative analyses to delay the onset and even alleviate symptoms. This represents a complex challenge for clinicians in terms of optimal management, due to its multiple motor and non-motor manifestations, which evolve over time. Its diagnosis is essentially clinical and depends on the therapists expertise and experience in neurological assessment. Furthermore, motor signs remain the main distinguishing features of the disease and play a crucial role in its diagnosis.

## 1.2 Problem Formulation

This thesis aims to address the problem of identifying and characterizing rigidity patterns using different methodologies. Unlike other cardinal signs in PD that have been well characterized, rigidity remains poorly understood due to the involvement of different patterns observed in clinical neurology (43). Given this inherent heterogeneity, rigidity is considered a complex signal.

The assessment of rigidity in PD plays a crucial role in the clinical diagnosis and in defining the best rehabilitative treatment plan for patients. However, the lack of consensus regarding valid and reliable clinical measures to assess rigidity represents a significant challenge. Currently, the tools most used for this purpose are subjective, that is, they are subject to the therapist's experience, which can result in divergences between assessments carried out by different professionals (8). Consequently, its reliability across examiners and over time remains a controversial issue.

Furthermore, gaining a better understanding of rigidity could lead to individualized treatment approaches and optimization of pharmacogenomic studies for PD. To solve this problem, an experimental protocol was developed to systematically identify and characterize the rigidity of individuals with PD, with and without medication, and also in healthy individuals.

## 1.3 Research Objectives

The primary aim of this study was to investigate and assess the severity of rigidity in individuals diagnosed with PD, both with and without the influence of medication, and compare the findings to those of individuals without the disease.

The following methods were employed for the objective evaluation of rigidity: (i) surface Electromyography (sEMG) and IMU; and (ii) a Serious Game (SG) developed to evaluate the motor signs of PD.

## 1.4 Thesis Objectives

To achieve the research objectives, the following goals have been outlined:

- Conduct a comprehensive literature review focusing on the assessment of wrist rigidity in individuals with PD
- Develop a novel method to objectively evaluate rigidity in PD patients
- Establish a protocol for data collection involving PD patients ("on" and "off" states of medication) and healthy individuals, facilitating comparative analysis of results
- Objectively assess rigidity through two distinct protocols: (i) utilizing sEMG and IMU, and (ii) employing a SG approach
- Obtain insights into the mechanisms of wrist rigidity in PD patients through data collection and signal processing techniques
- Compare the outcomes obtained from different assessment protocols and determine the most effective method for evaluating rigidity

- Correlate experimental data to discern various manifestations of rigidity and their underlying factors

## 1.5 Desired Outcome of the Thesis

It was expected that it would be possible to effectively quantify and analyse wrist rigidity in patients with PD. To achieve this, information from muscles and movement were obtained, which provides direct information about the neuromuscular activity of individuals. The analysis of sEMG and inertial signals would allow for a detailed and reliable assessment of rigidity.

Furthermore, it was expected that the incorporation of a SG could enrich and improve the assessment of wrist rigidity in patients with PD. Data from patients' interaction with the game would be combined with muscular signals captured by the devices, enabling a comprehensive analysis of rigidity.

The use of SG would represent a more engaging, fluid, and attractive alternative compared to conventional rigidity assessment methods. The simplicity and playful nature of the game could increase patient engagement and collaboration, making the assessment process more enjoyable and efficient.

It was expected that, through the application of advanced signal processing techniques, it would be possible to extract relevant features related to rigidity. An expected important result would be the identification of significant associations between these characteristics and clinical assessments of rigidity, as well as the distinction between patient and control groups, highlighting the effectiveness of analysis methods in detecting and quantifying rigidity in patients with PD.

## 1.6 Research Methodology

This study consisted of four stages. Initially, in order to understand the aspects of rigidity in PD, a study was carried out in several scientific databases and academic repositories. This made it possible to understand the main signs and symptoms of the disease, understand the main characteristics of rigidity, and how it is assessed in clinical practice, in addition to understanding which joint is most affected by rigidity. From this, a literature review was carried out on the assessment of wrist rigidity, the joint most affected in individuals with PD. This review provided insights into the latest technologies in this field, and encompassed searches in eight different databases, resulting in the inclusion of 28 pertinent articles.

The second part involved the analysis, choice and development of the methods used to assess wrist rigidity. Therefore, it was defined, based on the literature, that the sEMG and IMU sensors would be used together with a serious game. Furthermore, the experimental

protocol was defined, which consisted of initially performing several movements with the wrist joint while the corresponding signals were recorded. These movements were based on gold standard scales for assessing rigidity. The collection also included the application of the SG RehaBEElitation. The study included 15 PD patients in "on" and "off" medication states, along with 15 healthy individuals.

In the third part, the recorded signals were processed, including filtering, classification, feature extraction, and correlation analysis. The recorded signals from sEMG and IMU sensors were subjected to filtering techniques to remove unwanted noise and artifacts, ensuring high data quality. After signal classification, feature extraction techniques were implemented to identify relevant patterns in the data that could be correlated with rigidity severity.

Finally, a correlation analysis was performed to investigate the relationship between the features recorded from experimental data and the clinical results of rigidity assessment. This procedure made it possible to identify which features of the signals were most strongly associated with the presence and intensity of rigidity, providing valuable insights for the objective assessment of this clinical manifestation in patients with PD.

## 1.7 Scientific Novelty of this Thesis

By integrating sEMG and IMU sensors, this thesis provides a new method of objectively quantifying rigidity, offering a instrumented analysis of this symptom. Furthermore, the use of a SG improves the assessment process, providing an easy-to-use and engaging platform for patients.

In addition, the work contributed significantly to advanced signal processing and analysis techniques, such as Power Spectral Density (PSD), specifically applied to signals from individuals with PD. These techniques are essential for calculating relevant information from sEMG and IMU sensors data, enabling a deeper and more detailed understanding of rigidity in PD patients.

## 1.8 Practical Value of the Research Findings

Objective assessment of rigidity in PD is essential for clinical practice and improving patient care. By accurately and reliably measuring this symptom, we can facilitate early diagnosis of PD and monitor its progression over time. Additionally, this assessment provides valuable insights for personalized therapeutic adjustments and development of more effective interventions.

These methods also drive clinical research and the development of new therapies for PD. By providing objective and reliable data, researchers can deepen the understanding on the disease and identify potential therapeutic targets. In addition, the use of these

methods in clinical trials facilitates the evaluation of the effectiveness of new interventions, accelerating the translation of scientific discoveries into tangible benefits for patients.

By integrating advanced sensors, wearable devices, and digital platforms, these systems can provide more detailed, real-time analysis of rigidity, enabling a more personalized approach to disease management. Furthermore, these technologies facilitate the collection and sharing of data, promoting collaboration between healthcare professionals and boosting research in the area. Thus, the development of new systems and technologies becomes an essential piece in advancing healthcare for PD patients, complementing efforts for more accurate and effective assessment of rigidity and other symptoms of the disease.

## 1.9 Dissemination of the Research Results

The research findings were disseminated through twenty-two scientific communications, including six peer-reviewed journal papers and sixteen conference proceedings. In addition, the system was officially registered at the National Institute of Industrial Property (INPI).

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## 1.10 Thesis Structure

This thesis is structured into five chapters:

- Chapter 1: Introduction

  In this chapter, the formulation of the problem, the relevance of the thesis, the objectives, the expected results and the structure of the manuscript are presented. In addition, the dissemination of the research results is detailed.

- Chapter 2: Parkinson's disease and rigidity

  This chapter addresses several aspects related to Parkinson's Disease (PD) and rigidity. It also includes a literature review on the assessment of wrist rigidity in individuals with PD.

- Chapter 3: New methodology for quantitative evaluation of rigidity

  In this chapter, the process of developing and validating a method for assessing rigidity using sEMG and IMU signals is detailed.

- Chapter 4: Development of a SG and Human Machine Interface (HMI)

  This chapter presents the development of an interface and validation of a SG for assessing rigidity in patients with PD.

- Chapter 5: Serious game for objective evaluation of rigidity in Parkinson's Disease

  This chapter presents the implementation and results of using a SG to assess rigidity in patients with PD.

- Chapter 6: Final considerations

  The last chapter describes the conclusions and final considerations of the study, including possible directions for future research.

This thesis also contains a section of bibliographical references. The volume of the document is 110 pages, in which 60 Figures and 10 tables are included. Additionally, 124 items are cited in the thesis.

## 1.11 Relevant Considerations

This study was the result of a cotutelle doctorate between the UFU (Brazil) and the UL (France), funded by the CAPES-COFECUB programme (process number: 88881.370894/2019-01). The doctoral student conducted her research at UFU from August/2019 - April/2022 and August/2023 - June/2024, and at UL from April/2022 - August/2023 (process number: 88887.662002/2022-00).

# 2

# Parkinson's Disease and Rigidity

The work of this chapter has been published previously in:

- ALVES, Camille Marques; REZENDE, Andressa Rastrelo; MARQUES, Isabela Alves; MENDES, Luanne Cardoso; SÁ, Angela Abreu Rosa de; VIEIRA, Marcus Fraga; JÚNIOR, Edgard Afonso Lamounier; PEREIRA, Adriano Alves; OLIVEIRA, Fábio Henrique Monteiro; SOUZA, Luciane Pascucci Sande de; BOURHIS, Guy; PINO, Pierre; ANDRADE, Adriano de Oliveira; MORÈRE, Yann; NAVES, Eduardo Lázaro Martins. Wrist Rigidity Evaluation in Parkinson's Disease: A Scoping Review. **Healthcare**, MDPI AG, v. 10, n. 11, p. 2178, Oct. 2022. ISSN 2227-9032. DOI: 10.3390/healthcare10112178

## 2.1 Parkinson's Disease

Parkinson's disease is a complex, progressive, neurodegenerative disease described by James Parkinson in his 1817's publication, "Essay on the Shaking Palsy". It was described as an involuntary tremulous movement with decreased muscle strength, with a tendency to bend the trunk forward. Furthermore, James Parkinson stated that PD was a different form of paralysis, termed "shaking palsy", characterized by tremors and festination, but without any sensory impairment (51).

The incidence of PD is linked to risk and protective factors. The most important risk factor is age, but PD risk also appears to be associated with industrial chemicals and pollutants such as pesticides, solvents and metals. The factors that affect disease duration are less known, but increased longevity also translates into longer disease duration (36). It is estimated that the incidence of PD ranges from 5 per 100,000 to more than 35 per 100,000 new cases annually. The incidence increases 5 to 10 times from the sixth to the ninth decades of life (117). The prevalence of PD also increases with age. Thus, as the global population ages and industrialization increases, the prevalence of PD is expected to dramatically increase, doubling over the next 2 decades. Accompanying this increase, the

social and economic burden of PD will increase unless more effective treatments, cures, or means of prevention are identified (123).

Pathologically, PD is defined by the loss of dopaminergic neurons in the Substantia Nigra (SN) pars compacta, located in the midbrain and associated with Lewy bodies, which are cytoplasmic inclusions that include insoluble alpha-synuclein aggregates, in which an example can be seen in Figure 2.1. With the destruction of dopaminergic neurons, the axons that start from the midbrain and project to the striatum in the spinal cord center of the brain are lost (117). In this way, communication between the SN and the striatum is impaired, preventing the release of dopamine. As this neurotransmitter is responsible for transmitting the information necessary for the correct control of movements, its deficiency predominantly affects the individual's motor function, also interfering with the cognitive systems (86).

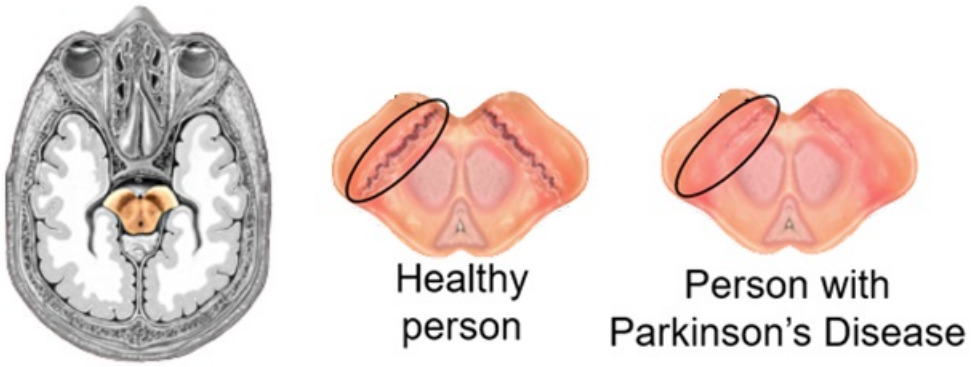


Figure 2.1 – Mesencephalon of healthy subjects and PD patients.

The neuropathological hallmarks of PD are the degeneration of dopaminergic neurons in the SN and intraneuronal protein aggregates, which are called Lewy bodies and Lewy neurites. It has long been considered that 50% to 70% of SN dopaminergic neurons die by the time clinical motor symptoms become evident (117). However, more recent work suggests that the loss of dopaminergic terminals in the striatum, as opposed to the loss of neurons in the SN, is crucial for the onset of motor symptoms. The clinical diagnosis of PD is based mainly on motor features such as slowly progressive asymmetric resting tremor, rigidity and bradykinesia, although non-motor features including anosmia, constipation, depression and rapid eye movement sleep behavior disorder may develop years before motor deficits (123). During later stages of the disease, additional non-motor features such as autonomic dysfunction, pain, and cognitive decline may appear.

Thus, the main motor symptoms, also known as cardinal signs, of PD are: bradykinesia, which manifests as slowness of movement; muscle rigidity, defined as an increase in muscle tone when the limb is passively moved; rest tremor, defined as a repetitive movement of any limb that occurs when that part of the body is not actively moving; and postural instability, which refers to an impaired reaction when balance is disturbed.

Late-onset motor symptoms include gait freezing, speech difficulties, falls and swallowing difficulties (82).

In this thesis, we will focus specifically on the assessment of rigidity in patients with PD. While rigidity is a key symptom, it is important to note that the other cardinal symptoms of PD, such as tremor and bradykinesia, have been studied in of this thesis (73). The focused approach allows for a more in-depth analysis and understanding of rigidity and its implications in PD.

## 2.2 Rigidity

Rigidity is one of the cardinal characteristics of PD. Rigidity can be defined as an increase in resistance to passive movement, which is considered constant over the entire tested range (17). Decreased dopamine levels in the basal ganglia are strongly associated with rigidity. However, there are different opinions as to the underlying pathophysiological mechanisms (59). Some authors identify excessive monosynaptic stretching reflexes, long latency stretching reflexes, and the development of a tonic stretching reflex and a shortening reaction as the main abnormalities, whereas others highlight the influence of a reduced frequency on the discharge of neurons from the subthalamic nucleus and the alteration of connectivity between the networks connecting the cerebellum, motor cortex and temporal, occipital and caudate nuclei in patients with moderate PD (17).

Despite extensive research, the pathophysiology of rigidity remains unclear. For example, some research shows the involvement of velocity-dependent spinal stretch reflexes in rigidity, whereas it is traditionally considered independent of movement velocity (59, 132). Although the origin of rigidity is in the central neural pathways, some recent studies suggest that non-neuronal changes in the biomechanical properties of elongated tissues (muscles, tendons and connective tissue) may contribute to rigidity (97). Increased elasticity in elongated muscles was found in individuals with PD, whereas viscosity, reflecting the velocity-dependent biomechanical resistance in elongated tissues, can also be increased in PD, correlating with the clinical classification of rigidity (69).

Another mechanism involved in rigidity is an abnormal response to shortening of the antagonist muscle. In healthy individuals, antagonist muscle activity is suppressed during stretching. In PD, an exaggerated electromyographic response may be recorded in the antagonist muscles, resulting in an almost constant joint torque regardless of joint position (53). This rigidity hinders the movement of the limbs, among them one of the most affected is the wrist (30).

Clinically, rigidity is most commonly assessed as part of the motor section of the Movement Disorder Society - Unified Parkinson's Disease Rating Scale (MDS-UPDRS) (47). The examiner assesses overall rigidity according to severity, distribution and whether rigidity is present at rest and in the unmedicated state.

### 2.2.1 Wrist Rigidity

Wrist rigidity primarily affects flexion movements, inducing sudden movements of the wrist joint. This type of rigidity directly affects the quality of life of these people, often making daily life tasks impossible. In this sense, the assessment of wrist rigidity, performed through an efficient approach, is of great importance, because from this the degree of limb impairment can be defined, as well as evaluating the evolution of a particular treatment, in addition to individualize the rehabilitation process (126).

The clinical assessment of PD rigidity is based on a scoring system using clinical scales, such as the MDS-UPDRS (47). However, as it is a scale that depends on the therapist's expertise, it can lead to discrepancies and measurement errors (43, 98). Recent studies have demonstrated efforts to develop objective methods for assessing muscle tone and rigidity, which are crucial for obtaining quantitative, reliable and repeatable data (102). However, there are still few studies who do this type of assessment in the wrist, directly implying the rehabilitation of this joint.

### 2.2.2 Wrist Rigidity Evaluation

Such as aforementioned, the most used clinical tool for evaluating patients with PD is the MDS-UPDRS (47). The MDS-UPDRS was designed to follow the longitudinal course of the disease, and serves as an assessment of the patient's motor and non-motor characteristics. It is divided into four parts: Part I – non-motor experiences of daily life; Part II – motor experiences of daily life, Part III – motor assessment; and Part IV – motor complications (114). Another scale often used to assess PD is the Hoehn & Yahr, created in 1967, which is a simple staging scale that assesses the general severity of parkinsonism based on bilateral motor dysfunction, motor disability, gait impairment, and balance impairment (18).

## 2.3 State of the Art

The prevailing clinical scales, notably the Unified Parkinson's Disease Rating Scale (UPDRS), are often perceived as a qualitative means of assessment (48). Their widespread use stems from their straightforward application, rendering them accessible and practical in clinical settings. Nonetheless, this very simplicity is subject to criticism, as it relies solely on precise clinical observations (46, 43). Consequently, the primary challenge lies in devising quantitative methods that are both easily interpretable and implementable in clinical practice, irrespective of the therapist's expertise.

Despite notable advances, assessing rigidity in individuals with PD remains a difficult task, with limited focus on quantitative assessment tools for the wrist joint (43). Recognizing the need to improve methodologies for assessing wrist rigidity in PD, it is

imperative to thoroughly examine the pertinent literature that has addressed this issue. Although previous reviews have been performed (43, 122, 90, 80, 1), they did not offer direct solutions for wrist rigidity, as their scope mainly covered other symptoms of PD, such as bradykinesia and tremor, often in different joints. Furthermore, these studies highlight the importance of establishing a quantitative measurement standard for these signals using innovative sensors and technologies. Therefore, a literature review was conducted with the aim of comprehensively exploring existing methodologies for assessing wrist rigidity and evaluating its developmental status.

### 2.3.1 Literature Review

A scoping review was performed on studies that evaluated rigidity (8), following the methodological recommendations of the Joanna Briggs Institute for systematic scoping reviews (96). The target patient population was individuals with PD and the concept of interest was the assessment of wrist rigidity. Studies were included in the review if they met the following criteria:

1. Studies that addressed the evaluation of wrist rigidity in individuals with PD
2. Participants with PD of both sexes and any age
3. Randomized clinical trials, randomized controlled trials, clinical trials, case reports, or cohort studies
4. Full text written in English

Exclusion criteria were:

1. Incomplete studies that do not present results
2. Studies that address the assessment of wrist rigidity in individuals with PD, but do not focus on the main topic

The search methodology adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (93) guidelines. An exhaustive electronic search encompassed several databases, including PubMed, IEEE/IET Electronic Library, Web of Science, Scopus, Cochrane, Bireme, Google Scholar, and Science Direct.

Key terms were meticulously explored within the title, abstract, and keywords of relevant papers, employing logical conjunctions such as “OR” and “AND”. The search query employed across all databases included: **Parkinson AND** (**Evaluation OR Assessment OR Exoskeleton**) **AND** (**Stiffness OR Rigidity**) **AND** (**Wrist OR Hand**). No temporal restrictions were applied, extending the search period up to July 2022.

After applying the search strategy in all databases, the studies were saved and organized in Rayyan – Intelligent Systematic Review (92). The selection process of the studies was performed following the steps below:

1. First, the title and abstract of the articles were read and analysed, considering the inclusion criteria

2. Next, the selected studies were read in full, performing a second filtering, and those that did not fit the inclusion criteria were excluded

3. Finally, data and characteristics were extracted, in addition to the quality evaluation of the selected studies

The data extracted from the chosen studies was compiled into a comprehensive table, where each entry corresponded to a distinct study. The collected information encompassed the type of study, publication year, sample size, participant characteristics, and the method of evaluation employed.

### 2.3.2 Description of the included studies

As depicted in Figure 2.2, after removing duplicates, a total of 294 studies were identified across 8 databases. Subsequently, following the title and abstract screening process, 234 studies were excluded. In the subsequent step, full-text screening was conducted on the remaining 59 studies, leading to the inclusion of 28 studies for analysis. The exclusion of the remaining 32 studies was primarily attributed to population criteria (3), outcomes (24), and study design (5).

The selected studies include 15 case series, 4 cross-sectional studies, 7 case control and 2 cohort studies. The year of publication of the selected studies ranged from 1988 to 2021. There is an increase in wrist rigidity in PD research, particularly in the past decade, when 18 out of the 28 selected studies were published.

## 2.4 Methods of Evaluation

In the studies selected for analysis, various types of sensors were employed to evaluate wrist rigidity in patients with PD, as shown in Figure 2.3.

Inertial sensors featured in four studies (95, 64, 14, 30), used alone in one study (69), and in combination with force sensors in two others (94, 85). One study (52) employed the UPDRS for evaluation, whereas three others conducted assessments during Deep Brain Stimulation (DBS) surgery (64, 14, 30), employing a classification model to differentiate between rigid and non-rigid states. Another study introduced a novel technique utilizing

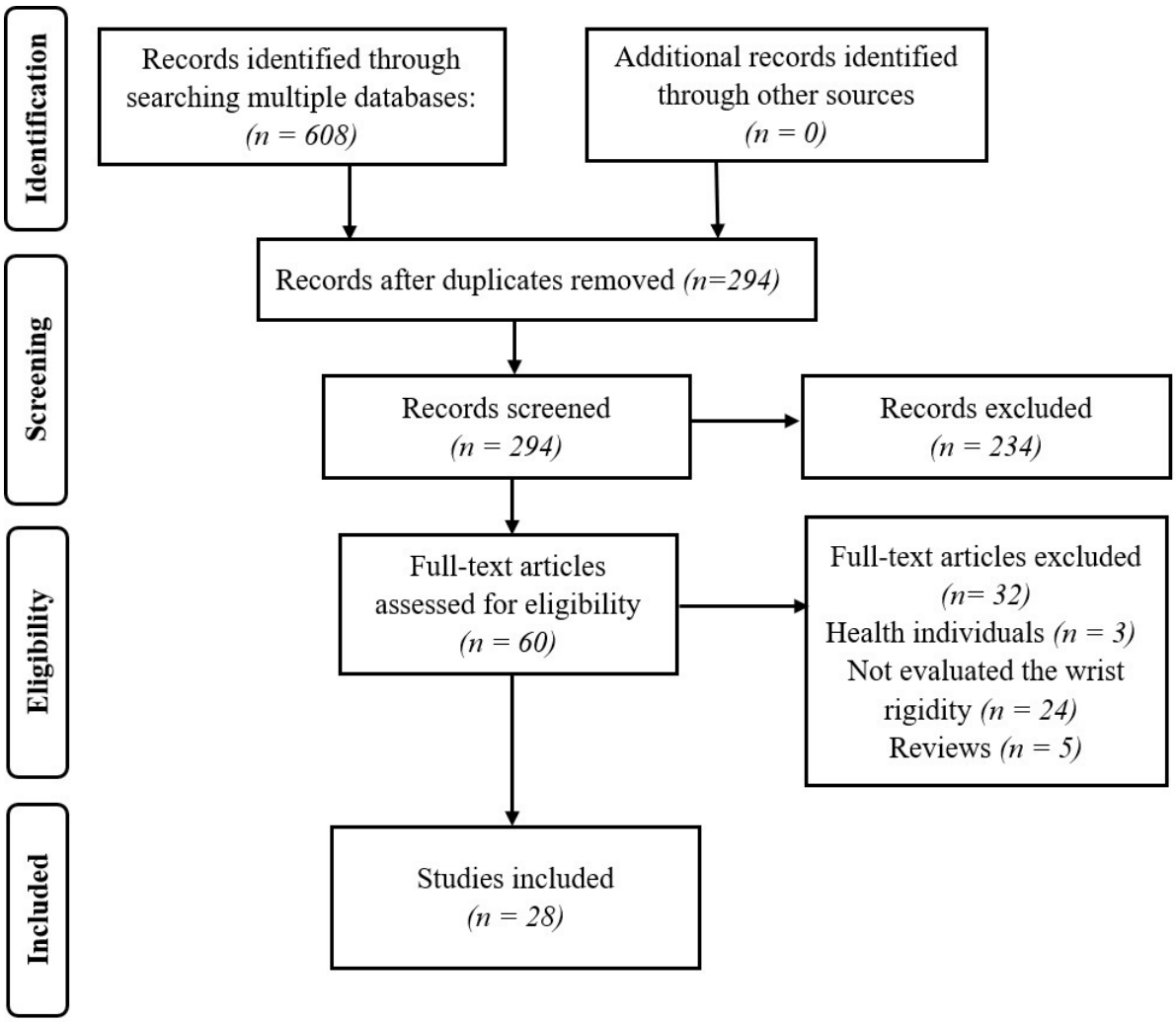


Figure 2.2 – PRISMA flow diagram illustrating the studies selection.

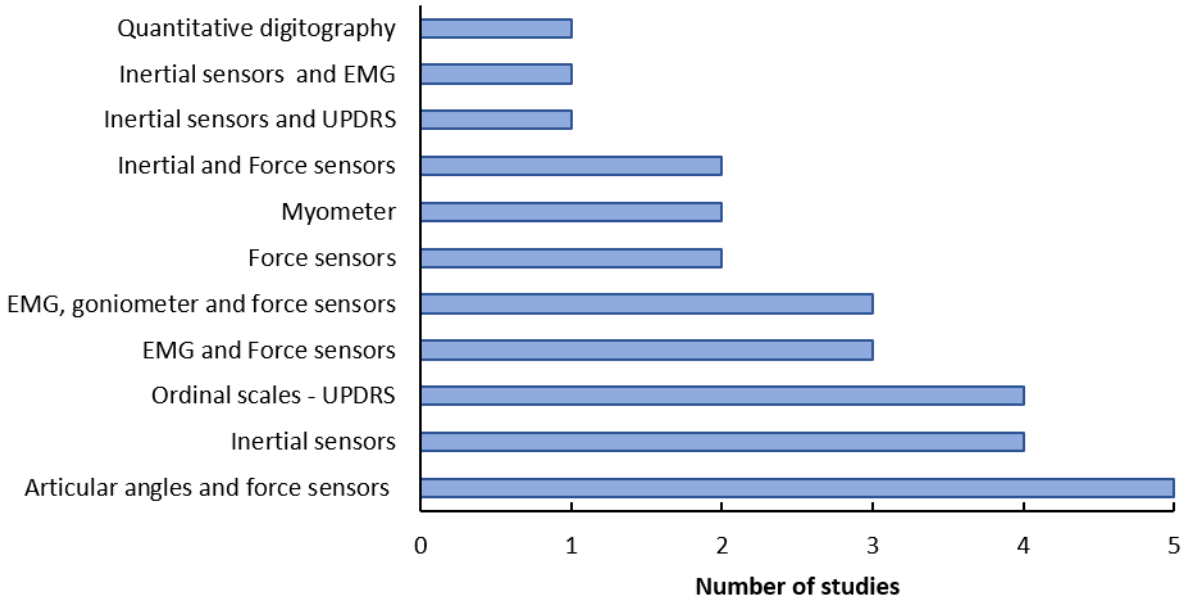


Figure 2.3 – Methods used to assess wrist rigidity in the selected studies.

quantitative digitography (127), wherein participants performed movements on a keyboard, while application force was measured to compare rigidity and tremor parameters with the UPDRS.

Two studies employed the Myotonometer, a device measuring muscle biomechanical and viscoelastic properties (104, 103), with stretches manually performed by examiners. This method obtains natural oscillation data, measuring acceleration and "voltage" parameters, thus estimating muscle tone (Hz) and rigidity (N/m) (114). Additionally, three studies combined sEMG with goniometers and force sensors (99, 57, 63).

Despite the diversity of sensors utilized, a notable minority of studies (about 15%) (133, 79, 70, 124) relied on ordinal scales for assessment. Although widely used in clinical settings, these scales have limitations, chiefly due to the dependence on therapist experience, leading to subjective and unreliable assessments.

### 2.4.1 Methods Evaluating Muscular Signals

Eight studies were included, and their summaries are presented in Table 2.1. Three studies utilized sEMG in conjunction with goniometers (for measuring joint angles) and force sensors (99, 57, 63). Two studies used sEMG exclusively with force sensors (131), and one study combined sEMG with inertial sensors (69).

While not all studies provided correlation results with clinical scales, sEMG has been extensively employed to examine muscle physiology in patients with PD, demonstrating a good correlation with clinical scales assessing rigidity. Several studies reported a highly significant correlation between normalized stretch-related sEMG and the degree of rigidity. The viscous damping constant showed the strongest correlation (mean = $0.77 \pm 0.22$) with clinical measures and had the highest number of limbs with significant positive correlations (57%) (57). Additionally, clinical and device assessments using sEMG were significantly correlated, though the relationship was modest (Spearman's rho = 0.382, p = 0.002) (63).

Two studies utilized the Myotonometer, a device designed to measure the biomechanical and viscoelastic properties of muscles (104, 103). In both studies, the stretches were manually performed by the examiner. This method captures natural oscillation data by measuring acceleration and voltage parameters, which estimates muscle tone (Hz) and rigidity (N/m). Neither study found significant positive correlations between clinical rigidity scores and viscoelastic rigidity values (before PWM-s: $\rho = 0.12$, $P = 0.3$; and after PWM-s: $\rho = 0.284$, $P = 0.1$).

| Study | Year | Method of evaluation | Evaluation Protocol | Results |
|---|---|---|---|---|
| (104) | 2017 | Myotonometer (measure of biomechanical and viscoelastic properties of muscle) | During the "off" state, one examiner flexed and extended the wrist joint as in a regular clinical examination for ten times and after that the measurements were performed by the second examiner. Five consecutive measurements were made after the passive wrist movements. | Effective deep brain stimulation and increased rigidity can significantly change viscoelastic rigidity in the resting muscles in patients with Parkinson's disease, especially if evaluated after passive wrist movements. |
| (99) | 2016 | EMG, articular angle and force sensor | Participants were tested in both the "on" and "off" states. Rigidity was quantified by rigidity work score and slopes of the moment-angle plots during both flexion and extension. Reflex response was quantified by mean EMG amplitudes of forearm musculature. | The data suggest that the presentation of rigidity used in the determination of diagnosis, treatment and prognosis in PD will not be affected by the continuous nature of the movement trajectory used during clinical assessment. |
| (57) | 2014 | EMG, articular angle and force sensor | Rigidity was evaluated during DBS surgery; The therapist performed with a resistive torque to six cycles of flexion and extension movement imposed on the wrist was measured. | Intraoperative quantification of rigidity during DBS surgery is possible with the suggested system and measures, which would be helpful for the adjustment of electrode position and stimulation parameters. |
| (63) | 2012 | EMG, articular angle and force sensor | The rigidity was evaluated by flexion and extension passively of the wrist. The signals were collected during the movements. A maximum of 14 cycles per condition was performed. | The study provides evidence consistent with a mechanistic link between oscillatory activity at low frequency and Parkinsonian rigidity and, in addition, validates a new method for rigidity quantification at the wrist. |
| (98) | 2012 | EMG and force sensor | Subjects' tested hand was passively displaced through 60° and 90° ranges, and the velocities of $50^{o}$/s a 280°/s. Joint angular position, resistance torque, and surface electromyography (EMG) of the wrist flexors and extensors were recorded. Rigidity was quantified by normalized work scores and normalized angular impulses for flexion and extension, separately. | Both work scores and angular impulses revealed that the larger displacement amplitude and the higher velocity were associated with significantly greater rigidity, increased EMG ratio and mean EMG of stretched muscles. |
| (103) | 2011 | Myotonometer | The study was carried out in "off" state. Rigidity was measured through Myotonometer. The examiner flexed and extend the joint ten times. | Increased rigidity is associated with increased values of viscoelastic rigidity. The study supports the use of myotonometry for objective quantification of rigidity and in the future. This tool could prove to be helpful for optimizing deep brain stimulation settings in patients with Parkinson's disease. |
| (131) | 2004 | EMG and force sensor | The motor moved the wrist joint in movement of flexion and extension, with the velocity of $50^{o}$/s. The patients were evaluated in "on" and "off" state. | The shortening reaction was reduced after the medication. |
| (69) | 1992 | EMG and inertial sensors | EMG was recorded during the flexion and extension movements of the wrist joint. The patients were evaluated in "on" and "off" states. | EMG indicated that mild and moderate rigidity was consistently associated with increased stretch-related activity compared with non-rigid conditions. |

Table 2.1 – Characteristics of studies using Muscular Signals.

### 2.4.2 Methods Evaluating Capture of Movement

Eight studies were included and are summarized in Table 2.2. Inertial sensors were utilized in four studies (30, 95, 64, 14), combined with EMG in one study (69), and with force sensors in two other studies (94, 85). One study (52) employed the UPDRS. Three studies conducted evaluations during DBS surgery (30, 64, 14) and used a classification model to differentiate between rigid and non-rigid states.

Although the majority of studies using IMU sensors did not report correlation values with clinical scales, some devices were able to accurately classify 83.9% of the evaluated signals, in comparison to the UPDRS (30). Mann-Whitney rank order comparisons indicated that the median rigidity score for clinically classified rigid patients was significantly higher than the median control (U = 17, $p < 0.0001$) or the median rigidity score of non-rigid patients (U = 15, $p = 0.0001$) (21).

| **Study** | **Year** | **Method of evaluation** | **Evaluation Protocol** | **Results** |
|---|---|---|---|---|
| (95) | 2021 | Inertial sensors | The data collection was performed using inertial sensors (positioned on the back of the hand and on the back of the forearm). Different numbers of features were used to compare the values of sensitivity, specificity, precision, and accuracy of the classifiers. | The best performance for sensitivity and accuracy (0.875 and 0.800, respectively) was found in the SVM classifier, fed with 20% and 10% of the features, respectively, while the best performance for specificity and precision (0.933 and 0.917, respectively) was associated with the RF classifier fed with 20% of all the features. |
| (52) | 2019 | Inertial sensors and UPDRS | The participants were instructed to wear ActiGraphs for 7 consecutive days, for 24 hours a day. | Wrist monitors are likely to overestimate activity, particularly in people with tremor and dyskinesia. Nonetheless, activity monitors can be worn on the wrist if the aim is to monitor change rather than accurately record activity |
| (64) | 2019 | Inertial sensors | The system was used during the bilateral DBS surgery. The stimulation frequency was set at 130 Hz; voltage and placement were varied while rigidity was assessed, by imposition of passive wrist flexion. | The polynomial models used for measurements improvement were tested for a larger number of patients. An accuracy of 78% and a rigidity classification error of 3.5% was achieved. |
| (85) | 2017 | Inertial sensors and force sensor | The hand was passively moved by the examiner, while stabilizing the lower arm. The force/moment sensor was attached to the hand of the examiner using a strap. Moment arm of the sensor to the patient's wrist was measured using a ruler. | The PowerGlove measured a difference in off- vs. on-medication condition in all tasks in the presented patients with most of its outcome parameters. |
| (14) | 2016 | Inertial sensors | The system was used during the bilateral DBS surgery. The stimulation frequency was set at 130 Hz; voltage and placement were varied while rigidity was assessed, by imposition of passive wrist flexion. | The system computed a set of polynomial mathematical models, specific for low and high initial rigidity states, which classified correctly 82.0% of the evaluated signals, with a mean error of 3.4%, which supports the reliability of this solution. |

| Study | Year | Method of evaluation | Evaluation Protocol | Results |
|---|---|---|---|---|
| (30) | 2015 | Inertial sensors | The system was used during the bilateral DBS surgery. The stimulation frequency was set at 130 Hz; voltage and placement were varied while rigidity was assessed, by imposition of passive wrist flexion. | The descriptor significantly ($p<0.05$) distinguished between non-rigid and rigid states, and the classification model labelled correctly 83.9% of the evaluated signals against the blind-agreement of two specialists. |
| (94) | 2001 | Articular angles and inertial sensors | The examiner repeatedly flexes and extends the joint as in a regular clinical examination. The movements are imposed through two air-filled pads held distal to the joint. The pads are connected to a differential force transducer which measures the resultant force applied to the pads. A solid-state piezoelectric gyroscope mounted on one of the force pads monitors the imposed angular velocity from which is computed displacement. | Examiners tended to overrate rigidity on the UPDRS scale. Mechanical impedance was nonlinearly related to UPDRS ratings of rigidity at wrist. |
| (21) | 1994 | Articular angles and force sensor | The therapist moved the patient's wrist in flexion and extension while the signals were collected. | The device presented 89% of specificity and 82% sensitivity. The device also presents a great portability. |

Table 2.2 – Characteristics of studies that used capture of movement.

### 2.4.3 Methods that Used Mechanized and Force Sensors

Seven studies were included and are summarized in Table 2.3. In the studies by Xia et al. (130, 131), the stretching velocity was controlled at $50^{o}$/s. Teräväinen et al. (121) compared different velocities and found that higher velocities were more sensitive for detecting parkinsonian rigidity. Force sensors alone were used in two studies (102, 84), while they were combined with (EMG) analysis in three studies (98, 97, 132). Powell et al. and Xia et al. (98, 132) also tested different velocities and observed greater rigidity at higher speeds.

Most of the studies did not provide comparison results with clinical scales. However, it was noted that the p-value obtained when evaluating the differences between PD OFF and PD ON using a device ($p = 0.016$) was lower than that obtained by the MDS-UPDRS Part III score ($p = 0.031$). This suggests a potential greater sensitivity of the device compared to the clinical score (134). Spearman's correlation analysis showed mild to moderate correlations between device scores and UPDRS rigidity scores in the off-medication state ($\rho = 0.482$, $p = 0.111$ for the slowest movement; $\rho = 0.578$, $p = 0.049$ for the faster movement). In the on-medication state, there was a low correlation between device and clinical rigidity scores for slower movements ($\rho = 0.324$, $p = 0.305$) and no correlation for faster movements ($\rho = 0.284$, $p = 0.437$) (102).

| Study | Year | Method of evaluation | Evaluation Protocol | Results |
|---|---|---|---|---|
| (102) | 2020 | Force sensors | PD subjects were assessed in the "on" and "off" medication conditions. Angle and torque data were recorded for the actuated joint. The torque perturbation was applied five times, thus leading to an overall duration of the session equal to 105s. | The device was able to successfully estimate the rigidity depending on the movement direction. Moreover, the device allowed to discriminate both Healthy subjects from PD subjects, and PD subjects in "off" condition from PD subjects in "on" condition |
| (84) | 2019 | Force sensors | It was measured at the "on" and "off" states. The wrist was evaluated 3 times without and 3 times with the Froment maneuver. | A minimum-maximum limit forming study was done for rigidity values between 0-5 using both with Froment and without Froment rigidity values' scores which was the last stage. |
| (134) | 2018 | Goniometer and force sensor | Hand was positioned in the device in such a way that the wrist joint aligned with the center of rotation of the plate. After that, 10 repetitions of a flexion movement (from 30° to -60°) followed by an extension movement (from -60° to 30°) were conducted. The constant velocity phase ranged from 7° to -37°. | This device proved to have sufficient accuracy and sensitivity to precisely measure the interaction torque at the wrist joint and to differentiate PD rigidity from normal muscle tone. |
| (97) | 2011 | Force sensor and EMG | A servomotor executed the flexion and extension of the wrist, with and without a concurrent gripping activation in the contralateral hand. EMG and torque were collected during the movement. The patients were evaluated in "on" and "off" states. | The subjects presented a significantly enhanced resistance in "off" compared to healthy control. The medication reduced difference in torque resistance between controls and PD patients in the passive and activation conditions. |
| (132) | 2009 | Force sensor and EMG | The servomotor executed the movements of flexion and extension and the velocity was constant at either 50 or 280°/s. EMG was recorded at the flexors and extensors. The patients were evaluated in "on" and "off" state. | The torque resistance scores were more strongly correlated with the EMG ratios than with EMG of the stretched muscles alone. The strongest and significant correlation was found between the torque resistance score and EMG during the extension at high velocity in the "off" state. |
| (130) | 2006 | Articular angles and force sensor | The movements of flexion and extension were carried out by a servomotor and with a constant velocity of $50^{o}$/s. The patients were evaluated in "on" and "off" states. | The rigidity was more readily elicited in extension movements. Compared with controls the scores were higher for patients in "on" state. |
| (121) | 1989 | Articular angles and force sensor | The individual's hand was oscillated passively in a range of angular velocity of 12 to 240 degrees per second. The objective rigidity score was expressed in Newton-meter-degrees. | The rigidity was more pronounced at faster movement velocities in patients with PD. The higher velocities were the most sensitive for detecting parkinsonian rigidity. |

Table 2.3 – Characteristics of studies that used force sensors.

### 2.4.4 Ordinal Scales

Five studies were included and are summarized in Table 2.4. Despite the diverse range of sensors used, five studies (133, 79, 70, 124) utilized ordinal scales to evaluate

individuals. Although these scales are prevalent in clinical practice, they have notable limitations, such as dependence on the therapist's experience, leading to subjective and potentially unreliable assessments.

One study introduced a novel approach using quantitative digitography (127), where participants performed movements on a keyboard, and the force applied was measured. This method allowed for the comparison of rigidity and tremor parameters with the UPDRS. Significant associations were found between the rigidity sub-score and release slope ($\rho = -0.43$, p = 9.78e-9).

| **Study** | **Year** | **Method of evaluation** | **Evaluation Protocol** | **Results** |
|---|---|---|---|---|
| (127) | 2021 | Quantitative digitography | Individuals performed repetitive alternating finger tapping on tensioned, engineered keys on a digitography device, which senses the amplitude displacement and timing of keystrokes and then compared the results with UPDRS. | Quantitative digitography technology and the rigidity metric provide a critically important supplement to video MDS-UPDRS assessments of PD in clinical trials. |
| (133) | 2016 | Ordinal Scale | All patients were examined in the "on" condition. The Hoehn and Yahr (H&Y) disability scale and Unified Parkinson's Disease Rating Scale (UPDRS) were used to assess the severity of the disease. | The comparison of the mean indices of electrophysiologic parameters indicated subclinical median and ulnar nerve demyelination both at the wrist and at the elbow in the patient groups where a longer disease duration and mild tremor and rigidity scores are prominent. |
| (79) | 2008 | Ordinal scale | The evaluation was carried out while the patients were in the "on" state. The evaluation was carried out by two therapists using a rigidity scale. | With each of the attentional tasks, rigidity increased significantly from baseline. The effect of contralateral hand opening-closing on rigidity was much larger than any of the attentional tasks. |
| (70) | 1993 | Ordinal scale | The patients were evaluated in "on" and "off" states. Wrist extension movement of $10^{o}$ was applied at velocities 100 and 200°/s. | The results cannot be taken as definitive evidence against a reflex origin of rigidity and suggest that parkinsonian rigidity cannot be uniquely attributed to the increased reflex responsiveness measured by the present laboratory techniques. |
| (124) | 1988 | Ordinal scale | Two therapists executed random movements of wrist flexion and extension at varying speeds and scored accordingly the scale defined. | The two evaluations presented 80% of agreement and a weighted Kappa value of 0.636. |

Table 2.4 – Studies that used only ordinal scales.

### 2.4.5 Applicability of the Methods in Clinical Practice

The integration of new rigidity assessment methods into clinical practice and their adaptability to different contexts are crucial aspects to consider. Especially during times of prominence for remote assessments, such as during the COVID-19 pandemic, it is essential to look for methods that can be easily used at home. By analyzing the articles in this review, it was possible to assess the feasibility of these methods in a variety

of clinical situations, including outpatient visits, post-operative monitoring, telemedicine, and home assessments. Figure 2.4 illustrates the distribution of these methods in different scenarios, highlighting the importance of devices adapted for telemedicine.

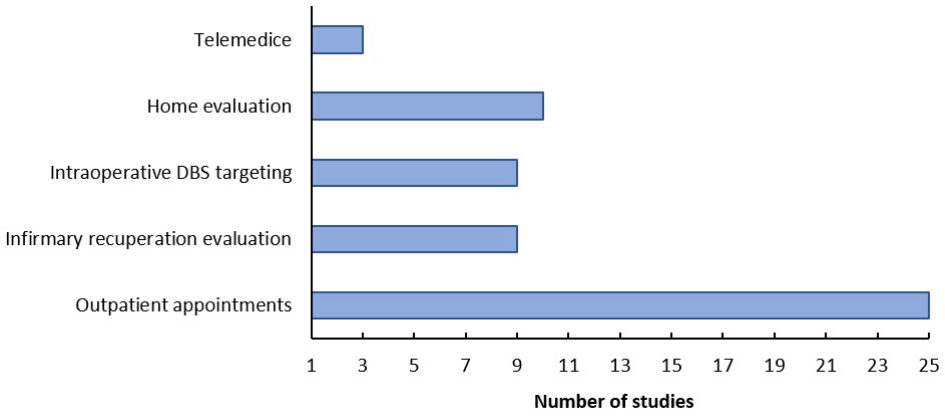


Figure 2.4 – Applicability of the methods.

By evaluating the articles in this review, the practical application of these methods was assessed across different clinical scenarios. For instance, outpatient visits benefit from the enhanced accuracy and objectivity provided by combining goniometers and force sensors. Post-operative monitoring, especially following procedures like DBS surgery, can leverage classification models that differentiate between rigid and non-rigid states, thus ensuring precise follow-ups.

Telemedicine and home assessments present unique challenges and opportunities. Methods involving IMU and SG show great promise due to their portability and ease of use. These tools can be employed by patients in their own homes, facilitating continuous monitoring and real-time feedback without the need for frequent clinic visits. The development of user-friendly interfaces and clear instructions is vital to maximize the effectiveness of home-based assessments.

## 2.5 Discussion

This scoping review covered 28 studies that explored the most common methods for assessing wrist rigidity in people with PD. Most of these studies used quantitative approaches associated with the UPDRS, widely used in clinical practice for this purpose. There is also a greater concentration of studies selected in the last 10 years, indicating a growing demand for objective methods that offer more reliable results. This increase in publications can be attributed to the need for therapists to seek and develop alternative methods that are intuitive and easy to interpret.

The determination of rigidity in PD involves a complex interplay between neural and non-neural components, both contributing to the unique manifestation of this symptom

(130, 132, 131). Non-neural components refer to the mechanical properties of muscle fibers, whereas neural components, such as shortening reflexes, are intrinsic to the pathophysiology of the condition (130, 132, 131). Previous studies have highlighted that these aspects can be identified using sEMG and force sensors (98, 97, 132). Research that employed the combination of these sensors demonstrated promising results, showing good correlation with routinely used clinical scales (98, 97, 132).

On the other hand, other studies have explored the use of inertial sensors and goniometers (to measure joint angles) in assessing wrist rigidity (95, 64, 14, 30). Inertial sensors, specifically, are employed to measure angular velocity in the assessment of rigidity in PD (95, 64, 14, 30). These investigations revealed that muscle viscosity and elasticity during rigidity episodes are distinct from those observed in healthy states (95). Combining data from inertial sensors and goniometers can allow detection of fluctuations in Parkinsonian rigidity, whereas joint range of motion is often used as an indirect measure of the progression of this symptom (37). In many cases, the presence of rigidity is associated with a reduction in range of motion, which may serve as an additional indicator of disease severity (37).

In the studies analysed, a diversity of protocols used to evaluate rigidity was observed, with emphasis on the variation in stretching speeds used (98, 132, 69, 70, 121). While some traditional approaches suggest that Parkinsonian rigidity is independent of velocity, unlike spasticity, which is influenced by it (70), more recent studies question this view (43, 98). More recent research indicates that rigidity is influenced by angular velocity and joint range of motion, suggesting that Parkinsonian rigidity is modulated by these factors (43, 98). Discrepancies in experimental protocols, such as the application of different stretching speeds, lead to varying results. While some studies, such as those by Powell et al. and Xia et al. (98, 132), investigated and compared different stretching speeds, others, such as Meara et al. (70), applied different speeds, but did not make comparisons between the results obtained. These findings provide valuable insights into the biomechanical underpinnings and physiological characteristics of rigidity, contributing to the development of new methods for clinical assessment of rigidity in PD.

This research highlights the importance of considering the applicability and usability of rigidity assessment devices in clinical practice, especially in different clinical settings. Although many of the devices identified have not yet been used in clinical practice, there are indications of where they could be applied, with the majority being viable for outpatient consultations. However, the complexity and size of these devices can make them difficult to implement in settings other than clinical offices. Furthermore, adapting these devices for use in telemedicine is also a relevant point, although some studies suggest limitations in the remote measurement of rigidity. However, there is potential for remote implementation of certain technologies after validation testing and adequate patient training with the devices. These aspects highlight the need to consider not only the technical

effectiveness, but also the practicality and adaptability of rigidity assessment devices to ensure their effective integration into clinical practice and in the context of telemedicine.

## 2.6 Clinical Implications

Rigidity is a common symptom of PD, often affecting the wrist joint. This condition has a significant impact on patients' ability to perform daily activities and quality of life. Diagnosing and monitoring rigidity is essential in clinical practice, as it allows for more accurate monitoring of treatment and the safe evaluation of new medications. However, the challenge of integrating these new technologies into clinical routine arises. Therefore, additional tests with existing technologies are necessary, prioritizing those that are simple to use. Furthermore, the results must be reliable and easy to interpret.

## 2.7 Conclusion

The findings of this review indicate a growing interest in objective methods for assessing wrist rigidity in PD over recent years. Researchers are increasingly focusing on methods that offer reliable results and consider various aspects of rigidity. Three main methods are used to quantitatively assess wrist rigidity in PD patients: servomotors, inertial sensors, and biomechanical as well as neurophysiological measurements of muscles. However, despite these advancements, none of the proposed devices have been integrated into clinical practice. This could be attributed to the continued preference for applying clinical scales, as well as the limited number of precise studies utilizing these new technologies. To address this gap, further research involving larger sample sizes and examinations conducted during clinical procedures is needed. Additionally, the development of standardized protocols for conducting these evaluations is essential for advancing the field.

# 3

# New Methodology for Quantitative Evaluation of Rigidity

## 3.1 Background

As mentioned before, rigidity is a frequent and incapacitating motor symptom of PD. It involves heightened resistance to limb movement, causing challenges in everyday tasks and a decline in quality of life for patients. A precise and unbiased evaluation of rigidity is vital for tracking disease advancement, assessing treatment outcomes, and modifying therapeutic approaches.

The evaluation of rigidity in clinical assessments can vary depending on the examiner's experience, leading to inconsistent result interpretation. Utilizing information obtained from sEMG and inertial signals has shown potential for assessing rigidity in PD patients (43). In this context, the choice of appropriate evaluation methods becomes essential. After the complete review of the literature, presented in Chapter 2, sEMG, IMU and Force sensors emerged as promising tools for assessing rigidity in patients with PD. sEMG and force sensors offers insights into muscular activation and recruitment patterns, whereas inertial signals capture information from the body's acceleration and orientation for an objective analysis of rigidity and motor function.

Inertial sensors and sEMG devices are generally more compact, lightweight, and easier to integrate into wearable systems, making them ideal for use outside of laboratory environments (43). In contrast, force sensors are often bulkier and more complex to set up, limiting their applicability to controlled settings. Additionally, inertial sensors and sEMG provide a more comprehensive understanding of motor function by capturing dynamic movement and muscle activation patterns, whereas force sensors are more specialized and can miss out on the broader context of body movement. This flexibility and ease of use make inertial sensors and sEMG more suitable for continuous, real-world monitoring of rigidity in PD, allowing for better patient mobility.

Additionally, these techniques can provide a more thorough evaluation of rigidity, considering various factors of motor function like flexibility, velocity, and synchroniza-

tion (83). Thus, creating and verifying rigidity assessment methods using sensors shows potential for enhancing the treatment of PD and patient's quality of life.

## 3.2 Electromyography (EMG)

EMG is the clinical study of the electrical activity of muscle fibers, muscles and motor neurons. The analysis of EMG may reveal motor neuron dysfunction, muscle dysfunction, or problems in nerve-to-muscle signal transmission (15). The signal represents the anatomical and physiological properties of the muscles; it can be collected in two ways: surface and intramuscular. These signals are recorded by non-invasive electrodes and invasive electrodes, respectively.

Currently, the signals detected on the surface are preferentially used to obtain information about the time or intensity of superficial muscle activation (27). As they are not invasive, they are easier to use and do not cause discomfort to patients, however, there is a greater occurrence of interference from the activity of other muscles, adjacent to those analyzed. This phenomenon is called crosstalk, and can be reduced by the differential configuration, in which two electrodes are used on the same muscle in order to alleviate the noise in common mode. These electrodes can also be active or passive, with the first having a pre-amplification stage.

The sEMG signal can be contaminated by many artifacts, both from the skin and from the environment. The amount of tissue between the contracting muscles and the electrodes, along with their thickness, also affects the amplitude of the sEMG signal (55). Filters and signal amplification can partially reduce these effects. Therefore, the sEMG must be processed and analyzed to obtain the necessary information.

### 3.2.1 sEMG for Rigidity Analysis

Objective assessment of rigidity can be performed using sEMG, which allows for detecting changes in muscle tone and defining the underlying physiological mechanisms (23). Evaluating rigidity using sEMG signals includes using filtering and feature extraction methods, like Power Spectral Density (PSD), which measures signal energy distribution across frequencies. PSD is frequently used in analysing biological signals (88).

Analyzing muscle signal spectral characteristics with PSD can help detect rigidity. Muscle rigidity related to PD can cause abnormal muscle recruitment patterns and increased activity at specific frequencies, which is reflected in the sEMG signal's PSD.

For example, during rigidity, there may be an increase in muscle activity at specific frequencies. By calculating the PSD of the sEMG signal, it is possible to identify these changes and quantify the magnitude and distribution of muscle activity at different frequencies. Therefore, combining electromyography with signal processing techniques such as PSD analysis is a promising approach to identify and understand rigidity patterns.

Various studies have demonstrated the efficacy of sEMG in detecting rigidity in PD patients. Cantello et. al(23) explored the use of sEMG to detect muscle activity patterns associated with rigidity, showing that sEMG could identify abnormal muscle co-activation and increased muscle tone, which are key indicators of rigidity. Some studies used PSD analysis to examine the spectral characteristics of sEMG signals from PD patients and found significant increases in power within specific frequency bands, correlating with the severity of rigidity (109). Similarly, Kwon et. al (56) utilized sEMG to study the effects of medication on rigidity, highlighting how sEMG could quantify changes in muscle activity pre- and post-medication, thus demonstrating its utility in monitoring treatment efficacy.

In conclusion, combining sEMG with advanced signal processing techniques such as PSD analysis provides a powerful approach to objectively assess and understand rigidity in PD. These methods offer detailed insights into the muscle activity patterns associated with rigidity, enabling more accurate diagnosis and monitoring of the disease.

## 3.3 Inertial Measurement Unit (IMU)

Wearable motion sensors are highly relevant in healthcare and monitoring daily life due to their small size, light weight, and moderate power usage. The most common sensors include triaxial accelerometers, gyroscopes, and magnetometers, often combined into IMU (116). Advances in miniaturization and data storage allow these sensors to collect continuous and prolonged motion data in everyday environments. In this way, it is possible to provide a more comprehensive assessment of the motor symptoms of PD (11).

#### Accelerometers

An accelerometer is a device designed to measure translational acceleration resulting from applied forces. This acceleration is directly related to the weight experienced by a mass within the accelerometer's frame of reference, following Newton's second law of motion. Typically, an accelerometer comprises a small mass, known as a proof mass or seismic mass, connected to the instrument case via a spring mechanism. When subjected to acceleration along its sensitive axis, the test mass moves in relation to the instrument case. This displacement generates a force proportional to the extension or contraction of the spring, allowing the measurement of the applied acceleration by observing the displacement of the test mass (28).

While there are many different types of accelerometers, the majority function using the straightforward spring and mass arrangement previously mentioned (28). Three single-axis accelerometers are often employed in applications that need three-dimensional acceleration data, such as navigation.

The fundamental components of a single-axis accelerometer are:

- **Proof Mass (m)**: A small mass that responds to the applied acceleration.
- **Spring (k)**: Connects the proof mass to the accelerometer case and provides a restoring force proportional to the displacement.
- **Damper (b)**: Provides damping to the system, reducing oscillations and stabilizing the proof mass.

When the accelerometer experiences an acceleration $a$ along its sensitive axis, the proof mass $m$ displaces by $x$ from its equilibrium position. According to Newton's second law, the force $F$ acting on the proof mass is given by:

$$F = m \cdot a$$

This force causes the spring to stretch or compress, generating a restoring force proportional to the displacement $x$. Hooke's law describes this restoring force:

$$F_s = -k \cdot x$$

The damping force $F_d$ provided by the damper is proportional to the velocity $v$ of the proof mass:

$$F_d = -b \cdot v$$

The equation of motion for the system is:

$$m \cdot \frac{d^2x}{dt^2} + b \cdot \frac{dx}{dt} + k \cdot x = 0$$

By measuring the displacement $x$ of the proof mass, the applied acceleration $a$ can be determined.

In practical applications, three single-axis accelerometers are often combined to measure three-dimensional acceleration. Each accelerometer in the arrangement measures acceleration along one of the three orthogonal axes (X, Y, Z), providing a comprehensive measurement of the acceleration vector in three-dimensional space.

### Gyroscopes

Gyroscopes serve as crucial components mounted on structures to detect angular velocity resulting from rotation. They come in various classes, each characterized by distinct physical mechanisms and technological implementations.

Typically, gyroscopes incorporate vibrating masses that oscillate along a designated drive axis. When subjected to rotation, a secondary vibration occurs along a perpendicular sensing axis, causing displacement from the original trajectory of the mass (115). This displacement, induced by rotation around its axes, leads to changes in capacitance within the gyroscope, facilitating the detection of angular velocity. By integrating the signal

obtained from these capacitance changes, guidance information can be derived, aiding in navigation and orientation tasks.

The fundamental components of a gyroscope are:

- **Drive Mass**: The mass that oscillates along the drive axis.
- **Sensing Mass**: The mass that detects the perpendicular oscillation induced by rotation.
- **Capacitive Sensors**: These sensors detect changes in capacitance due to the displacement of the sensing mass.

When the gyroscope experiences rotation, the Coriolis effect causes the drive mass, which is oscillating along its primary axis, to induce a perpendicular oscillation in the sensing mass. This can be described by the Coriolis force equation:

$$F_C = 2m(\mathbf{v} \times \mathbf{\Omega})$$

where $F_C$ is the Coriolis force, $m$ is the mass, $\mathbf{v}$ is the velocity of the oscillating mass, and $\mathbf{\Omega}$ is the angular velocity vector.

The displacement caused by this force changes the capacitance between the sensing mass and fixed electrodes. The change in capacitance $\Delta C$ is proportional to the displacement $x$, which in turn is proportional to the angular velocity $\Omega$:

$$\Delta C \propto x \propto \Omega$$

By measuring the change in capacitance, the angular velocity can be determined. Integrating this angular velocity over time provides orientation information, which is crucial for navigation systems.

In practical applications, gyroscopes are often combined with accelerometers to form IMU, which provide comprehensive data on both linear and angular motion.

### Magnetometers

A three-axis magnetometer is a device created to identify and quantify the orientation and intensity of magnetic fields in its vicinity. In its natural state, this magnetic field typically corresponds to and mirrors the Earth's magnetic field (107).

Magnetometers are essential devices used in several applications, including navigation, geophysics, and environmental monitoring. They operate by employing one or more magnetic sensors that detect changes in magnetic flux density, which can be caused by surrounding ferrous objects, electrical currents, or natural phenomena. Magnetometers provide valuable information about the orientation, location, and environmental conditions by measuring changes in the magnetic field along three perpendicular axes (107).

The fundamental components of a magnetometer are:

- **Magnetic Sensors**: These sensors detect variations in magnetic flux density.
- **Three-Axis Measurement**: The magnetometer measures magnetic fields along three perpendicular axes, typically denoted as X, Y, and Z.

The operation of a magnetometer can be described using the following principles:

- **Detection of Magnetic Flux Density**: The magnetic sensors within the magnetometer detect the magnetic flux density ($B$) along the X, Y, and Z axes. This detection is based on the Hall effect or other magnetic sensing technologies.
- **Measurement of Magnetic Field Components**: The magnetic flux density along each axis is measured and represented as $B_x$, $B_y$, and $B_z$. The total magnetic field vector ($\mathbf{B}$) can be expressed as:

$$\mathbf{B} = \begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix}$$

- **Calculation of Field Magnitude and Direction**: The magnitude ($|\mathbf{B}|$) and direction of the magnetic field can be calculated using the components measured along the three axes. The magnitude is given by:

$$|\mathbf{B}| = \sqrt{B_x^2 + B_y^2 + B_z^2}$$

The direction can be determined using the vector components.

By integrating data from the three axes, a magnetometer can provide precise and comprehensive information about the magnetic field in its environment, aiding in various scientific and practical applications.

### 3.3.1 Inertial Sensors for Rigidity Analysis

Processing inertial signals from an IMU involves several steps to extract relevant information about the movement and orientation of the object to which the IMU is attached.

Initially, inertial sensors in the IMU, such as accelerometers and gyroscopes, record the linear and angular accelerations experienced by the object in which they are installed. These raw signals are often affected by noise and distortion, so the first step in signal processing is to perform filtering to remove unwanted artifacts and improve data quality. Commonly used filtering techniques include low-pass filters to eliminate high-frequency noise and high-pass filters to remove low-frequency drift. For example, a Butterworth filter, known for its smooth frequency response, can be employed to achieve this purpose (33, 58).

After filtering, relevant features are extracted from the inertial signals to describe specific aspects of the object's motion or dynamics. Previous studies have investigated the application of PSD to the evaluation of inertial signals (2), so that it is possible to decompose the variation of acceleration and angular velocity at different frequencies. This is essential for identifying movement patterns, including muscle rigidity in conditions such as PD. For example, muscle rigidity can manifest itself in low-frequency components in acceleration signals.

## 3.4 State of the Art

In the assessment of rigidity in PD using sEMG, several studies have provided valuable insights. Ferreira (43) conducted a systematic review on the quantitative measurement of rigidity in PD, highlighting the presence of an exacerbated long-latency reflex in sEMG signals of individuals with PD. Endo (38) introduced a novel method for the systematic analysis of rigidity in PD, showing significant differences in sEMG activity between control subjects and PD patients with varying levels of rigidity. In contrast, the study by Berardelli (16) investigated the size of the first agonist sEMG burst during wrist movements in PD patients, providing insights into muscle activity patterns. Additionally, the work of Rissanen (108) analyzed dynamic muscle contractions in PD patients using sEMG and acceleration measurements, offering a method for discriminating muscle activity between PD patients and healthy controls. These studies, although not directly focused on rigidity assessment, contribute to the broader understanding of sEMG analysis in motor function evaluation in PD.

Analyzing the accelerometer signals in the context of assessing motor function in PD is crucial for understanding movement patterns and abnormalities. The significant difference observed between groups, particularly in the X and Y axes, suggests distinct characteristics in wrist movements that can be attributed to the responsibility of the Y axis for wrist flexion and extension movements. Some previous studies also used an accelerometer to quantify rigidity. For instance, the study of Mak (65) focused on quantifying trunk rigidity in PD patients, indicating the feasibility of objective measures to differentiate PD patients from control subjects based on rigidity levels. These findings are in line with the present study, highlighting the difference between the groups and the correlation with MDS-UPDRS. In a related context, the work of Daneault (31) on smartphone monitoring of PD emphasized objective quantification of symptom severity using wearable sensors, including accelerometers.

The studies by Endo et al. and Lee et al. (39, 59) provide valuable insights into the velocity-dependent features of muscle tone and the pathophysiology of spasticity and rigidity in patients with PD. Endo et al. (39) investigated the velocity-dependent characteristics of muscle tone using a torque meter during elbow flexion at a constant speed,

revealing velocity dependence in rigidity among individuals with PD. Similarly, Lee et al. (59) conducted a quantitative analysis of the velocity-related pathophysiology of spasticity and rigidity in the elbow flexors, indicating that rigidity and spasticity exhibit approximately equal velocity-dependent properties. In previous studies, Kwon et al. (56) compared sEMG during passive stretching and shortening phases of muscles to study parkinsonian rigidity, emphasizing the increased resistance during passive joint movement as a cardinal feature of PD. Powell et al. (98) investigated amplitude- and velocity-dependency of rigidity measured at the wrist in PD, elucidating the biomechanical underpinnings and physiological characteristics of rigidity. These findings underscore the importance of movement speed in assessing muscle rigidity and motor symptoms in PD.

## 3.5 Materials and Methods

### 3.5.1 Rigidity Evaluation

Assessing rigidity, as previously stated, is a crucial part in the diagnosis and monitoring of neurological disorders, such as PD. In this context, the use of sEMG and IMU, can play a fundamental role in obtaining objective and accurate data.

The electromyograph is a device designed to capture the electrical signals produced by muscles during contraction/distension. Through strategically positioned electrodes, the device records muscle activity, providing valuable information about muscle rigidity in PD patients. The amplification and filtering of these signals are essential to guarantee the quality of the data collected (27).

On the other hand, the IMU is a sensor capable of measuring the orientation and acceleration of an object in three-dimensional space. Composed of a gyroscope, accelerometer and magnetometer, the IMU provides accurate data on the patient's movements during rigidity assessment.

In this study, we used sEMG and IMU to assess rigidity in PD patients and healthy individuals. The sEMG device was previously developed and validated at the Núcleo de Tecnologia Assistiva (NTA) at the Federal University of Uberlândia (UFU). The capture device using IMU, so-called Tremor Detection Technology - TREMSEN, was also developed and validated in previous studies by the Núcleo de Inovação e Avaliação Tecnológica em Saúde (NIATS) at UFU.

The decision to develop our own sEMG system stems from the need to adapt the device specifically for this study. Additionally, develop customized software for data collection, allows precise control of data acquisition settings and real-time monitoring. This software ensures that sEMG signals are accurately captured and processed according to the specific requirements of this study. This approach provides greater flexibility for modifications

based on iterative testing and feedback, ensuring the device meets the unique challenges of our research. Furthermore, developing an in-house system is more cost-effective compared to commercial devices.

In the same sense, the TREMSEN device, developed and validated at UFU, was selected due to its proven reliability and accuracy in capturing high-resolution data (12). This capability is crucial for a comprehensive rigidity analysis. The development of the TREMSEN system within the same research environment ensures seamless integration with the customized sEMG system, facilitating a cohesive and efficient assessment process, adapted to the specific needs of this study.

Next, the operation and configuration of these devices will be described in detail, as well as the experimental protocol used for data collection. This information is fundamental to understanding how the data was acquired and analyzed, contributing to an accurate and objective assessment of muscle rigidity.

**Electromyographic device**

The developed sEMG amplifier contains two channels, shown in Figure (3.1). The acquisition of the sEMG signals were carried out using standard disposable surface electrodes.



Figure 3.1 – sEMG device.

The initial phase involves differential amplification, which aims to eliminate typical noises that occur in the vicinity of the two electrodes. For this, an INA 155 instrumentation amplifier, was used, wich is known for its high Common Mode Rejection Ratio (CMRR) of 90 dB. The purpose of this stage was to amplify the input signal by a factor of 20.

The second stage consists of a passive RC filter to eliminate possible low frequency components from the skin. Then, signal amplification was performed, since the muscle signal detected in the skin has low amplitude, around 10 mV, and with the aim of improving the Signal-to-Noise Ratio (SNR). An MCP601 amplifier with adjustable gain was

utilized for this stage, allowing the signal to be increased by a factor of either 760, 1000, or 1200.

The third stage consists of filtering the sEMG signal. Filtering is necessary to delimit the frequency band that the signal is acquired. The sEMG signal spectrum is tipically between 20 Hz and 1000 Hz, with a greater signal predominance from 20 Hz to 250 Hz. For this stage, a 20 Hz high-pass filter and a 500 Hz low-pass filter were designed. Signal digitization was performed using the Arduino Uno microprocessor. This step is responsible for discretizing the analog sEMG signal. The resolution of the microprocessor used is 8 bits, and the sampling rate was 1000 Hz, obeying the Nyquist theorem (22). Figure 3.2 shows the electrical diagram of one channel.

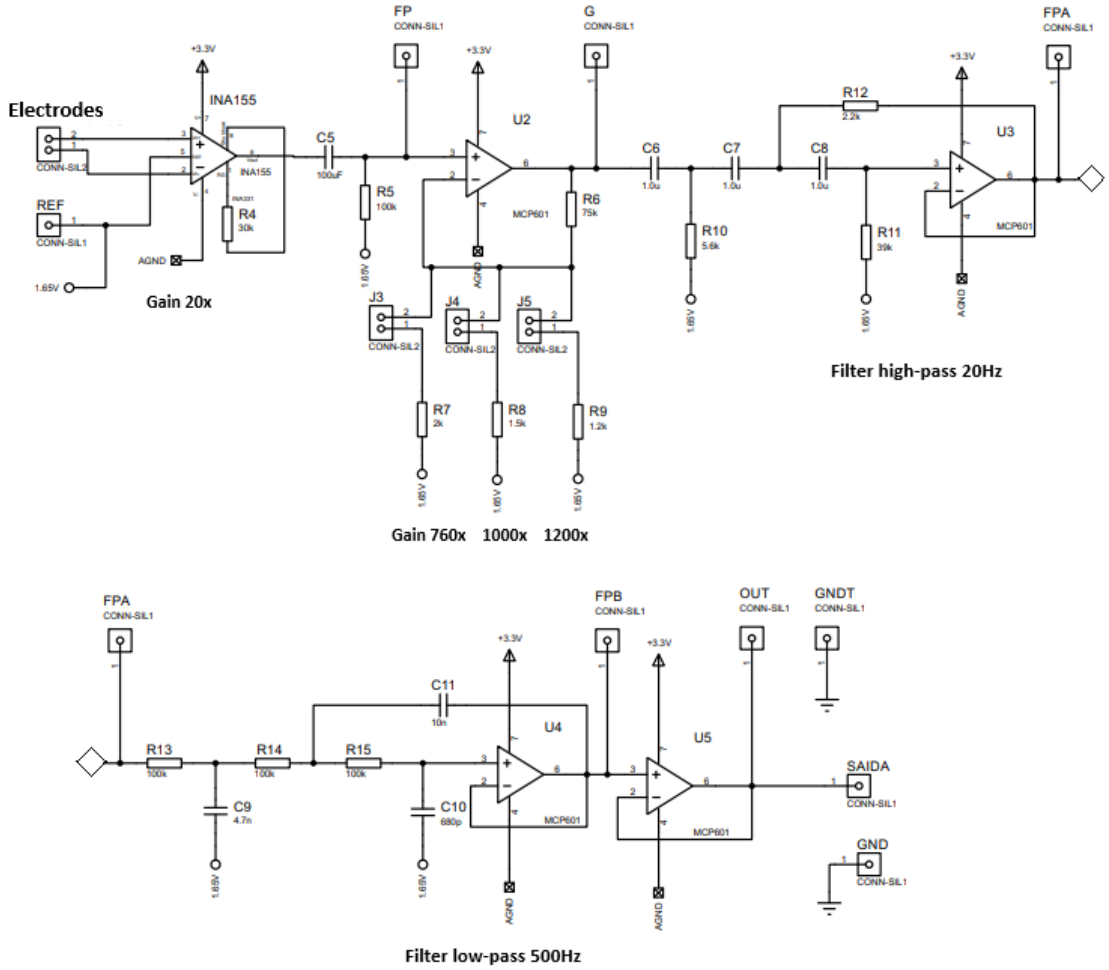


Figure 3.2 – sEMG circuit diagram.

The choice of Arduino Uno for signal digitization is driven by several key factors. Its 8-bit resolution, while corresponding to 256 discrete levels, is adequate for the typical voltage range of sEMG signals when amplified to fit within the 0 to 5 volts input range, providing sufficient detail for analysis. The Arduino Uno is cost-effective, widely accessible, and offers enough processing power for real-time signal acquisition and basic filtering. Its extensive support community and flexibility for integration with other sensors, like IMU, further enhance its suitability for this application, making it an ideal

choice for prototyping and development in this study. Figure 3.3 shows the diagram of all the stages of the acquisition system.

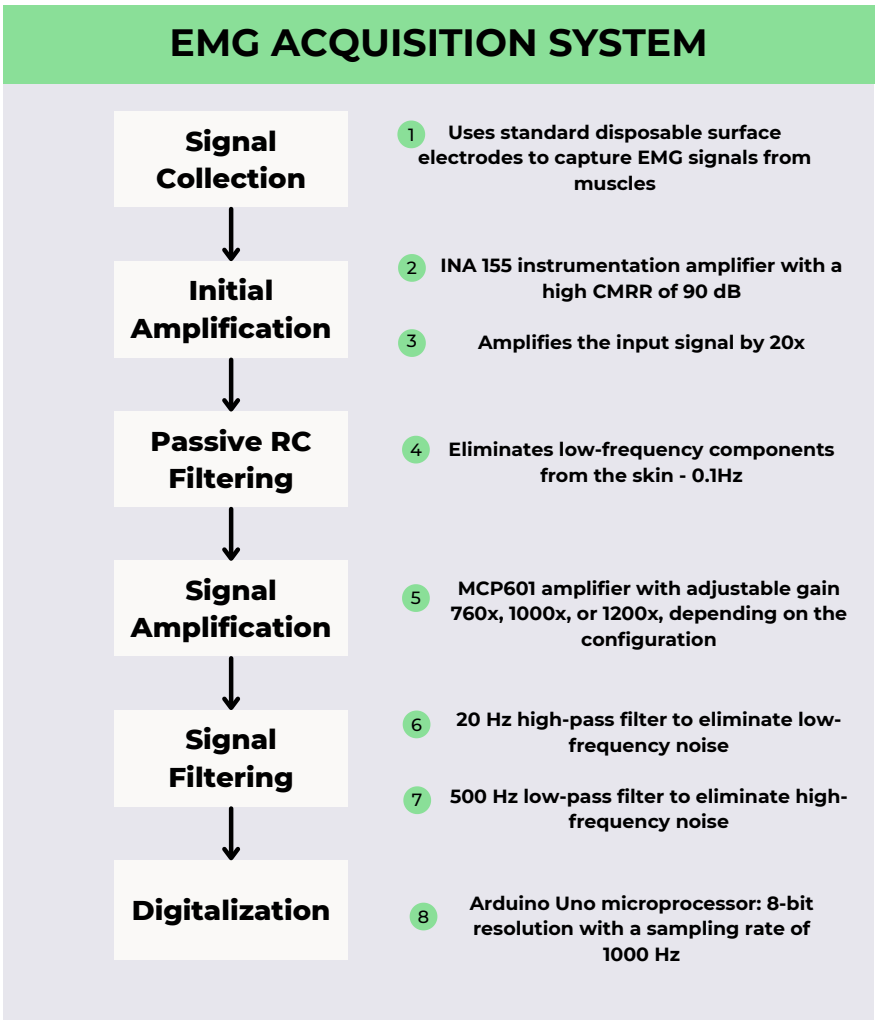


Figure 3.3 – sEMG circuit diagram.

The system's general interface was developed in the C# language, using the Visual Studio platform. On the interface, it is possible to view the data collected in real time.

The experimental procedure involved positioning two sEMG sensors on the participants' forearm, specifically on the flexor and extensor muscles of the wrist. The placement of the sEMG sensors can be seen in Figure 3.4. Data were collected from the most affected side of individuals with PD and from the dominant hand of healthy individuals.

### IMU device

The TREMSEN system (Precise Tremor Detection Technology, National Institute of Intellectual Property - Brazil - BR 10 2014 023282 6) (87) was used for data acquisition, 3.5. Each IMU consists of a gyroscope (L3G4200D, STMicroelectronics, Switzerland) and a combined accelerometer and magnetometer unit (LSM303DLM, STMicroelectronics, Switzerland).

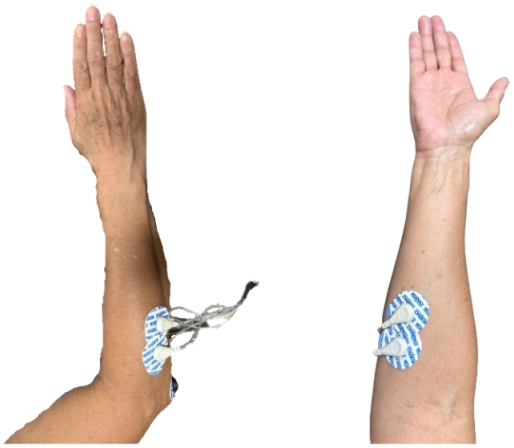

Figure 3.4 – sEMG electrodes positioning.

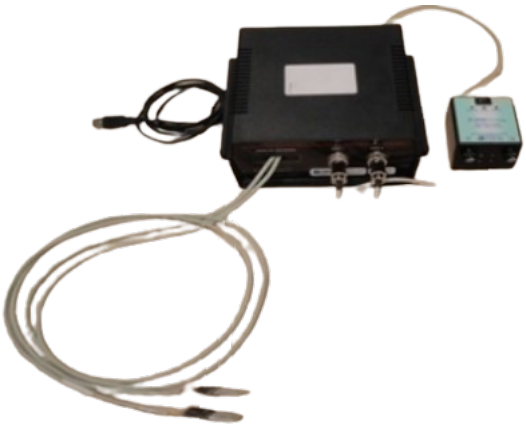

Figure 3.5 – TREMSEN device.

IMU sensitivity settings can be adjusted individually via I2C communication. Gyroscope, accelerometer, and magnetometer sensitivities were set to ±500 degrees per second (dps), ±4 g, and ±2 Gauss, respectively, for all participants. These settings were used in previous studies (101), and were selected to avoid saturation of the signal conditioner. Signals were sampled at 50 Hz and digitized by a 12-bit analog-to-digital converter.

The experimental protocol involved placing two inertial measurement units IMU on the participants' hand and forearm. The IMU positioning can be seen in Figure 3.6. Data were collected from the most affected side of individuals with PD and from the dominant hand of healthy individuals.

### 3.5.2 Experimental Protocol

This research received approval from the Ethics Committee for Human Research at the UFU. The study consisted of fifteen individuals who had been diagnosed with PD, comprising the experimental group (Experimental Group (EG)), and an equal number of healthy persons, comprising the control group (Control Group (CG)). The participants in both groups were paired according to their age and gender. Participants in the EG

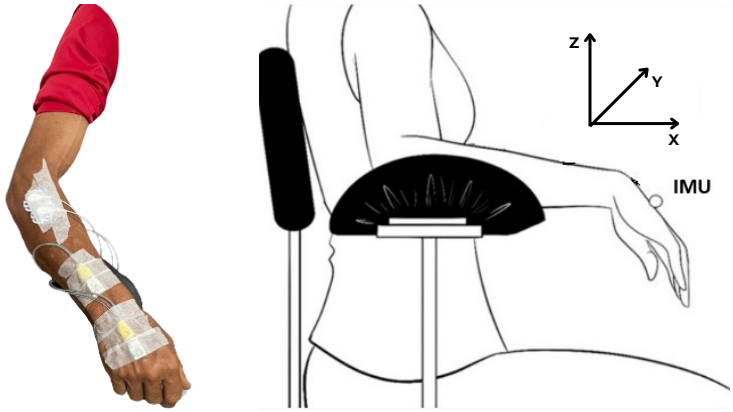


Figure 3.6 – IMU sensors positioning.

group were involved in two conditions: while they were under the influence of medicine ("on" medication state) and when they were not taking any medication ("off" medication state). The eligibility criteria were:

- having a confirmed diagnosis of PD, performed by a neurologist or geriatrician
- to be between 18 and 100 years old
- not have a history of other neurological or musculoskeletal diseases
- have wrist rigidity
- have a mild to moderate stage of PD (Hoehn and Yahr levels I, II, and III)
- have a Mini Mental State Examination (MMSE) score $\geq 21$
- not have severe visual and hearing impairments

At first, the participants completed the Free and Informed Consent Form. The data collection commenced by registering the participants' personal information, including their name, age, duration of the disorder, and affected side. Subsequently, the therapist conducted assessments of the patients using nominal scales, namely (MDS-UPDRS) and Hoehn & Yahr scale.

All assessments were conducted by the same professional, a physiotherapist with a Ph.D. in biomedical engineering and extensive clinical experience. This consistency ensured the reliability and accuracy of the evaluations across all participants.

Then, the process of collecting biological signals (electromyography and inertial sensors) through the devices began. Firstly, the person was asked to rest, to obtain their base signal. Next, the maximum voluntary contraction was measured. For this, 3 maximum contractions were performed for each muscle. Then, the data collection was divided into three stages: 15 passive stretches performed in fast velocity, 15 passive stretches performed slowly and 15 active movements. To collect this data, some steps were followed:

- Position the participant comfortably seated, respecting the angles of the joints
- Clean the skin with alcohol and cotton, in the place where the adhesive electrodes were fixed
- Position the electrodes and sensors to measure the muscle signal and also the inertial sensors, following the SENIAM (Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles) protocol (119);

The therapist performed passive stretching on the participant's wrist by aligning it with the forearm and then stretching it from maximum extension to full flexion, repeating this movement 15 times.

In the case of passive stretching, patients were instructed to keep the forearm and wrist in a neutral position and not to perform voluntary contractions during the collection. This procedure was performed at two different speeds, fast and slow, according to common clinical evaluations (47). Regarding active stretching, participants were instructed to perform the complete wrist extension and flexion movement 15 times. The signals were synchronized using a trigger connected to both devices.

### 3.5.3 Signal Processing Data

In many applications, processing inputs from diverse sources, such as sEMG and IMU, is essential. A number of crucial procedures must be followed while processing sEMG and IMU signals in order to extract pertinent and helpful data. This involves using amplification techniques to boost the amplitude of the signal, filtering to get rid of extraneous noise and artifacts, and rectification to make sure that only pertinent data is taken into account. To find patterns, trends, and distinguishing features in data, sophisticated signal processing techniques including spectrum analysis and feature extraction techniques are frequently used.

Understanding human movement and patterns of muscle and motor activity can be improved by combining sEMG and IMU signal processing. Consequently, signal processing is essential to deriving valuable and significant information from the unprocessed data that acquisition devices gather, allowing for more in-depth investigation and comprehensive comprehension.

#### sEMG signal processing

The processing of sEMG signals involves several steps to extract relevant information about muscle activity. The entire signal processing stage was carried out using the R-Studio and R language (113, 100). Figure 3.7 shows the flow diagram of the sEMG signal processing. Each of the steps carried out in this study is described below (27):

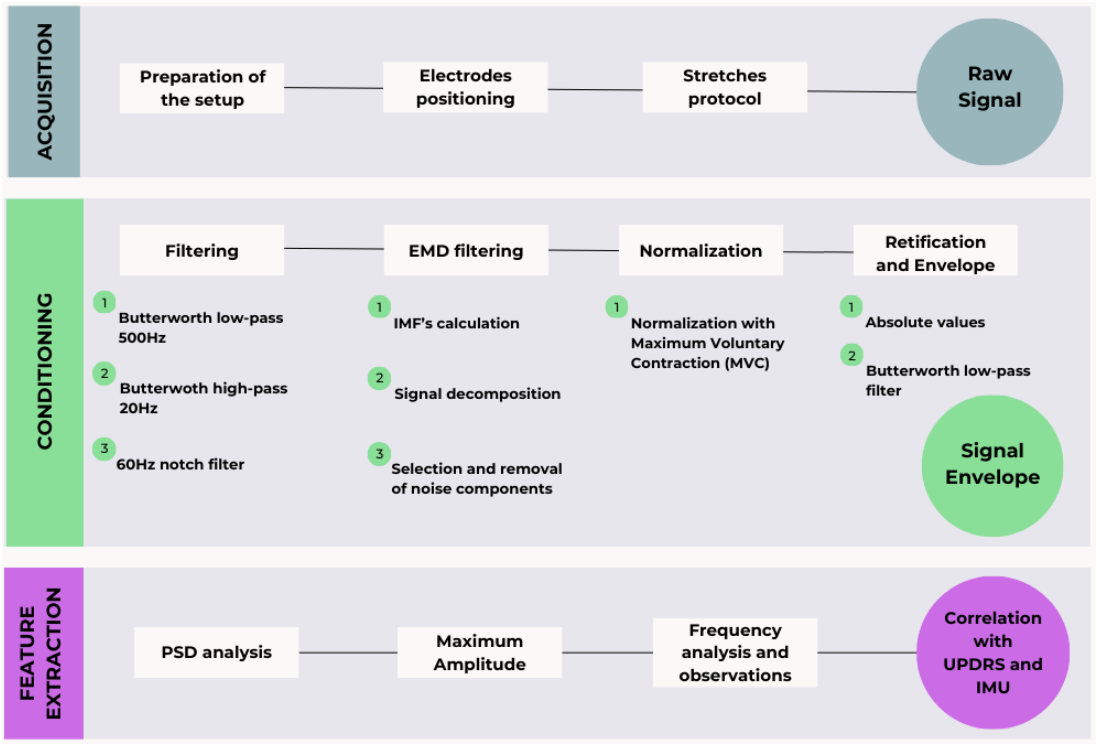


Figure 3.7 – sEMG signal processing steps.

- Signal Segmentation: To enable later synchronization with the signals from the IMU, the sEMG signals were first divided into segments based on a trigger. To guarantee that the sEMG and IMU data match the same events during analysis, this segmentation is crucial.

- High-Pass and Low-Pass Filtering: The sEMG signals were subjected to a high-pass filter and a low-pass filter to remove noise and ensure that only frequencies relevant for analyzing muscle activity are retained. At this stage, a Butterworth filter of order 4 was applied, a low pass with a cutoff frequency of 500 Hz, a high pass with a cutoff frequency of 20 Hz, and a notch filter at 60 Hz. The frequency values for the filters were chosen based on the typical characteristics of sEMG signals and the need to remove noise and irrelevant frequencies to accurately analyze muscle activity. sEMG signal spectrum primarily lies between 20 Hz and 1000 Hz, with a greater predominance from 20 Hz to 250 Hz (27). This step can be seen in the Figure 3.8.

- Filtering Using the Empirical Mode Decomposition (EMD) Method: The EMD approach is an effective way to break down complex signals, like sEMG signals, into their fundamental frequency components, called Intrinsic Mode Functions (IMF's). It functions in an adaptive manner, recognizing and isolating particular frequency patterns found in sEMG impulses. The description of this method can be explained by the steps:

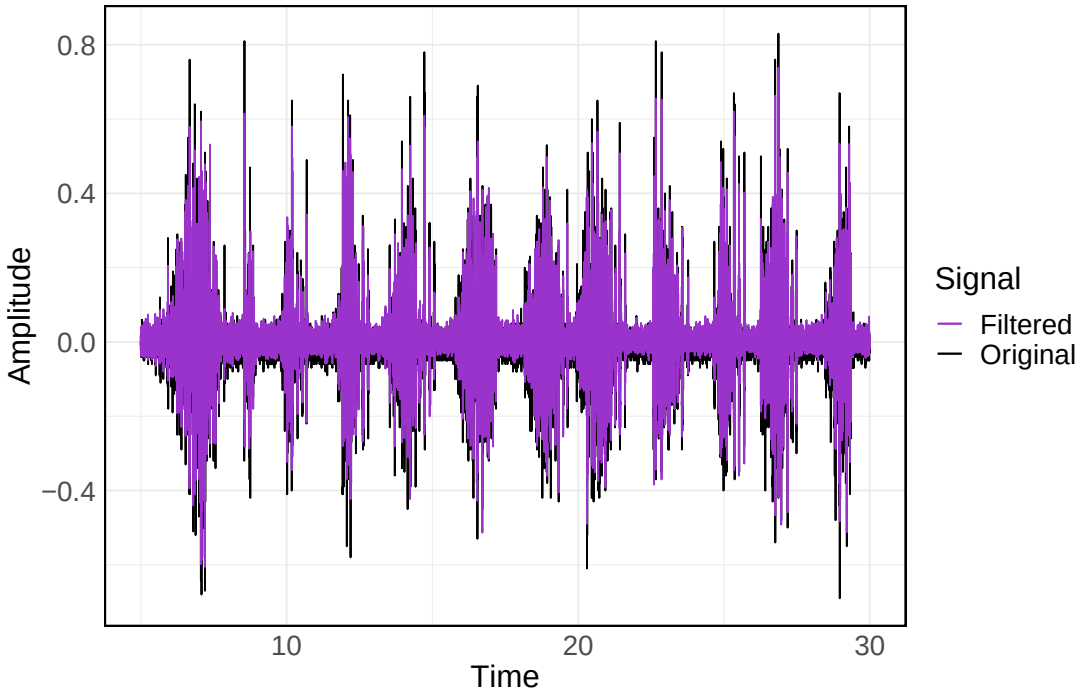


Figure 3.8 – Butterworth filtering.

1. **Identify Extremes**: Identify all the local maxima and minima of the signal $x(t)$.
2. **Envelope Construction**: Construct the upper envelope $e_{\max}(t)$ by interpolating between the local maxima, and the lower envelope $e_{\min}(t)$ by interpolating between the local minima.
3. **Mean Envelope Calculation**: Calculate the mean envelope $m(t)$:

$$m(t) = \frac{e_{\max}(t) + e_{\min}(t)}{2}$$

4. **Detail Extraction**: Extract the detail $h_1(t)$ by subtracting the mean envelope from the original signal:

$$h_1(t) = x(t) - m(t)$$

5. **Iteration and Sifting Process**: Treat $h_1(t)$ as a new signal and repeat steps 1-4 until $h_1(t)$ satisfies the conditions of an IMF.
6. **Extract IMF**: The first IMF is then $c_1(t) = h_1(t)$.
7. **Residual Calculation**: Subtract the extracted IMF from the original signal to obtain the residual $r_1(t)$:

$$r_1(t) = x(t) - c_1(t)$$

8. **Repeat for Residual**: Repeat the above steps for the residual signal $r_1(t)$ to extract further IMFs.

The signal $x(t)$ can thus be represented as a sum of IMFs and a final residual $r_n(t)$:

$$x(t) = \sum_{i=1}^{n} c_i(t) + r_n(t)$$

This comprehensive approach ensures that the EMD method adaptively isolates frequency components intrinsic to the signal, making it a powerful tool for filtering and analyzing sEMG signals. This step can be seen in Figure 3.9. This is particularly helpful for keeping parts of the signals that are relevant to muscle activity while also eliminating undesired artifacts and noise that could be present. The final EMD filtering can be seen in Figure 3.10.

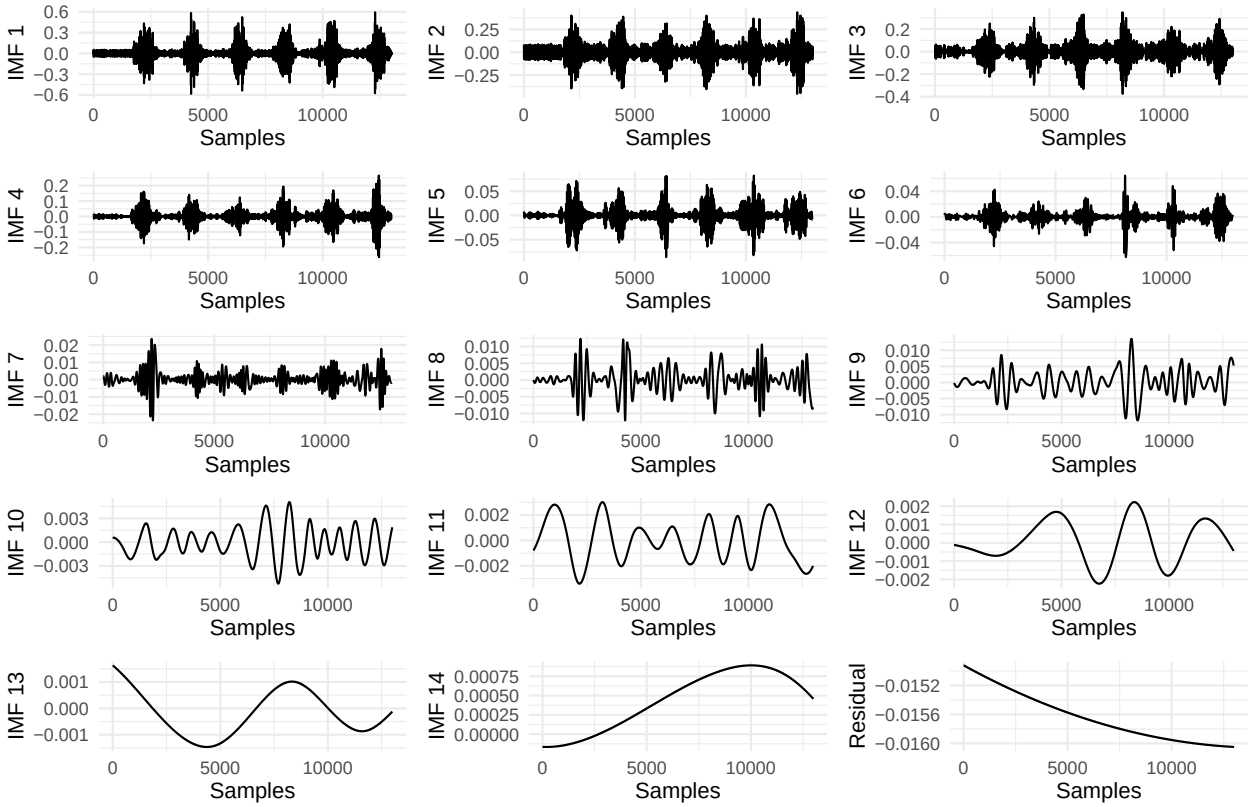


Figure 3.9 – EMD intrinsic components.

- Maximum Voluntary Contraction (MVC) Signal Normalization: Standardizing sEMG signal values requires the application of the MVC approach for signal normalization (27). This is particularly helpful because it unifies all signals on a standard scale for comparing various samples or people. In order to provide a more equitable and accurate comparison, normalization helps reduce differences in signal amplitude between people and data collection sessions.

- Rectification and Signal Envelope: After normalization, the sEMG signals are rectified to convert all negative components into positive ones. This highlights the

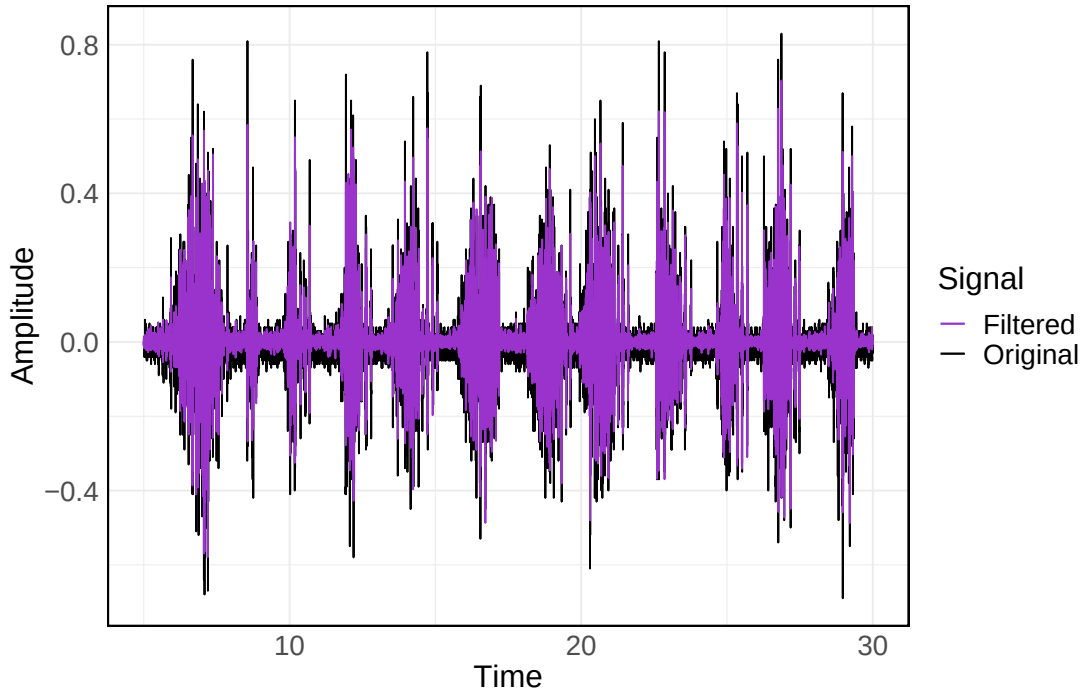


Figure 3.10 – EMD filtering.

magnitude of muscle activity, making it easier to detect and analyze muscle activation patterns over time. The signal envelope is then calculated to represent the envelope amplitude of the rectified signal. This provides a smoothed, continuous measurement of muscle activity, highlighting variations in the intensity of muscle contraction. This step can be seen in the Figure 3.11.

- Power Spectral Density (PSD): Finally, spectral analysis is performed to investigate the energy distribution in sEMG signals at different frequencies. PSD is calculated to identify muscle activation patterns across different frequency ranges. This could reveal important information about the modulation of muscle activity, allowing for a deeper understanding of muscle activity patterns associated with rigidity in patients with PD. An example of PSD can be seen in Figure 3.12.

### IMU signal processing

Data processing was performed in R-Studio using R (113, 100), full steps can be seen in Figure 3.13.

TREMSEN-Toolbox (12), which is a set of tools developed for processing signals collected with TREMSEN, was used for signal pre-processing. The objective of signal windowing was to select regions of interest, in this case synchronizing with the sEMG signal. The window size was defined using a pulse, generated by a button (trigger), which was sent to the TREMSEN device during data collection, indicating the beginning and end of each experimental activity. It was necessary to resample the signals, as the TREM-

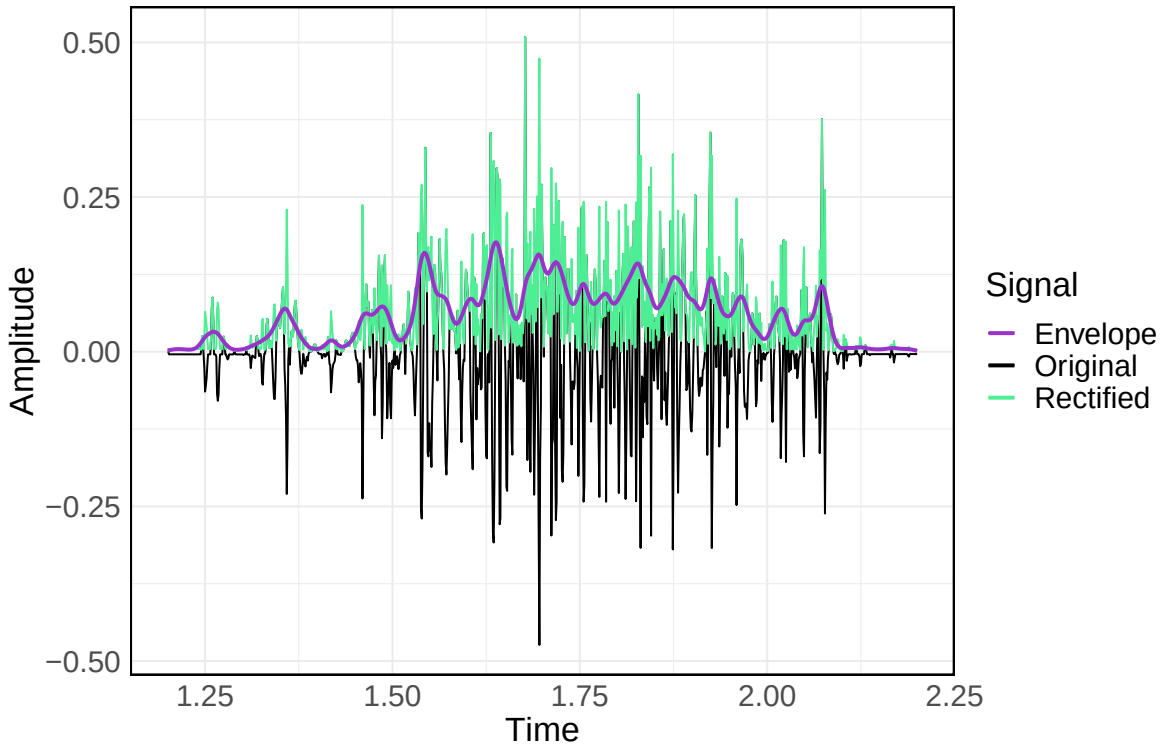


Figure 3.11 – Rectification and signal envelope.

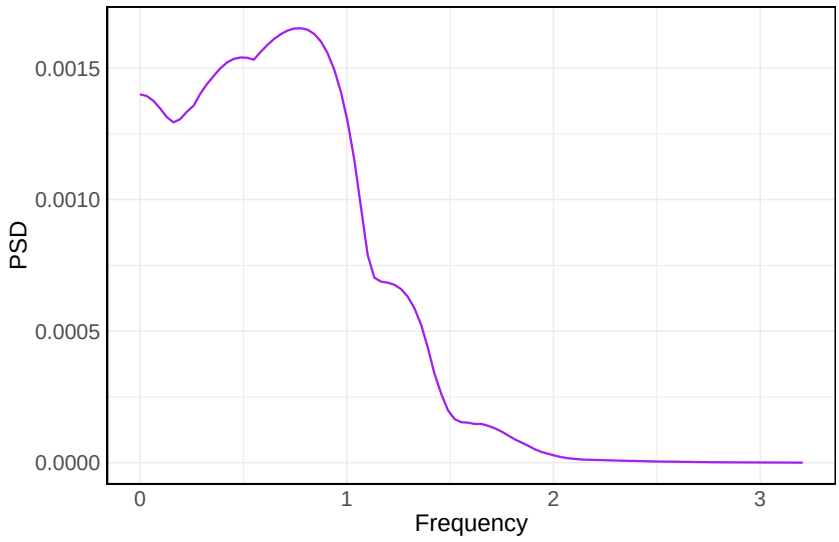


Figure 3.12 – Power Spectral Density of the sEMG signal envelope.

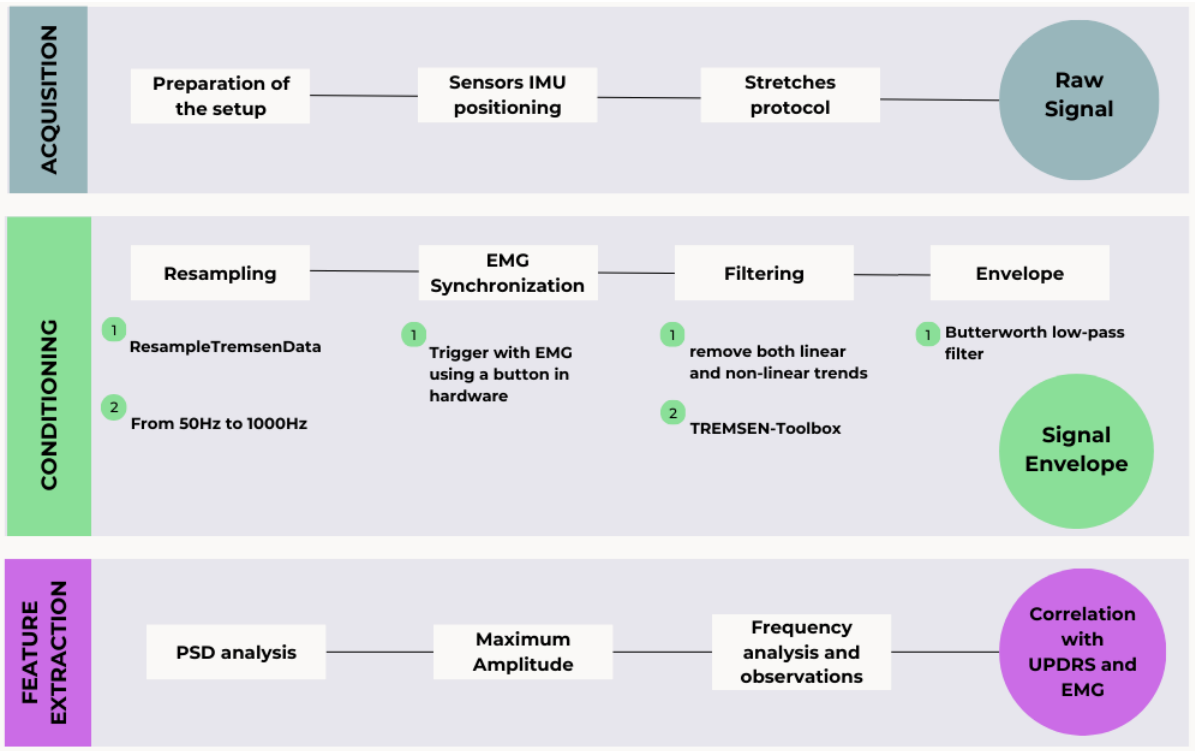


Figure 3.13 – Steps for processing IMU data.

SEN system has a fixed sampling rate set at 50 Hz. The ResampleTremsenData function, which uses a cubic spline (or Hermite) interpolation, was used for this purpose. This method ensures that the interpolated values follow the natural trajectory of the original data, preserving the signal's integrity and continuity. Cubic spline interpolation minimizes the risk of introducing artifacts and maintains the smoothness of the data, making it suitable for further processing and analysis. Its effectiveness in maintaining the true characteristics of the signal makes it an ideal choice for resampling the TREMSEN data.

The signal processing procedure involved the utilization of TREMSENToolbox and Thresholding libraries from the PDpack package to effectively remove both linear and non-linear trends. These libraries were specifically chosen due to their robust algorithms tailored for trend removal, ensuring accurate extraction of signal features. Following trend removal, the envelope technique was applied to accentuate amplitude characteristics over time, as depicted in Figure 3.14. This technique offered a refined visualization of signal intensity variations, facilitating the identification and mitigation of tremors within the signal. Then, the signals were subjected to PSD analysis, as shown in Figure 3.15. By calculating the PSD of these signals, it is possible to analyze the distribution of energy at different frequencies associated with movement.

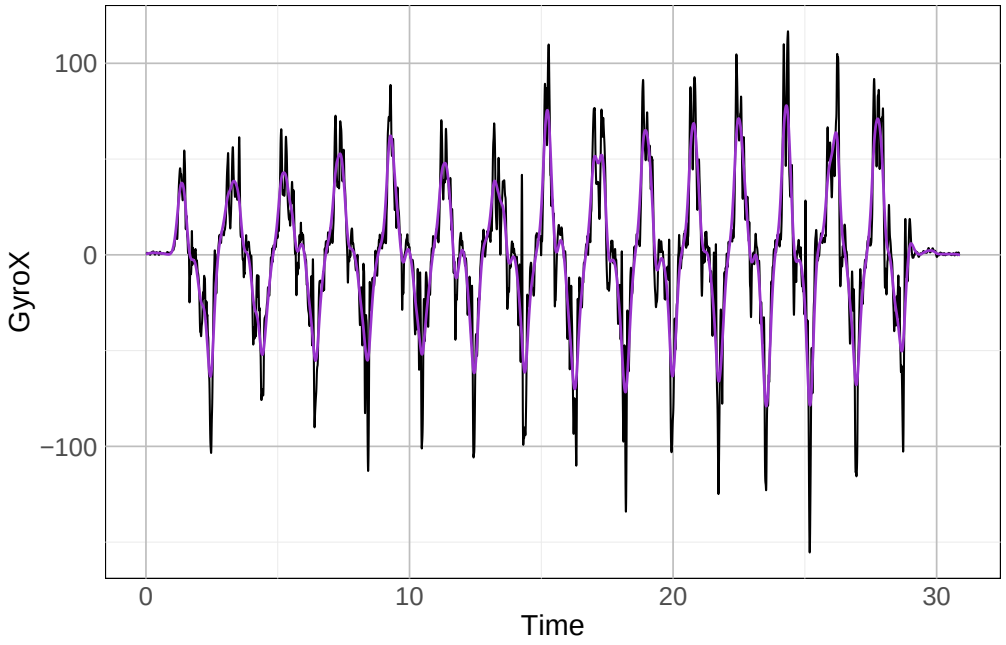


Figure 3.14 – Envelope of the IMU signals.

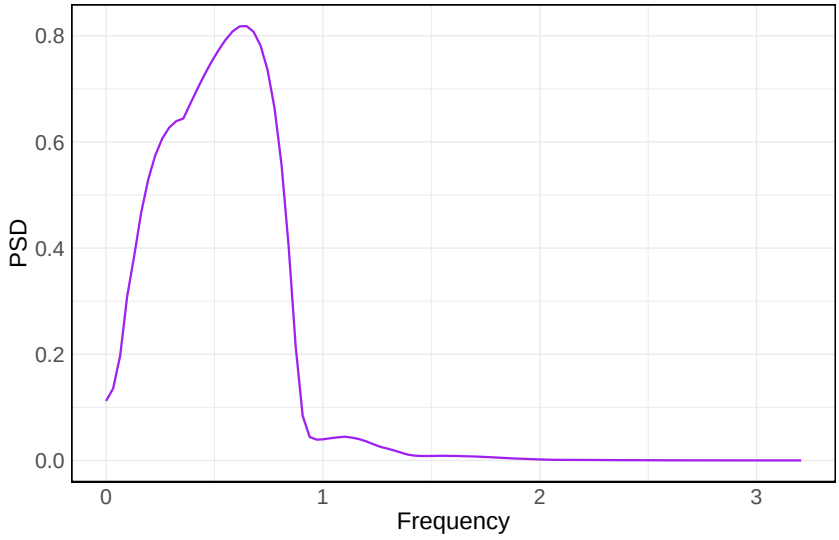


Figure 3.15 – PSD analysis for Gyroscope signals.

## 3.6 Results

For this experiment, 15 participants with PD and 15 healthy participants were recruited. Groups are gender and age matched. Each group was composed of 10 men and 5 women with an average age of 66.27 years. Table 3.1 summarizes the main characteristics of the participants.

Table 3.1 – Main characteristics of the participants of the study.

| **Control Group** | | | | **Experimental Group** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | **PD - OFF** | | **PD - ON** | |
| **ID** | **Sex** | **Age** | **MM** | **ID** | **Sex** | **Age** | **MM** | **UPDRS** | **H&Y** | **UPDRS** | **H&Y** |
| **79** | M | 82 | 27 | **65** | M | 57 | 29 | 61 | 3 | 25 | 2 |
| **72** | M | 64 | 29 | **53** | M | 80 | 21 | 49 | 2 | 25 | 2 |
| **59** | M | 80 | 23 | **25** | M | 64 | 25 | 58 | 2 | 26 | 2 |
| **37** | M | 66 | 30 | **43** | M | 77 | 26 | 44 | 2 | 31 | 2 |
| **76** | M | 51 | 30 | **68** | F | 59 | 30 | 47 | 3 | 24 | 2 |
| **75** | F | 56 | 30 | **24** | F | 64 | 29 | 48 | 2 | 39 | 2 |
| **46** | M | 77 | 29 | **28** | M | 70 | 28 | 41 | 2 | 20 | 2 |
| **78** | M | 62 | 23 | **66** | M | 73 | 28 | 45 | 3 | 42 | 3 |
| **69** | M | 60 | 30 | **40** | F | 60 | 30 | 29 | 2 | 12 | 1 |
| **80** | M | 80 | 27 | **60** | F | 66 | 29 | 29 | 1 | 16 | 1 |
| **71** | F | 69 | 30 | **39** | F | 69 | 30 | 70 | 3 | 37 | 2 |
| **73** | F | 59 | 30 | **36** | M | 60 | 25 | 54 | 2 | 31 | 2 |
| **77** | F | 62 | 23 | **49** | M | 50 | 29 | 59 | 4 | 35 | 3 |
| **74** | M | 55 | 30 | **29** | M | 68 | 25 | 52 | 2 | 38 | 2 |
| **35** | M | 71 | 29 | **26** | M | 77 | 27 | 38 | 1 | 11 | 1 |
| **OM** | | 66.27 | 28 | | | 66.27 | 27.4 | 48.26 | 2.27 | 27.47 | 1.94 |
| **SD** | | ±9.89 | ±2.78 | | | ±8.37 | ±2.56 | ±11.42 | ±0.79 | ±9.82 | ±0.59 |

OM: Overal Mean; SD: Standard Deviation; MM: Mini-Mental; H&Y: Hoehn & Yahr

The study employed ANOVA to assess age differences between the healthy and PD groups, revealing no significant distinction ($p>0.05$). Subsequently, the Kruskal-Wallis rank sum test was utilized to compare MDS-UPDRS III scores in medication "on" and "off" states, yielding a statistically significant difference ($p<0.05$) between these conditions. Conversely, ANOVA analysis on Hoehn and Yahr scores across medication states showed no substantial disparity ($p>0.05$). These findings suggest that while medication status influences motor function, it does not notably impact disease severity as measured by the Hoehn and Yahr scale.

The values related to upper limb rigidity, as assessed by items 3.3b and 3.3c of theMDS-UPDRS Part III, are summarized in Table 3.2. This table provides a detailed comparison of the rigidity scores in the different medication states, highlighting the variability and trends observed in the study participants.

The PSD obtained for healthy individuals and PD in the "on" and "off" states was compared in all the situations. Figure 3.16 shows an example of spectrum for the 3

Table 3.2 – Rigidity regarding superior members of the participants of the study.

| | PD - OFF | | | PD - ON | | |
|---|---|---|---|---|---|---|
| **ID** | **3.3b** | **3.3c** | **TOTAL** | **3.3b** | **3.3c** | **TOTAL** |
| **65** | 3 | 3 | 6 | 1 | 1 | 2 |
| **53** | 1 | 1 | 2 | 0 | 0 | 0 |
| **25** | 2 | 2 | 4 | 1 | 1 | 2 |
| **43** | 1 | 1 | 2 | 0 | 0 | 0 |
| **68** | 2 | 1 | 3 | 0 | 0 | 0 |
| **24** | 3 | 2 | 5 | 1 | 1 | 2 |
| **28** | 1 | 1 | 2 | 0 | 0 | 0 |
| **66** | 0 | 2 | 2 | 0 | 2 | 2 |
| **40** | 2 | 1 | 3 | 0 | 0 | 0 |
| **60** | 0 | 2 | 2 | 0 | 0 | 0 |
| **39** | 1 | 2 | 3 | 0 | 0 | 0 |
| **36** | 2 | 2 | 4 | 0 | 0 | 0 |
| **49** | 2 | 2 | 4 | 1 | 1 | 2 |
| **29** | 2 | 2 | 4 | 2 | 2 | 4 |
| **26** | 2 | 2 | 4 | 0 | 0 | 0 |
| **OM** | 1.6 | 1.73 | 3.33 | 0.4 | 0.53 | 0.93 |
| **SD** | 0.91 | 0.59 | 1.23 | 0.63 | 0.74 | 1.28 |

groups (15 healthy participants and 15 PD in “off” and PD “on” states), with matched ages between participants (healthy and PD), for sEMG evaluations.

It can be observed that the frequency contents of the PSD progressively reduce with the increase of rigidity, suggesting changes in muscle function when the patient is in the “off” medication, which is consistent with the UPDRS values (3). Another interesting fact was that healthy people showed greater power value in the frequencies evaluated. The lower power amplitude observed in individuals with PD could mean changes in rhythmic muscular behaviour caused by rigidity. This highlights a notable decrease in oscillatory patterns within the signal, underlining a diminished muscle fluctuation, even during the execution of a motor activity (43).

### 3.6.1 Active movements

Firstly, the situation where the subject performs the movement by itself was analysed (active movement). The PSD was calculated for each signal segment. This resulted in an energy distribution of the signals at different frequencies, as the one shown in Figure 3.16. Differences in spectral features, such as maximum amplitude between groups were identified and analysed. The Kruskal-Wallis test was applied to evaluate possible differences between groups.

Highlighting differences in spectral characteristics between groups may be critical to understanding changes in muscle function in patients with PD. For this, a boxplot, shown in Figure 3.17, was employed to compare the three groups: “off” medication, “on” med-

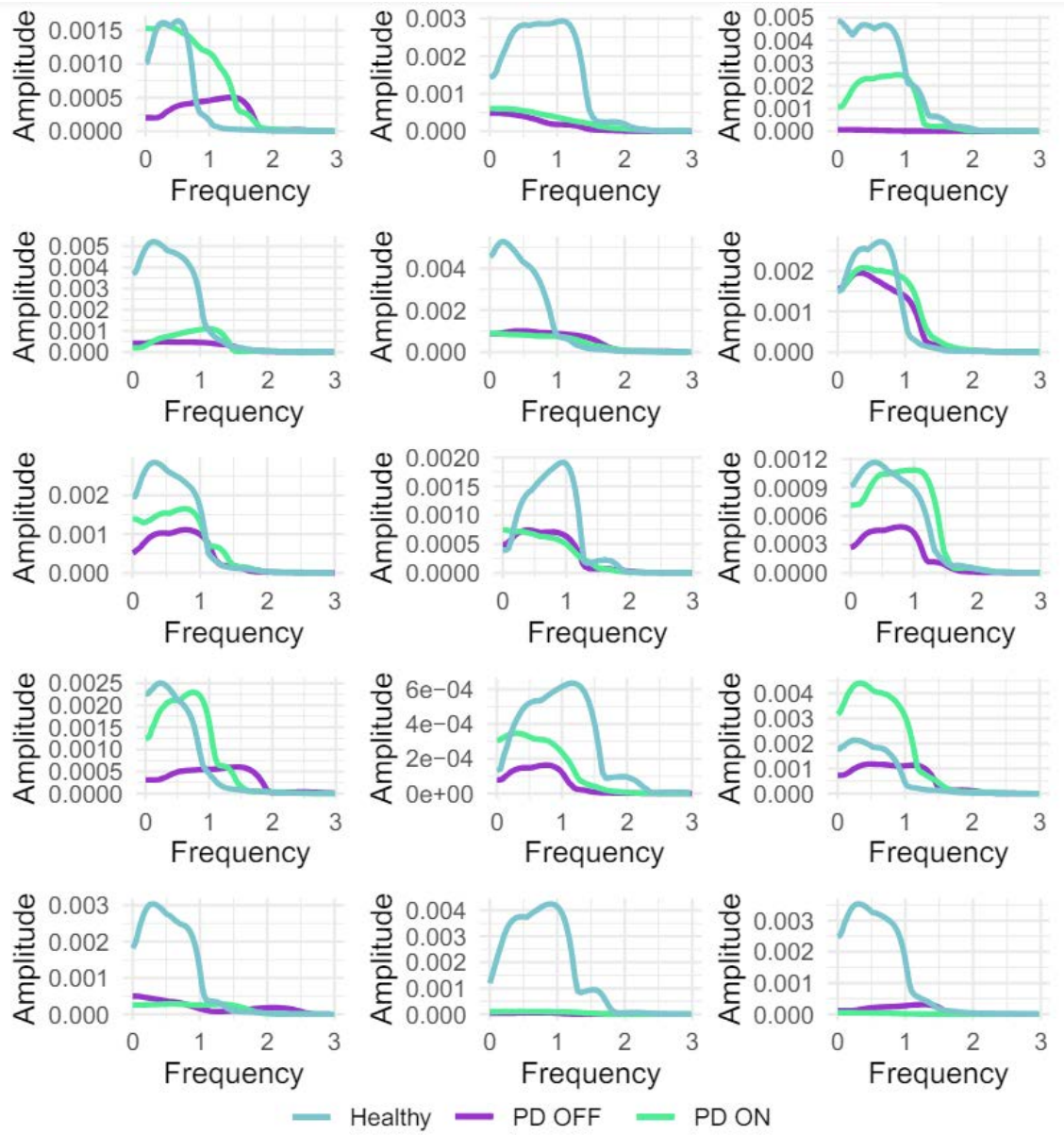


Figure 3.16 – PSD for the sEMG in extensor muscle for the three groups.

ication, and healthy individuals, in addition to analyzing the two specific muscles. The importance of this analysis lies in the ability to identify distinct patterns of muscle activity between groups, highlighting differences in muscle function associated with the level of rigidity and medication status.

The maximum value of PSD in sEMG signals from wrist flexor and extensor muscles reveals differences between healthy individuals and patients with PD. In PD, especially during the medication "off" state, muscle rigidity reduces this value, reflecting the difficulty of the neuromuscular system in responding to motor commands. With medication ("on"), there is a temporary improvement, but the value may still not reach healthy levels.

Regarding accelerometer signals during active movements, we can also observe a significant difference between the groups, shown in Figure 3.18. However, for the X and Y axes this difference is more evident. This can be observed since axis Y is responsible for

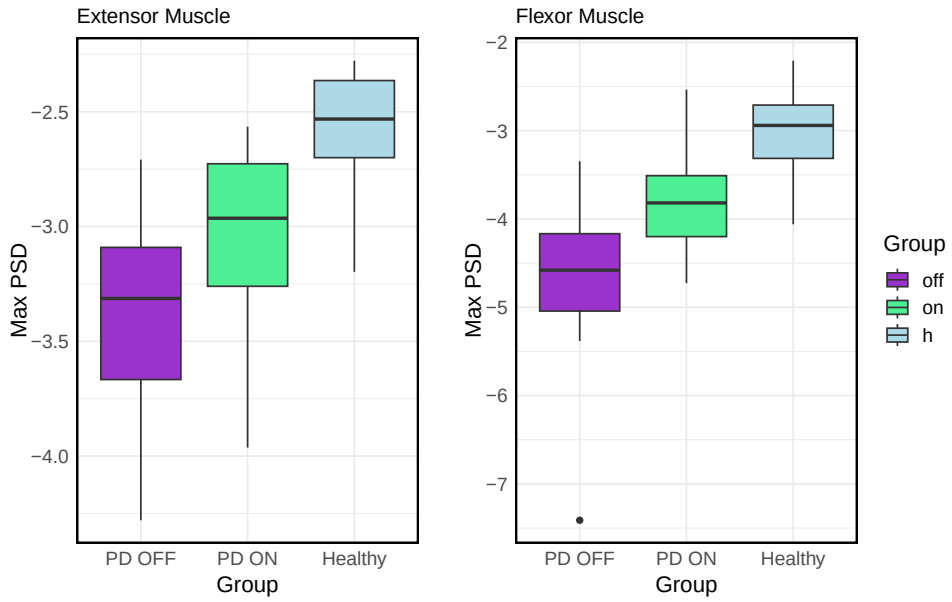


Figure 3.17 – Boxplot with the difference between the groups during the active movements. a) Extensor muscle. b) Flexor muscle.

wrist flexion and extension movements, in the TREMSEN equipment.

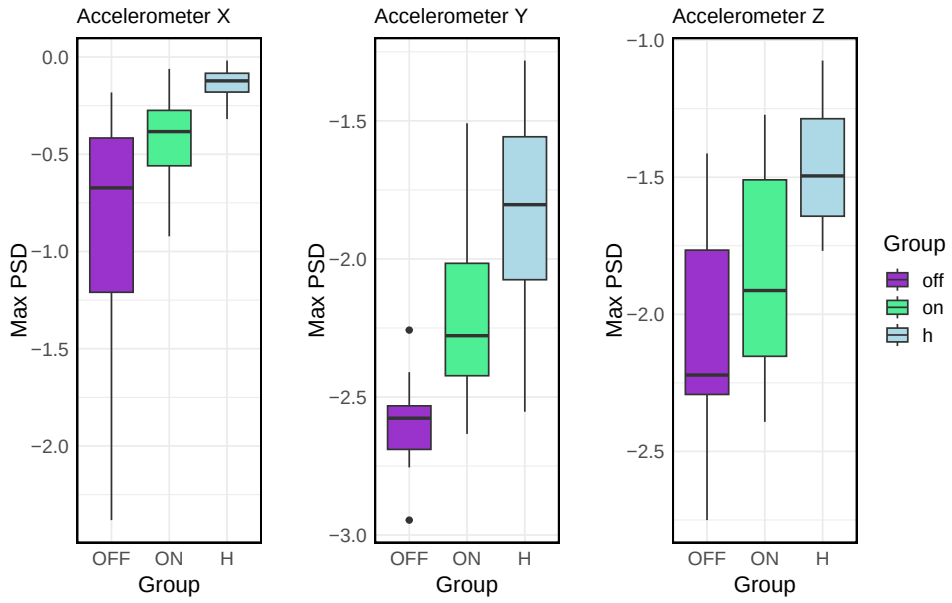


Figure 3.18 – Boxplot with the difference between the groups during the active movements.

For TREMSEN, the Z axis is observed in the adduction and abduction movements of the wrist, which can occur simultaneously with other movements, highlighting the importance of considering multidimensional variations in inertial sensor data for a comprehensive assessment of motor function in PD.

The gyroscope data is detailed in the Figure 3.19. There were also significant differ-

ences between the groups for the three axes.

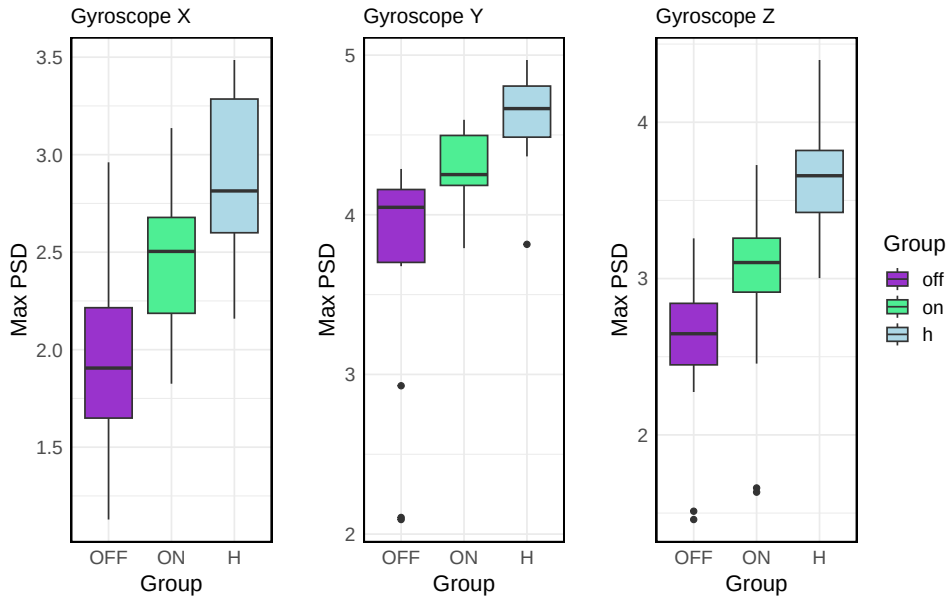


Figure 3.19 – Boxplot with the difference between the groups during the active movements.

PSD analysis on the gyroscope revealed that healthy subjects showed a greater PSD value compared to PD groups. This suggests that healthy individuals may be executing movements with greater angular velocity or with more fluid movement patterns compared to the EG group.

The analyses during active movement for the magnetometer can be seen in the Figure 3.20.

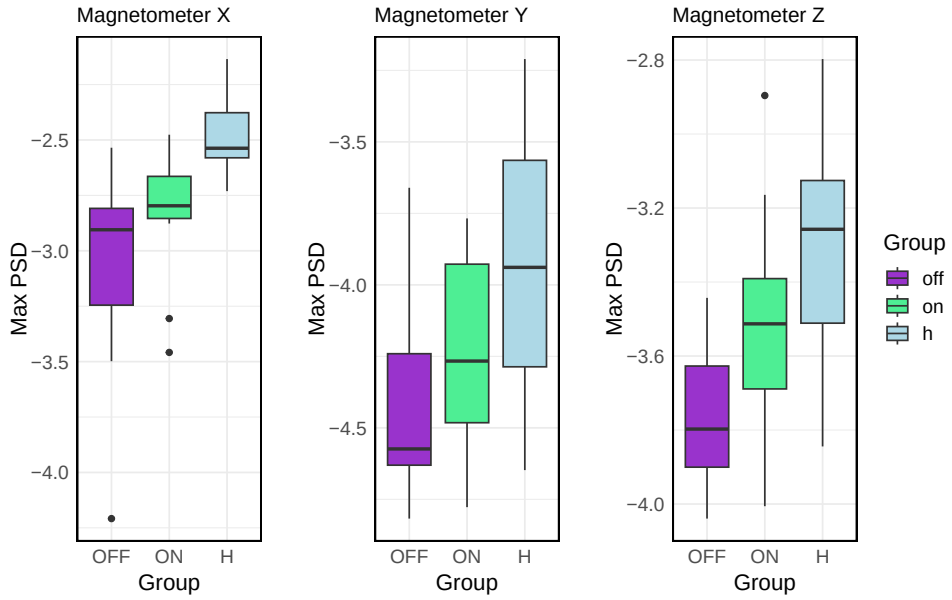


Figure 3.20 – Boxplot with the difference between the groups during the active movements.

The magnetometer proved capable of distinguishing healthy individuals from patients with PD, indicating its usefulness in analyzing movement. However, the differences observed between the "on" and "off" groups may not be as pronounced as expected, suggesting a relatively lower sensitivity in this specific context.

The Kruskal-Wallis test was applied to evaluate possible differences between groups. The correlation with the MDS-UPDRS, was also measured regarding rigidity values (Part III, items 3.3b and 3.3c). In Table 3.3 it is possible to see the results.

| Sensor | Correlation UPDRS | Statistical Difference (p-value) OFF - H | ON - H | ON - OFF |
|---|---|---|---|---|
| **AccX** | -0.70 | $< 0.001$ | 0.15 | 0.007 |
| **AccY** | -0.59 | $< 0.001$ | 0.006 | 0.003 |
| **AccZ** | -0.59 | $< 0.001$ | 0.009 | 0.08 |
| **GyroX** | -0.75 | $< 0.001$ | 0.02 | 0.006 |
| **GyroY** | -0.60 | $< 0.001$ | 0.17 | 0.003 |
| **GyroZ** | -0.48 | $< 0.001$ | $< 0.001$ | 0.10 |
| **MagX** | -0.78 | $< 0.001$ | 0.009 | 0.10 |
| **MagY** | -0.16 | $< 0.001$ | 0.08 | 0.33 |
| **MagZ** | -0.58 | $< 0.001$ | 0.07 | 0.02 |
| **M. Extensor** | -0.73 | $< 0.001$ | 0.006 | 0.03 |
| **M. Flexor** | -0.55 | $< 0.001$ | 0.02 | 0.002 |

Table 3.3 – Statistics regarding active movements evaluations.

The variables AccX, GyroX, MagX, and sEMG in the extensor muscle had strong correlations (>0.7) with UPDRS. Furthermore, statistical analyses found significant disparities across groups in a variety of characteristics. For all factors, the "off" and "h" groups showed the most significant differences. The variables AcxX, GyroX, GyroY, MagX, and sEMG in the flexor muscle showed the most changes between the "on" and "off" groups. These findings show that these sensors and sEMG data could be effective in identifying rigidity between Parkinson's disease stages.

### 3.6.2 Slow passive movements

To evaluate the influence of speed on rigidity detection, slow passive movements of wrist extension and flexion were conducted. During these movements, the therapist performed the actions according to the clinical assessment scales, aiming to replicate as much as possible the conditions found in clinical practice. This approach allowed for a more accurate analysis of rigidity at different movement speeds.

For this, the same parameters were analyzed in all conditions, allowing for a direct comparison between different movement speeds. First the sEMG for both muscles, flexor and extensor, as shown in Figure 3.21.

It was observed that it was possible to distinguish between the groups using sEMG data, although this differentiation was more evident for the flexor muscle compared to

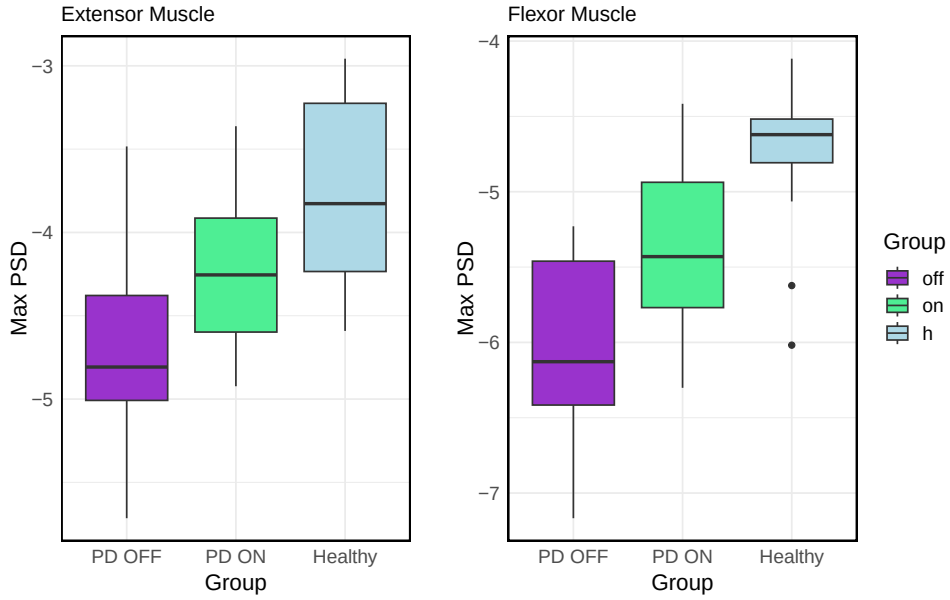


Figure 3.21 – Boxplot with the difference between groups during slow passive movements.

the extensor.

In Figure 3.22, it is possible to observe the results for the three groups using the accelerometer.

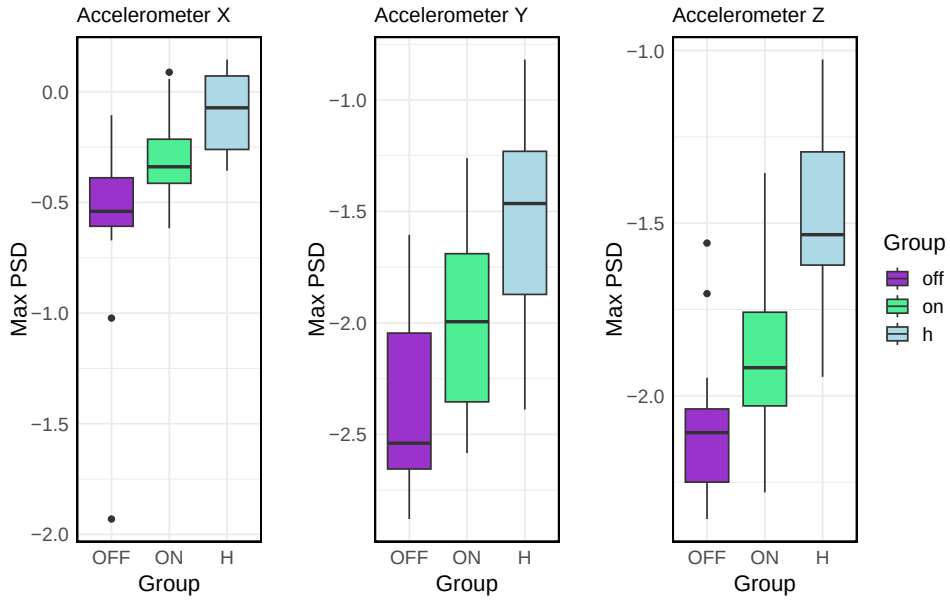


Figure 3.22 – Boxplot with the difference between the groups during slow passive movements.

The results also showed that the most evident differences in the accelerometer data were observed in the Z axis. This suggests that movement along this axis may be especially relevant for distinguishing between the groups studied, when applied at slow speed.

The results for gyroscope data can be seen in Figure 3.23.

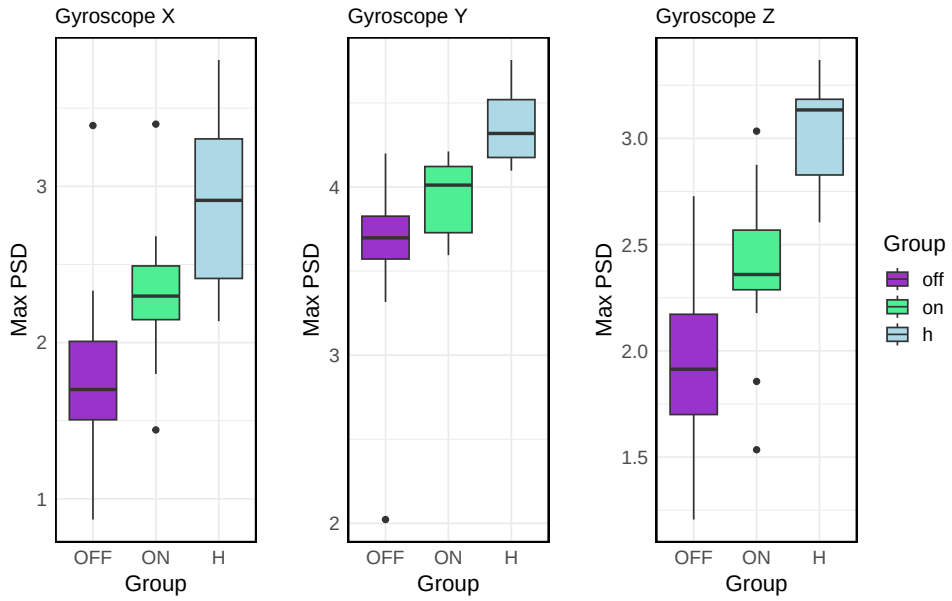


Figure 3.23 – Boxplot with the difference between the groups during slow passive movements.

The results also revealed that the gyroscope was able to distinguish between the three groups studied, with the most significant differences observed in the Y and Z axes. Certainly, the gyroscope's less pronounced differences can be attributed to the slower, controlled speed of the movements. Because the gyroscope is sensitive to angular velocity and spatial orientation, subtle variations in these measurements may be more difficult to detect in slow movements.

The results for magnetometer data can be seen in Figure 3.24.

The analysis of the magnetometer data revealed a greater difference in Y-axis recordings compared to the X and Z axes. Due to the controlled and slower execution of the movements, the magnetometer's Y axis stood out in detecting variations in wrist flexion and extension. This occurred because the Y axis was more aligned with the plane of movement of the wrists during the assessment. Thus, the magnetometer was able to more accurately capture subtle changes in these specific directions.

The Kruskal-Wallis test was applied to evaluate possible differences between groups. The MDS-UPDRS values, was also measure regarding rigidity (Part III, items 3.3b and 3.3c). Table 3.4 shows the results.

The results of the correlation between sensor variables and the MDS-UPDRS score indicate a moderate relationship between these measurements and the severity of rigidity associated with PD. Furthermore, when comparing the differences between the groups, it was observed that most variables showed statistically significant differences between the "off" and "h" groups, as well as between the "on" and "off" groups. However, the

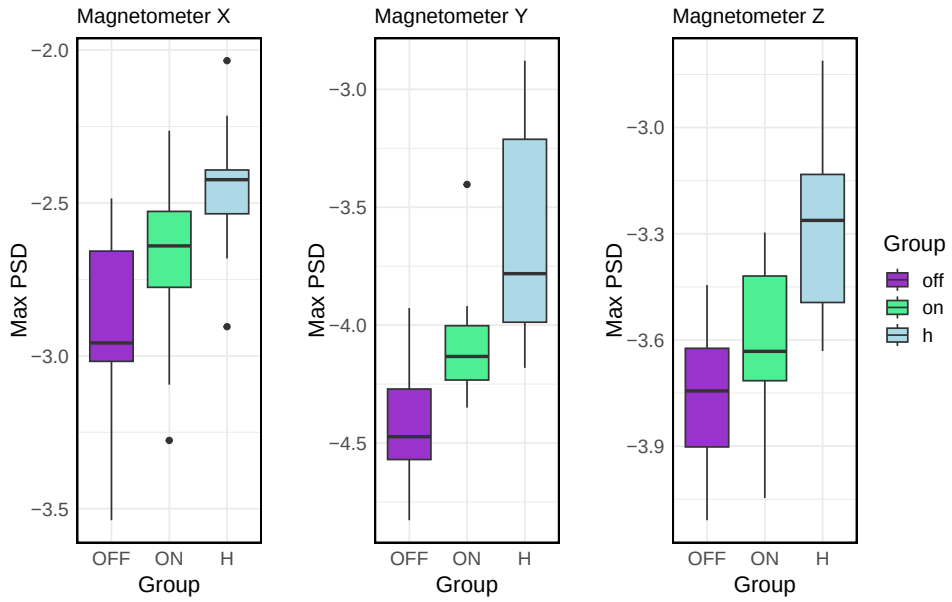


Figure 3.24 – Boxplot with the difference between the groups during slow passive movements.

| Sensor | Correlation UPDRS | Statistical Difference (p-value) OFF - H | ON - H | ON - OFF |
|---|---|---|---|---|
| **AccX** | -0.65 | $< 0.001$ | 0.15 | 0.02 |
| **AccY** | -0.65 | $< 0.001$ | 0.02 | 0.07 |
| **AccZ** | -0.68 | $< 0.001$ | $< 0.001$ | 0.05 |
| **GyroX** | -0.62 | $< 0.001$ | 0.01 | 0.03 |
| **GyroY** | -0.62 | $< 0.001$ | 0.004 | 0.04 |
| **GyroZ** | -0.66 | $< 0.001$ | $< 0.001$ | 0.003 |
| **MagX** | -0.34 | $< 0.001$ | 0.04 | 0.04 |
| **MagY** | -0.67 | $< 0.001$ | $< 0.001$ | 0.02 |
| **MagZ** | -0.68 | $< 0.001$ | $< 0.001$ | 0.16 |
| **M. Extensor** | -0.42 | $< 0.001$ | 0.05 | 0.08 |
| **M. Flexor** | -0.64 | $< 0.001$ | 0.02 | $< 0.001$ |

Table 3.4 – Statistics regarding slow passive movements evaluations.

differences between the "on" and "h" groups were less pronounced compared to the other comparisons. These results highlight the ability of sensors to distinguish between different stages of rigidity in PD, and suggest their potential as tools for objective assessment of this clinical feature.

Notably, even at slower speeds, the sensors detected significant differences between patient groups, indicating that rigidity can be objectively assessed in a variety of movement contexts. Sensor analysis revealed that certain axes and variables were more sensitive to variation in rigidity at slower speeds. For example, in the case of the accelerometer, the differences were more evident in the Y axis, whereas the gyroscope stood out especially in the Y and Z axes.

### 3.6.3 Fast passive movements

At this stage of the analysis, the movements were performed at a fast velocity, also under careful control of the therapist, in order to explore the responses of the sensors in more dynamic movement conditions. This approach allowed for the investigation about how sensor signals vary in response to rigidity during fast movements, replicating situations that may occur during daily activities or at times of greater functional demand.

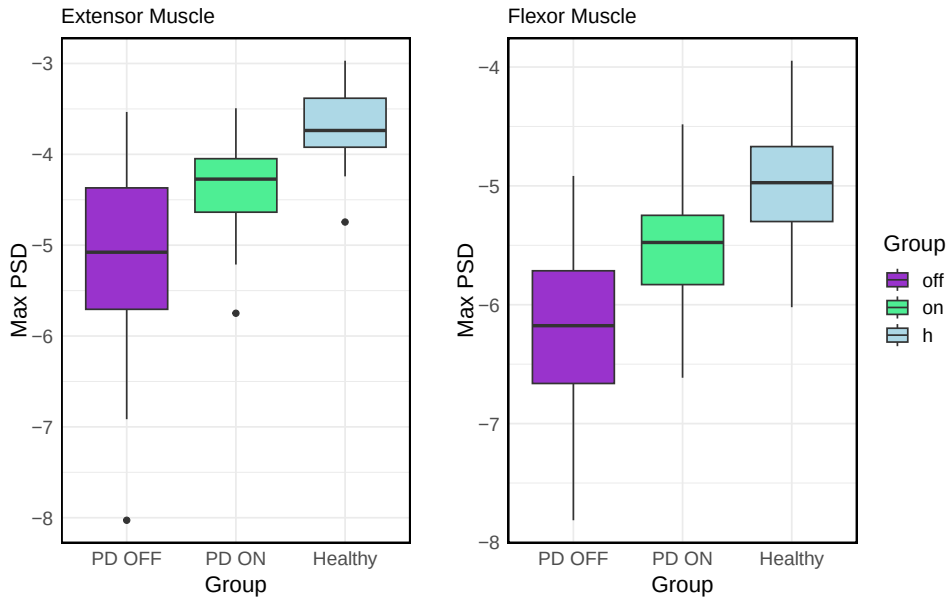


Figure 3.25 – Boxplot with the difference between the groups during the fast passive movements.

First the sEMG signals were analysed (Figure 3.25)). In the analysis carried out at a fast speed, it was observed that the sEMG signal was able to distinguish between the groups with greater clarity, especially in the wrist flexor muscle. This more evident differentiation in the flexor muscle may indicate a differential response of the muscles in relation to rgidity during fast movements, possibly reflecting distinct muscle activation patterns between the groups studied.

The accelerometer results can be seen in Figure 3.26. The accelerometer revealed significant differences between the groups, especially in the Y and Z axes, indicating distinct variations in acceleration during fast movements. This differentiated acceleration may reflect specific movement patterns associated with rigidity in patients with PD, suggesting an alteration in movement dynamics during tasks performed at fast speed. Healthy individuals showed a significantly greater acceleration compared to patients with PD. This greater acceleration may indicate a preserved ability to perform fast movements and less restriction in the execution of motor tasks, in contrast to patients with PD, who may present a more attenuated response due to muscle rigidity and other motor symptoms characteristic of the disease.

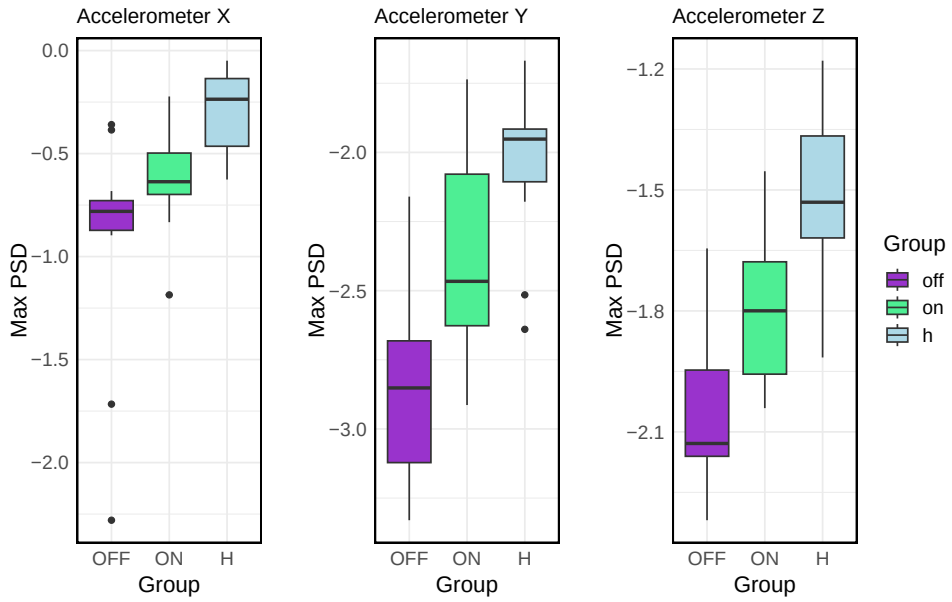


Figure 3.26 – Boxplot with the difference between the groups during the fast passive movements.

The gyroscope data results can be seen in Figure 3.27.

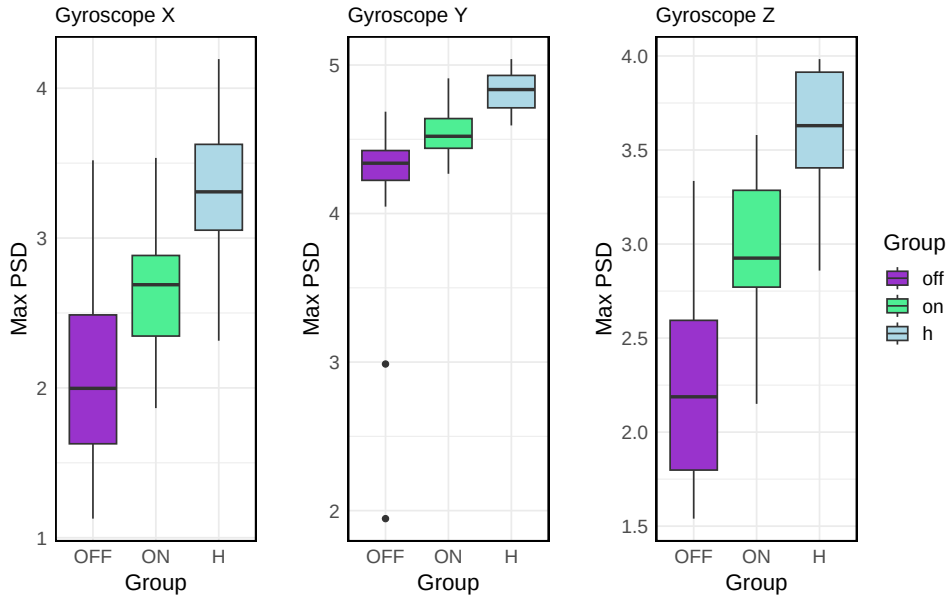


Figure 3.27 – Boxplot with the difference between the groups during the fast passive movements.

Like the accelerometer, the gyroscope also followed the trend of differences between groups. A greater amplitude was observed in the Y and Z axes, as well as in healthy individuals compared to patients with PD. This difference in the amplitude measured by the gyroscope between the groups highlights the detection of changes associated with rigidity in people with PD.

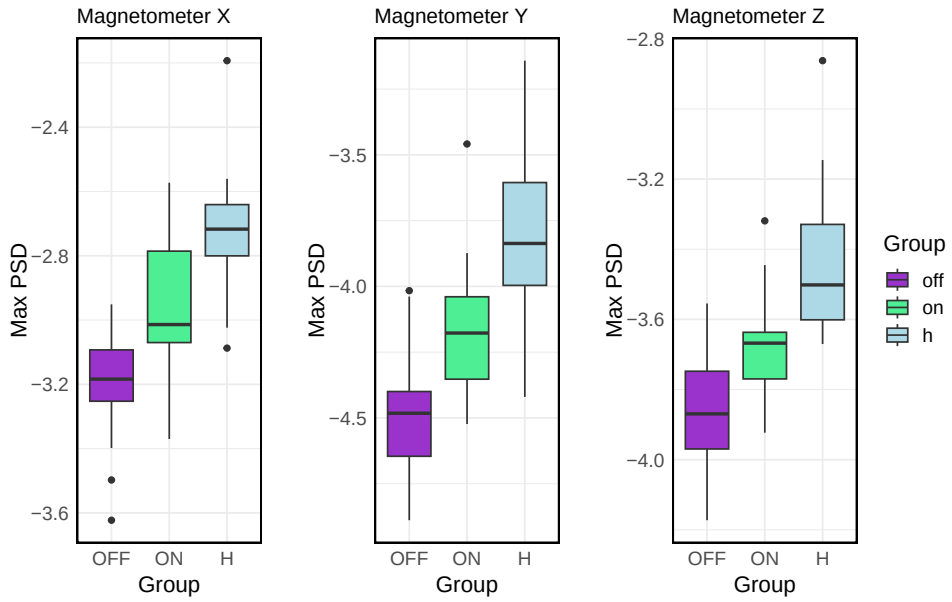


Figure 3.28 – Boxplot with the difference between the groups during the fast passive movements.

The magnetometer data can be seen in Figure 3.28. For high-speed movements, the magnetometer demonstrated good differences between all groups, in the three axes. It was also possible to observe a greater range of movement in the Y axis.

The Kruskal-Wallis test was applied to evaluate possible differences between groups. The correlation with the MDS-UPDRS values, was also measured regarding rigidity (Part III, items 3.3b and 3.3c). In Table 3.5 it is possible to see the results.

| Sensor | Correlation UPDRS | Statistical Difference (p-value) OFF - H | ON - H | ON - OFF |
|---|---|---|---|---|
| **AccX** | -0.77 | $< 0.001$ | 0.02 | 0.06 |
| **AccY** | -0.66 | $< 0.001$ | 0.01 | $< 0.001$ |
| **AccZ** | -0.74 | $< 0.001$ | 0.001 | $< 0.001$ |
| **GyroX** | -0.61 | $< 0.001$ | 0.004 | 0.01 |
| **GyroY** | -0.58 | $< 0.001$ | 0.23 | 0.01 |
| **GyroZ** | -0.78 | $< 0.001$ | $< 0.001$ | $< 0.001$ |
| **MagX** | -0.55 | $< 0.001$ | 0.005 | 0.009 |
| **MagY** | -0.54 | $< 0.001$ | 0.005 | 0.01 |
| **MagZ** | -0.75 | $< 0.001$ | 0.004 | 0.03 |
| **M. Extensor** | -0.58 | $< 0.001$ | 0.04 | 0.02 |
| **M. Flexor** | -0.55 | $< 0.001$ | 0.03 | 0.01 |

Table 3.5 – Statistics regarding fast passive movements evaluations.

During fast movements, the results revealed that the variables AccX, AccZ, GyroZ and MagZ exhibited a strong correlation with the MDS-UPDRS, whereas the remaining variables showed a moderate correlation. For differences between groups, all sensors showed statistically significant differences, except GyroY, when comparing groups of healthy indi-

viduals ("h") and those with PD in the "on" state. In general, more significant results were observed when the movements were performed at a fast speed, when compared to those at a slow speed. This suggests that analysis of data collected during faster movements may offer better discrimination between the groups studied. This increase in speed can amplify differences in the signals captured by the sensors.

### 3.6.4 General analysis

Analyzing the three scenarios, active, slow passive, and fast passive movements, it is possible to highlight that the Fast Passive situation presented the highest correlation with PD. This strong correlation suggests that speed may be a sensitive indicator for assessing rigidity in people with PD.

Regarding the relevance of the sensors, it is possible to highlight that the accelerometer in all three situations showed a strong correlation with the MDS-UPDRS, in the three axes, X, Y and Z. The gyroscope sensor, mainly in the Y and Z axes, also showed a significant correlation with MDS-UPDRS in all situations and a strong difference between groups. As for the magnetometer, although it showed statistical differences between the groups, its correlations with the MDS-UPDRS were less pronounced compared to the other sensors. sEMG sensors also played a significant role in differentiating the groups and correlating with the severity of PD symptoms, especially for active and slow passive movements.

Therefore, it is possible to highlight the sensors that were most relevant for the analysis of rigidity, during fast passive movements, shown in Figure 3.29.

## 3.7 Discussion

This chapter was dedicated to proposing an innovative protocol for evaluating wrist rigidity in individuals with PD, based on the execution of movements at different speeds. We sought to integrate data from the MDS-UPDRS, sEMG, and inertial sensors to provide a comprehensive and objective approach to assessing rigidity, one of the hallmark motor symptoms of PD. By developing this protocol, it was possible to aim to overcome the limitations of conventional assessment methods, which are often subjective and dependent on the assessor's experience, by offering a more accurate and evidence-based methodology for assessing wrist rigidity, a crucial aspect in the clinical management of PD.

According to a systematic analysis conducted for the Global Burden of Disease Study 2018, disability attributed to PD is escalating at a faster rate compared to any other neurological disorder (36). Recognizing the cardinal signs of PD, including rigidity, is fundamental in the diagnostic process (49). Rigidity, characterized by increased resistance to passive limb movement, is a key feature in identifying PD. The assessment of rigidity plays a pivotal role in the comprehensive evaluation of individuals suspected of having PD

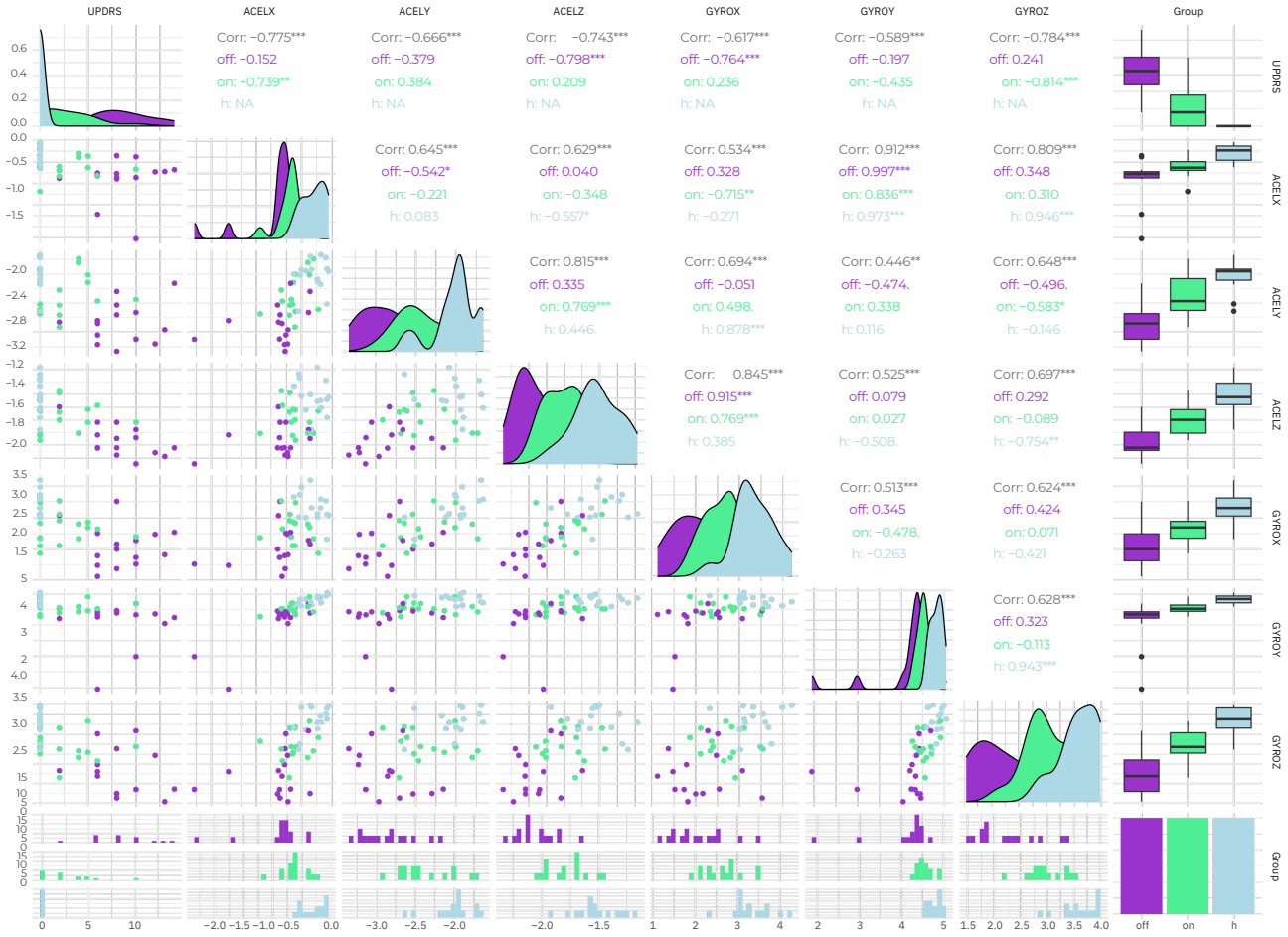


Figure 3.29 – Main differences for sensors in fast passive movements.

(49). Utilizing tools such as the MDS-UPDRS can aid in evaluating rigidity and other motor symptoms in PD patients (47). However, this is a subjective assessment of the disease. Thus, in this sense it is necessary to search for tools that can accurately and objectively assess signs, such as rigidity.

The assessment protocol proposed in this study involved three sets of movements to evaluate wrist rigidity in individuals with PD. Participants were instructed to perform wrist flexion and extension movements, with 15 repetitions as active movements. Subsequently, passive movements were conducted by the therapist, including 15 slow and 15 fast movements. This methodology aimed to explore the dependency of wrist rigidity on movement speed, a critical aspect for understanding the pathophysiology of PD and enhancing intervention strategies. By incorporating various types of movements, the assessment facilitated a comprehensive analysis of rigidity in diverse functional contexts, providing valuable insights into how rigidity responds to different motor demands. This enhanced understanding of the interplay between rigidity and movement speed can guide the development of personalized interventions tailored to manage the motor symptoms of PD effectively.

The results of the spectral analysis of the gyroscope signals indicated that healthy subjects showed greater PSD value compared to the EG groups, suggesting that these subjects may be executing movements with greater angular velocity or with more fluid movement patterns compared to the EG group. Analyzing gyroscope signals to quantify rigidity in PD is a valuable approach supported by various studies. For instance, (44) focused on gyroscopic signal smoothness assessment, emphasizing the estimation of geometric jolt in multidimensional gyroscopic signals. This study contributes to understanding signal characteristics relevant to rigidity assessment in PD using gyroscopes. Moreover, (64) introduced a novel quantitative wrist rigidity evaluation device for DBS surgery, highlighting the effectiveness of the device in classifying signals using gyroscopic data. This study provides insights into the application of gyroscopic signals for objective rigidity evaluation in PD patients.

Furthermore, magnetometer analysis demonstrated the ability to distinguish between healthy individuals and PD patients, although the differences observed between the "on" and "off" groups may not be as pronounced as expected. However, previous studies such as the research by (83) focused on the management of PD through wearable sensors, emphasizing the use of IMU composed of accelerometers, gyroscopes, and magnetometers to assess bradykinesia, rigidity, and tremors. This study highlights the relevance of magnetometer data in conjunction with other sensor data for assessing motor symptoms in PD. Therefore, the use of magnetometer analysis, in combination with gyroscopes and accelerometers, offers a comprehensive approach to quantifying rigidity in PD, providing valuable information for monitoring and managing motor symptoms in these patients.

Therefore, a multivariate approach that integrates data from multiple sensors is critical to understanding the mechanisms underlying rigidity in PD. By evaluating different protocols, such as active, passive slow and fast movements, it is possible to obtain a comprehensive view of rigidity in various motor conditions. This analysis allows the identification of distinct patterns of rigidity and understand how it varies in response to different motor demands and medication states.

### Active movements

The results of the assessment of active movements revealed distinct patterns of rigidity between participants with PD and healthy individuals. Spectral analysis of sEMG signals and inertial sensors revealed significant differences between groups of PD patients in different medication states and healthy individuals. A reduction in values of PSD was observed in the sEMG signals of the wrist extensor and flexor muscles in patients with PD, especially in the "off" medication state, reflecting the difficulty of the neuromuscular system in responding to motor commands. In the "on" state there was temporary improvement, but the amplitude may not yet reach the levels observed in healthy individuals.

Active movements stood out in the sEMG results, possibly due to the fact that par-

ticipants performed the movements on their own and in a more natural way. When movements are performed actively, individuals have more control over the amplitude, speed and coordination of movements, which can directly influence the muscle activation recorded by sEMG (40). In this sense, the voluntary execution of movements during the active assessment protocol can induce muscle activation patterns that are more natural and closer to everyday movement conditions. This contrasts with passive movements, in which movements are induced by the therapist and may not fully reflect the individual's motor control capacity.

Regarding the analysis of data collected from the IMU, accelerometers and gyroscopes demonstrated promising results when evaluating active movements. This can be attributed to the ability of these sensors to capture important information about the acceleration and speed of movements performed by participants.

In general, the results obtained during active movement revealed a good correlation between sensor data and MDS-UPDRS scores (Part III, items 3.3b and 3.3c). This correlation suggests that the sensors were able to effectively capture variations in muscle rigidity during the execution of movements. This result is probably attributed to the fact that the movements performed during the active assessment were the same on the scale, allowing for a direct assessment of motor symptoms (81). Furthermore, statistical analysis revealed significant differences between groups on several variables, indicating a clear distinction in rigidity between individuals with PD and healthy individuals.

**Slow passive movements**

Slow passive movements showed less significant results in relation to the analyzed variables. This observation can be attributed to several factors. Firstly, the low speed of passive movements may not cause the same magnitude of rigidity observed in active or fast movements. Muscle rigidity is often more pronounced during faster, more challenging motor activities. Furthermore, in the passive movement protocol, it is the therapist who performs the movements, which can result in a variation in the application of force and range of movements between participants. This can lead to an inconsistency in the data recorded by the inertial sensors and sEMG, thus reducing the sensitivity of the assessment. Therefore, slow passive movements may not be as effective as in fast movements to induce and detect muscle rigidity in individuals with PD (39).

This observation is supported by studies such as (89, 128), which have explored the effects of movement speed and type on muscle rigidity and motor control. Additionally, (20) have investigated the impact of passive movements on muscle rigidity and motor disturbances in various populations. These studies collectively highlight the importance of movement speed and active engagement in assessing muscle rigidity and motor function.

### Fast passive movements

Fast passive movements proved to be the most effective in inducing and detecting rigidity in patients with PD. These results highlight the significant influence of movement speed on the manifestation of muscle rigidity in these individuals. The speed of passive movements can trigger a more pronounced response from the neuromuscular system, increasing muscle rigidity more clearly than at slower speeds. This suggests that fast movements may be more effective for assessing muscle rigidity in patients with PD (39, 59, 98).

The results obtained with the accelerometer and gyroscope stood out as the most robust among the sensors analyzed. These sensors showed a clear differentiation between the groups studied, demonstrating a consistent correlation with the UPDRS scores. The clear separation between groups observed in sensory analyzes reinforces the ability of these devices to discern levels of muscle rigidity among participants. Furthermore, the agreement of the UPDRS values with the differences identified in the sensor data confirms the sensitivity of these devices in detecting even subtle variations in muscle rigidity.

Figure 3.29 visually illustrates this distinction among groups, highlighting the effectiveness of the accelerometer and gyroscope as objective rigidity assessment tools. The findings demonstrated a strong and meaningful correlation between sensor data and MDS-UPDRS scores, indicating a direct association between the assessed parameters and the severity of rigidity in individuals with PD. Moreover, the analysis of group distribution revealed significant distinctions between healthy participants and those with PD, as well as among PD patients in different medication states ("on" and "off"). This clear differentiation in group distribution underscores the sensors' capacity to accurately differentiate between varying levels of muscle rigidity and the clinical conditions of PD patients, enhancing the precision and thoroughness of rigidity assessment in PD.

### General considerations

Correlations between sensor data and MDS-UPDRS scores were consistent, indicating that sEMG and IMU signals may be useful for distinguishing rigidity between different disease states. Besides, it is an important tool to evaluate rigidity in a more quantitative method.

In addition to the correlations observed between sensor data and MDS-UPDRS scores, the analysis of PSD has provided valuable insights into the frequency characteristics of muscle activity and movement patterns in individuals with PD. By examining the PSD of signals captured by inertial sensors and sEMG, distinct spectral patterns associated with different disease states and severity levels were discerned. This analysis has enhanced our understanding of the underlying neuromuscular mechanisms contributing to rigidity in PD, revealing how specific amplitude components may correlate with clinical assessments

of rigidity.

## 3.8 Conclusions

This chapter presented an innovative protocol for the assessment of wrist rigidity in individuals with PD. Integrating data from diverse sources, including the MDS-UPDRS, sEMG, and inertial sensors, we developed a comprehensive and objective approach to assessing rigidity, one of the main motor symptoms of PD.

By performing different types of movements, including active, slow passive, and fast passive movements, we explored the relationship between rigidity and movement speed, providing valuable insights into the mechanisms underlying rigidity and its variations during different disease states. Our results indicate that active and fast passive movements were more effective in detecting rigidity. Furthermore, inertial sensors, especially accelerometer and gyroscope, have proven to be useful in assessing rigidity, showing a strong correlation with MDS-UPDRS scores (Part III, items 3.3b and 3.3c) and showing significant differences between groups of PD patients in different disease states.

Spectral analysis also complemented our findings by providing additional insights into the characteristics of muscle and movement activity associated with rigidity. These results highlight the importance of a multivariate and comprehensive approach to assessing rigidity in patients with PD, which have important implications for the development of more targeted and effective interventions to improve motor function and quality of life of these patients.

In this sense, the next chapter will focus on the development of a serious game and a control interface, specifically designed to measure the symptoms of PD, based on inertial sensors. This approach aims to provide an innovative and engaging method for the assessment and rehabilitation of motor symptoms in patients with PD.

# 4

# Development of Serious Game and Human Machine Interface

## 4.1 Background

Despite promising advances made in objectively quantifying rigidity in PD, there are still notable obstacles to overcome. Among these challenges is the pressing need for a more adaptive and engaging approach that empowers patients to actively participate in assessment processes, even when carried out remotely.

Serious Games emerges as a novel and promising strategy in this area. SGs are games designed not only for entertainment but also to incorporate elements of instruction or training. By providing a dynamic and interactive platform, SGs offer an engaging means to motivate patients during rigidity assessments.

SGs provide gamification features including challenges, prizes, and real-time feedback, which increase patient engagement and stimulation during rigidity measurement. SGs' interactive format also make it possible to tailor the approach to the unique needs and capabilities of each patient, increasing accessibility. This method not only makes the diagnostic procedure better for the patient, but it also creates new opportunities for remote rigidity monitoring and the creation of customized therapies based on quantifiable, objective data.

Previous studies highlight the potential of SGs to improve patient engagement and facilitate remote monitoring. For example, Marques et al. (67) demonstrated how SGs effectively increased patient motivation and adherence to therapeutic regimens. Similarly, Mendes et al. (76) emphasized the importance of customizable SGs in meeting individual patient needs and preferences. These findings highlight the importance of incorporating SGs into rigidity assessment protocols and underline the key role of HMI in enabling effective interaction between patients and technology.

In the context of integrating SGs into stiffness assessment protocols, the HMI plays a key role in facilitating effective interaction between patients and the system. The HMI serves as a bridge that enables continuous communication and control, improving the

overall user experience.

Previous research has highlighted the importance of designing intuitive and easy-to-use HMI to control SGss, especially in healthcare. For example, Desmet et al. (32) emphasized the importance of incorporating user-centered design principles in developing HMI for SGs-based interventions. By prioritizing ease of use and intuitive navigation, these HMI can empower patients to interact with SGs more effectively, thereby maximizing engagement and adherence to therapeutic regimens.

Furthermore, previous study highlighted the impact of HMI design on patient satisfaction and engagement levels (118). HMI that feature clear instructions, responsive feedback mechanisms, and customizable settings can significantly improve the user experience, promoting a sense of autonomy and control among patients.

Overall, the integration of SGss into rigidity assessment procedures depends on the development of user-centered HMI. By prioritizing ease of use, responsiveness, and personalization, these interfaces can optimize patient engagement, increase data collection efficiency, and improve the effectiveness of SGs-based interventions in healthcare settings.

## 4.2 The RehaBEElitation SGs

RehaBEElitation, a SGs with a bee theme created especially for PD monitoring and rehabilitation, was developed as part of the CAPES-COFECUB project (process number: 88881.370894/2019-01), which was also part of the works developed by Luanne Cardoso Mendes (73) and Rodrigo Ramos Rosa (111). The design and development of this SGs was a team effort comprising specialists from various disciplines, including biomedical engineering, computer science (with a focus on game design), physiotherapy, and physical education.

In RehaBEElitation, users take on the role of a bee that moves around a three-dimensional landscape. The game challenges are purposefully designed to mimic movements similar to those assessed in the MDS-UPDRS Part III, the gold standard assessment tool for people with PD. Hand flexion and extension, wrist adduction and abduction, finger tapping, and forearm supination and pronation are some of these motions. RehaBEElitation is a gamified method to therapy that attempts to improve patient engagement and motivation by using entertaining gameplay to not only assess progress, but also aid physical rehabilitation.

The four stages of the game are shown in Figure 4.1, with each stage corresponding to a real-world duty performed by a worker bee.

- Phase 1: Flower pollination

  The aim is to gathering pollen from one flower and transferring it to another. Yellow arcs are used to indicate flowers that have pollen available, whereas green arcs are

used to indicate flowers that require pollination. The player needs to move the bee vertically by extending and flexioning their wrist and horizontally by wrist adduction and abduction movements. The bee is guided to a flower that has pollen, the player closes their hand to collect it, and the bee is then moved to a blossom that does not have pollen, and open it.

- Phase 2: Giving the Larvae Food

  Feeding the bee larvae is the goal of this phase. The bee can only navigate the environment (left, right, up, and down) when the player's hand is closed. When the bee places itself in front of a larva, it opens hand and feeds the larva.

- Step 3: Gathering the Nectar

  The goal of this stage is to collect nectar from flowers. Water droplets indicate nectar-containing flowers. The player directs the bee to a nectar-filled flower, where it gathers the nectar by tapping its petals.

- Phase 4: Nectar Drying

  The goal of this stage is to dry the nectar that has been gathered to make honey. The honeycomb cells with nectar, denoted by light reflections, are where the player controls the bee. The bee flaps its wings more quickly by pronating and supinating its forearm, which helps the honey dry faster.




Figure 4.1 – Phases of the game (A) Phase 1: Pollinating the flowers. (B) Phase 2: Feeding the larvae. (C) Phase 3: Collecting the nectar. (D) Phase 4: Drying the nectar.

The SGs can be utilized to assess motor symptoms of PD, such as bradykinesia, tremor and rigidity. Evaluating these symptoms during a game session provides an excellent

alternative for monitoring patients' health status and disease progression. To achieve this, alongside using data gathered by the HMI through inertial measurement units, several markers were defined and incorporated into the game. These markers represent specific events that help characterize distinct occurrences. In total, 23 events were defined. All the events can be see in Table 4.1 (73). In green are those used in this study are highlighted for the rigidity assessment.

| Event ID | Event description | Observations |
|---|---|---|
| **1** | Bee standing still without moving in the scenario | In phases 2 and 4 |
| **2** | Bee moving forward | In phases 1 and 3 |
| **3** | Collects pollen | Movement of closing the hand |
| **4** | Deposits pollen | Movement of opening the hand |
| **5** | Bee moves to the right | Player with open hand |
| **6** | Bee moves to the right | Player with closed hand |
| **7** | Bee moves to the left | Player with open hand |
| **8** | Bee moves to the left | Player with closed hand |
| **9** | Bee moves up | Player with open hand |
| **10** | Bee moves up | Player with closed hand |
| **11** | Bee moves down | Player with open hand |
| **12** | Bee moves down | Player with closed hand |
| **13** | Collects nectar | Finger tapping movement |
| **14** | Dries nectar | Supination movement |
| **15** | Dries nectar | Pronation movement |
| **16** | Releases/deposits pollen at the wrong time (player's failure) | Negative feedback |
| **17** | Player hits the target and can perform the required movement | Visual and audible feedback |
| **18** | Player scores a point (audible feedback) | Positive feedback |
| **19** | Player doesn't move the bee in the game for 30 seconds (visual and audible feedback) | Reinforcement feedback |
| **20** | Player doesn't score a point for one minute and 20 seconds (visual and audible feedback) | Reinforcement feedback |
| **21** | Game time is over (game over) | Negative feedback |
| **22** | Player completes the level (visual and audible feedback) | Positive feedback |
| **23** | Phase is paused | Glove data are not recorded |

Table 4.1 – Events in the game.

## 4.3 Design Principles of a Human Machine Interface

A well-designed HMI should be able to give patients all the information they need to comprehend and complete the activities that the SGs requires them to do. The HMI needs to be user-friendly and intuitive, even for patients with less technological background. This could entail utilizing recognizable design components. In order to provide a consistent experience, the interface must also be flexible.

During assessment sessions, the HMI is crucial in gathering data as well. It can be made to automatically log pertinent data regarding the patient's performance, including movement patterns, precision, and reaction times. Afterwards, this data can be examined to evaluate rigidity and track the condition's evolution over time.

To sum up, a successful integration of SGss into rigidity assessment requires an efficient HMI control. In addition to facilitating active patient engagement in the evaluation process, HMI helps collect accurate and trustworthy data for clinical analysis by offering an easy and adaptable user experience.

## 4.4 HMI Device

Two versions of a lightweight mobile device, consisting of both hardware and firmware, were specifically designed for the purpose of interacting with the SGs RehaBEElitation. This device serves as the HMI. By allowing for the monitoring of the user's hand motions, this technology can serve as a versatile game controller, and also be utilized for assessing the motor signs of individuals with PD. The two versions of the HMI can be seen in Figure 4.2.

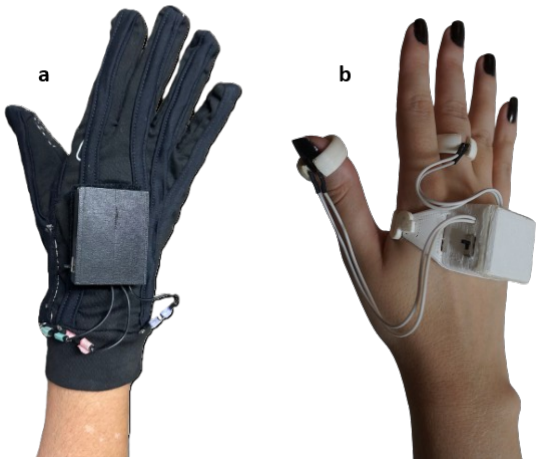


Figure 4.2 – HMI for the RehaBEElitation controlling. a) First version. b) Second version.

### 4.4.1 Development of the HMI

The hardware consists of inertial sensors (accelerometer, gyroscope and magnetometer) in addition to sensors to detect the hand and finger open and close. The values obtained from the sensors are read by a microcontroller, where the data are formatted and enveloped in User Datagram Protocol (UDP) type messages and sent, via Wi-Fi link, to a computer running suitable software for receiving the data. The message sent by the HMI contains 120 bytes of data formatted in the Open Sound Control (OSC) standard. OSC is an open, transport-independent, message-based communications protocol designed

for communication between computers, sound synthesizers, and other multimedia devices (13).

### First prototype

The device's hardware consists of inertial sensors (accelerometer, gyroscope and magnetometer) responsible for defining hand orientation information (rotation angles in the X, Y and Z axes). There are also touch sensors (capacitive sensors embedded in the microcontroller) responsible for providing information about the opening and closing movements of the index fingers and thumb, in addition to the opening and closing of the hand.

The MPU6050 IMU, which consists of a triaxial accelerometer and a triaxial gyroscope, was utilized to create the device. A digital processing unit on the MPU6050 also combines information from the accelerometer and gyroscope to provide sensor orientation in quaternion format. The triaxial QMC5883L magnetometer was employed as well. When using simply the values read from the MPU6050, errors in the estimated values of the Z axis rotation angles had to be corrected. To do this, an electronic compass had to be implemented, which required the usage of the magnetometer. The sensitivity of the accelerometer was set to $\pm 2g$, $\pm 2000^{o}/s$ for the gyroscope and 8 Gauss for the magnetometer, respectively. This configuration was defined experimentally and was the best observed.

The Esp32 microcontroller (Esp32 Wroom Module) was used, which obtained the data provided by the sensors via I2C bus. Figure 4.3 shows the electrical diagram of the circuit.

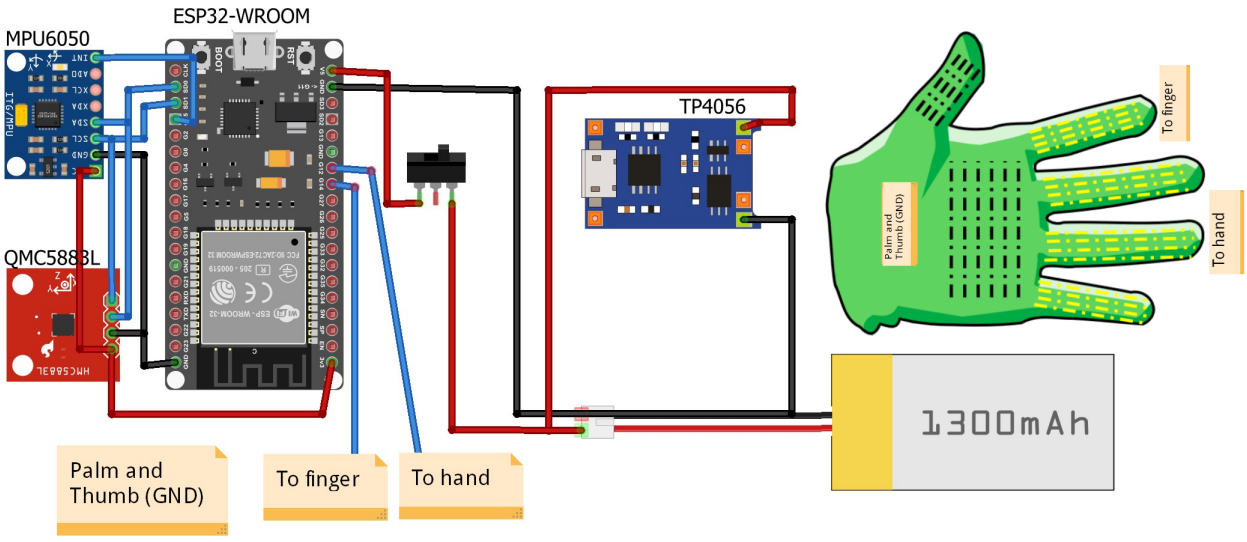


Figure 4.3 – Electrical diagram of the first prototype of the HMI.

The touch sensors used were capacitive sensors already embedded in the microcontroller. These sensors are available on specific pins of the microcontroller, and when a touch occurs on them, it is possible to measure the variation in the capacitance on the

pin, and consequently detect the touch. These sensors were assembled in a specific way to detect the opening and closing movement of the index and thumb fingers (tweezers) and hand. Thus, an assembly was determined, in which the sensor contact with the circuit reference (GND) was possible by obtaining a zero resistance value at the moment of touch. Figure 4.4 illustrates the positioning of the sensors implemented in the wearable device using a conductive thread.



Figure 4.4 – Conductive lines in the first prototype of the HMI.

**Second prototype**

For the second prototype, we chose to prioritize ease of use, handling and cleaning, as well as comfort during use. We sought to develop a device that was ergonomically designed, lightweight and easy to use. This included considerations regarding the weight of the device in the user's hand, ensuring it is comfortable during prolonged use. Additionally, the focus was on designing surfaces and materials that were easy to clean and maintain, ensuring hygiene and product durability. These choices prioritized hygiene and safety, particularly in light of the challenges posed by the COVID-19 pandemic, while simultaneously enhancing the overall user experience and satisfaction with the device.

The Esp8266 microcontroller (Wemos D1 Pro Module) was used, which obtained the data provided by the sensors via I2C bus. We choose to change the microcontroller board, thinking about the size of the final glove. Besides that, in this version a integrated sensor that already consists of both the MPU6050 and the HMC5883L was used, which differs from the first prototype version, where we had to use two separate boards. This improvement made the hardware more robust and lighter in weight and size. In Figure 4.5 it is possible to see the electrical diagram of the circuit.

Moreover, the decision was made to create and construct the second prototype utilizing flexible filaments, such as Flex TPU (Thermoplastic Polyurethane), owing to its numerous advantages. These materials offer a unique combination of flexibility and durability,

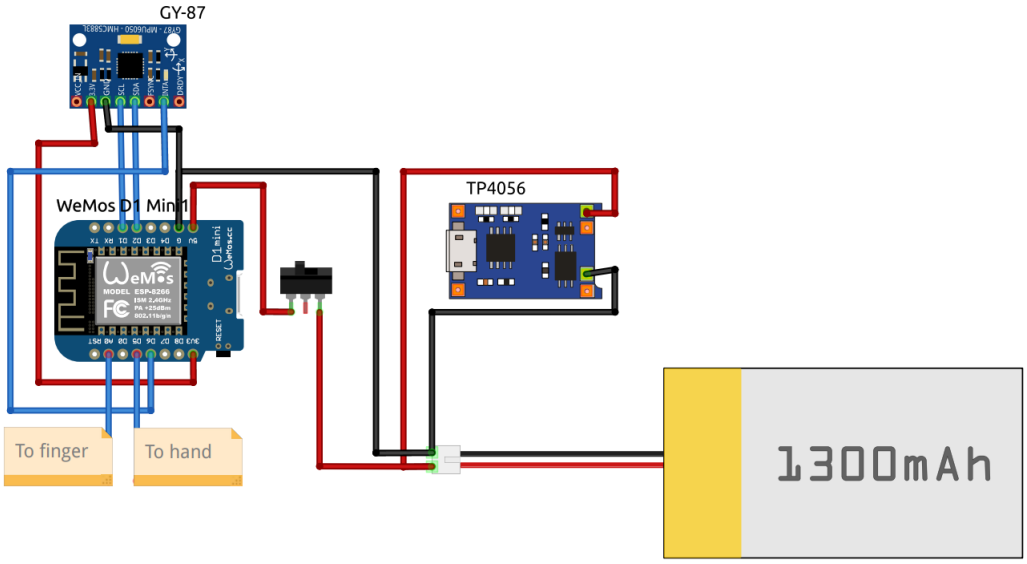


Figure 4.5 – Electrical diagram of the second prototype of the HMI.

making them ideal for devices that require impact resistance and comfort during use. The use of 3D printing allowed for precise and rapid customization of the design, enabling the creation of a device ergonomically adapted to users' hands. Figure 4.6 shows the design of the developed prototype.

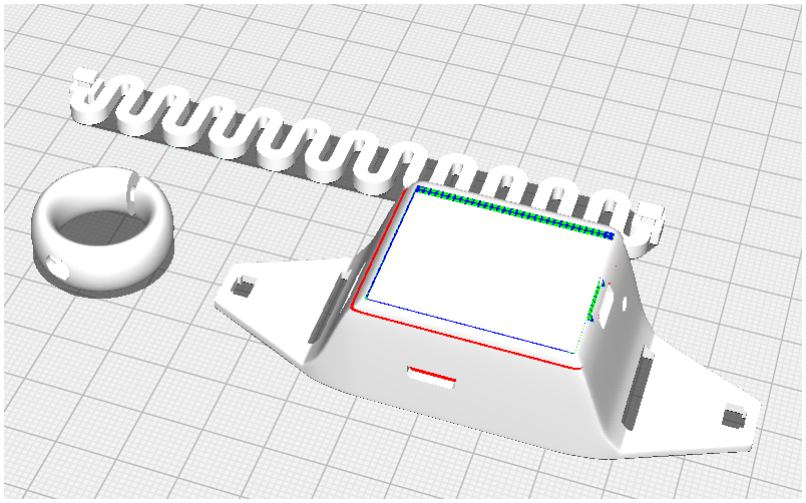

Figure 4.6 – 3D design of the prototype.

Light Dependent Resistor (LDR) sensor was used instead of conductive threads, aiming for a more practical and efficient approach. Resistive light sensors, or LDR, play the role of providing information about the opening and closing movements of the hand and fingers. This choice aims to simplify the use, handling and maintenance of the device.

LDR sensors, or Light Dependent Resistors, are devices that have the ability to detect variations in the intensity of incident light and convert these variations into changes in electrical resistance. They consist of a special semiconductor material that has an electrical resistance that decreases as the light intensity increases and vice versa. This

behavior makes them extremely useful in a variety of applications, from lighting control systems to presence detection devices.

For the HMI, these sensors were specifically mounted to detect the opening and closing movement of the hand and the touch of the fingers, in the shape of two rings. Thus determining an assembly, in which the sensor contacts the circuit reference (GND), obtaining a zero resistance value at the moment of touch. This can best be seen in Figure 4.7.

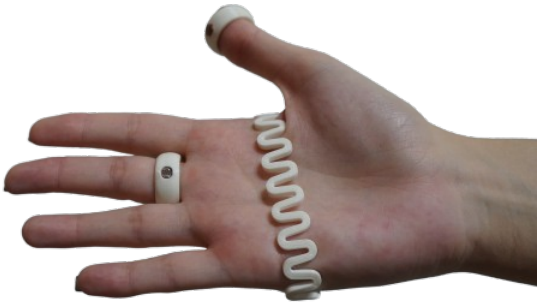

Figure 4.7 – LDR sensors in the HMI.

#### Sensor orientation

The orientation of the sensor in the HMI is crucial for accurately capturing and interpreting movement data. In this setup, the sensor was oriented such that the $Y$-axis pointed forward, the $Z$-axis was aligned vertically (up and down), and the $X$-axis extended to the sides (right and left). This configuration allows the sensor to effectively detect and differentiate movements around each of these axes. Specifically, movements along the $Z$-axis capture vertical displacements, such as raising or lowering the sensor. The $Y$-axis orientation allows for the detection of forward and backward motions. Lastly, the $X$-axis captures lateral movements to the right and left. Proper alignment of the sensor axes ensures accurate and reliable data acquisition, which is essential for precise motion analysis and interaction within the HMI system. Figure 4.8 shows this orientations in the HMI.

### 4.4.2 Firmware

The firmware that has been written is responsible for setting up the inertial sensors on the MPU6050 and HMC5883L modules. It also controls the I2C data bus, which facilitates communication between the two integrated circuits and the microcontroller. Reading the touch sensor states, setting up WiFi, putting together UDP packets, and transmitting

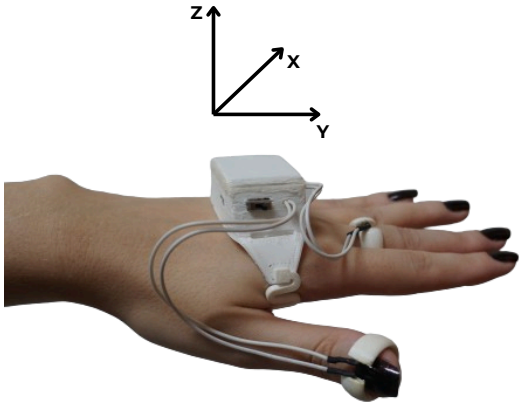


Figure 4.8 – HMI sensors orientation.

messages across the network are additional functions. The Arduino IDE platform was used to develop the firmware. Figure 4.9 shows the flowchart of the firmware.

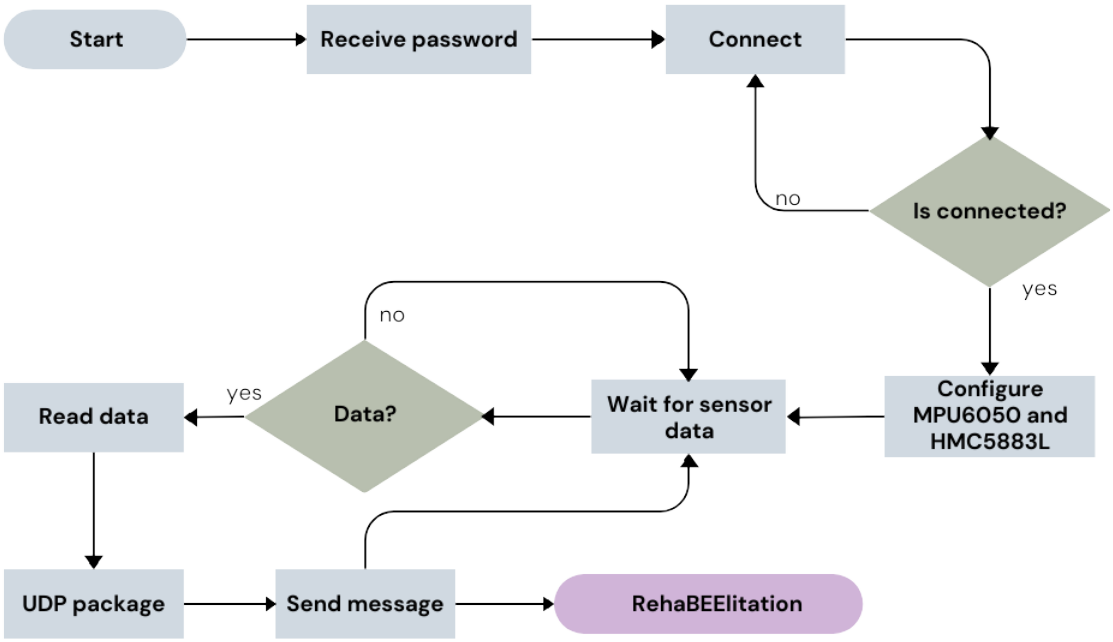


Figure 4.9 – Firmware flowchart.

## 4.5 Discussion

The integration of SGs and HMI into the assessment and rehabilitation of PD represents a significant leap forward in both the technological and clinical domains. The development of RehaBEElitation exemplifies how gamification can be effectively employed to enhance patient engagement and provide a stimulating environment for rehabilitation. This approach addresses several limitations of traditional PD assessment methods, offering a more interactive and patient-centered experience.

The iterative design process of the HMI devices highlights the importance of user feedback and continuous improvement. The transition from the first to the second prototype reflects a focused effort to enhance usability, comfort, and functionality. By integrating the inertial sensors (accelerometer, gyroscope, and magnetometer) into a single module and using the Esp8266 microcontroller, the second prototype not only reduced the overall size and weight but also improved the robustness of the device. The use of flexible filaments for the casing and the incorporation of LDR sensors for detecting hand and finger movements further streamlined the design, making it more practical for everyday use.

The firmware developed for the HMI ensures reliable data transmission and seamless interaction with the game software. By utilizing the OSC standard for message formatting and UDP packets for data transmission, the system maintains compatibility with various multimedia devices and software platforms. This technical foundation is crucial for the accurate collection and analysis of movement data, which can be used to assess rigidity and monitor disease progression.

The RehaBEElitation game itself provides a comprehensive platform for both assessment and rehabilitation. Each phase targets specific motor functions that are relevant to PD, such as wrist adduction and abduction, hand flexion and extension, and finger tapping. This design ensures that the movements required in the game are directly applicable to the clinical assessments used in PD management, such as those in the UPDRS Part III.

Incorporating SGss into PD management offers significant benefits. The interactive and engaging nature of games can increase patient motivation and adherence to rehabilitation protocols, which is often a challenge in traditional therapy. Additionally, the ability to perform assessments and rehabilitation exercises remotely is particularly advantageous in the context of the COVID-19 pandemic and other situations where in-person visits are challenging.

## 4.6 Conclusions

RehaBEElitation and its corresponding HMI device represent a pioneering approach in the field of PD assessment and rehabilitation. This work demonstrates that gamification, combined with advanced sensor technology, can provide an engaging, flexible, and effective method for managing PD symptoms. The iterative development of the HMI has led to a robust, user-friendly device that enhances the overall user experience and facilitates accurate data collection.

# 5

# Serious Game for Objective Evaluation of Rigidity in PD

## 5.1 Background

Researchers have shown the potential benefits of SGs in healthcare, including their effectiveness in promoting healthy lifestyle behaviors (32). Additionally, studies have demonstrated the feasibility of using SGs for upper limb rehabilitation in PD patients, showing improvements in coordination and motor skills (42). These findings underscore the potential of SGs as a complementary tool in PD management. Furthermore, the integration of SGs in rehabilitation programs has been associated with positive outcomes, such as improved motor performance and quality of life in PD patients (35). By incorporating motion capture systems and game-based interventions, individuals with PD can engage in tailored and motivating rehabilitation activities (54).

### 5.1.1 Rigidity Assessment Using the RehaBEElitation Serious Game

As stated earlier, the SG RehaBEElitation provides a novel method for evaluating symptoms and indicators in PD patients. It offers a more dynamic and interesting way to evaluate motor symptoms by combining gaming with assessment tasks.

The player's movements are recorded and analysed by the game during each phase, giving quantitative information on their motor function. RehaBEElitation can provide a more fun and approachable way to measure rigidity by gamifying the assessment process. This can encourage active participation and possibly increase patient engagement and compliance with rehabilitation programs. Furthermore, for comparative purposes between the proposed protocols, sEMG signals were collected while the participant played.

Apart from utilizing signals obtained through the use of IMU by the HMI, certain markers were designed and integrated into the game. Such markers are represented by

events, responsible for characterizing specific occurrences. Totally, 4 events were used in this study, shown in Table 5.1.1.

| Event ID | Description | Observations |
|---|---|---|
| 9 | Bee moves up | Player with open hand |
| 10 | Bee moves up | Player with closed hand |
| 11 | Bee moves down | Player with open hand |
| 12 | Bee moves down | Player with closed hand |

Table 5.1 – Selected events.

## 5.2 Experimental Protocol

Such as aforementioned, this research received approval from the Ethics Committee for Human Research at the Federal University of Uberlândia. It involved fifteen individuals diagnosed with PD, forming the experimental group EG, and an equal number of healthy individuals forming the control group CG. Participants in both groups were matched based on age and sex to ensure comparability.

The eligibility criteria for participants and the data collection protocol were consistent with those outlined in the previous section (subsection 3.4.2 Experimental Protocol). Specifically, individuals with PD interacted with the game under both "on" and "off" medication states to capture potential differences in motor function and rigidity.

Before engaging with the SG, individuals in the experimental group underwent assessment using the MDS-UPDRS Part III by a qualified physiotherapist. This assessment was conducted in each session, ensuring consistent evaluation of motor symptoms across different medication states.

### Experimental Setup

First, the participants were told to take a seat on a chair that was placed about a meter away from the TV screen that was showing the SG. Following a clinical evaluation, they wore the HMI device on the hand that was most affected by PD, in which the second prototype was used. The limb rested on a forearm rest to help with the necessary movements.

Electrodes were carefully positioned on the flexor and extensor muscles of the forearm in order to record the sEMG signals. These muscles are essential for evaluating motor function and rigidity in PD patients because they are involved in hand and wrist movements. The sEMG electrodes were positioned in accordance with established guidelines to guarantee precise documentation of muscle activity during the engagement with the significant game. The experimental setup can be seen in Figure 5.1.




Figure 5.1 – Experimental setup.

Participants were given brief explanations regarding the game's premise and goals prior to gameplay. After that, they had five minutes to spend in each of the four game phases, or until they had accomplished all of the objectives in each phase.

## 5.3 Signal Processing Data

To process the game signals, a similar approach to that used for the IMU signals was applied, as previously described in Chapter 3. Initially, any linear and non-linear trends from the signals were removed to ensure a more accurate representation of data variations throughout the game. This process was applied to all four phases of the game. Next, the envelope technique was applied to highlight the amplitude characteristics of the signals and facilitate the visualization of their temporal variations. A PSD analysis was performed on the signals to examine the power distribution at different frequencies. This analysis allowed identifying significant patterns and features in the game signals, which were relevant to the assessment of rigidity and other motor aspects of the participants.

For this stage of processing, specific events from the game were used (shown in Table 5.1.1), which determined the moments when participants were moving their hand up and down. This way, it is possible to correlate them with the movements carried out previously and also with the MDS-UPDRS Part III. Figure 5.2 shows the steps of the signal processing.

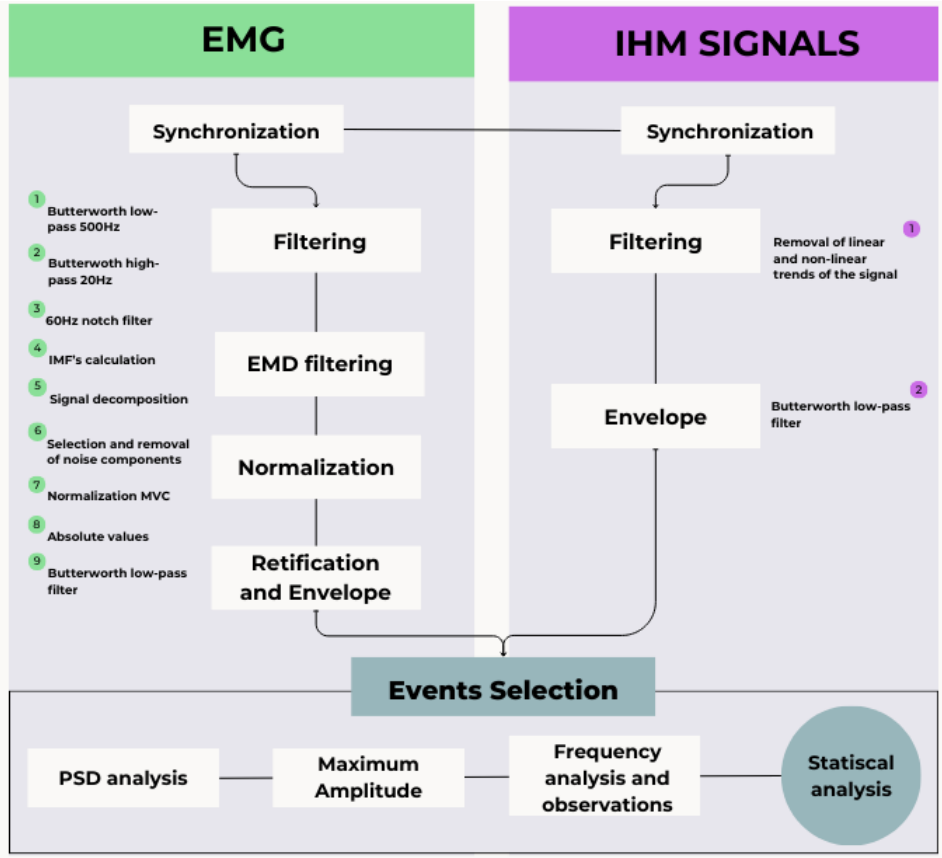


Figure 5.2 – Signal processing pipeline for the game data.

## 5.4 Results

As in chapter 3, the sEMG and SG signals underwent pre-processing and then feature extraction, using PSD. Firstly, the signals during the selected events were selected: (i) open hand up, (ii) open hand down, (iii) closed hand up and (iv) closed hand down. This way, it is possible to correlate the data obtained with the movements carried out by MDS-UPDRS and with the previously presented protocol. This procedure was carried out for the 4 phases of the game.

### 5.4.1 Phase 1

During phase 1, movements involving raising and lowering the hand were performed with both open and closed states (events 9, 10, 11, and 12. Shown in Table 5.1.1). For the analyses, the signal was specifically cropped to focus solely on these movements. All of the signals were analysed. Figure 5.3 illustrates the boxplots for PSD maximum values for the three groups.

In phase 1 of the game, participants control the avatar (represented by the bee) as they navigate the garden scene. This activity involves greater motor complexity, with the coordination of muscles and joints to direct the avatar in different directions and interact with elements of the virtual environment. Studies show that during more complex and

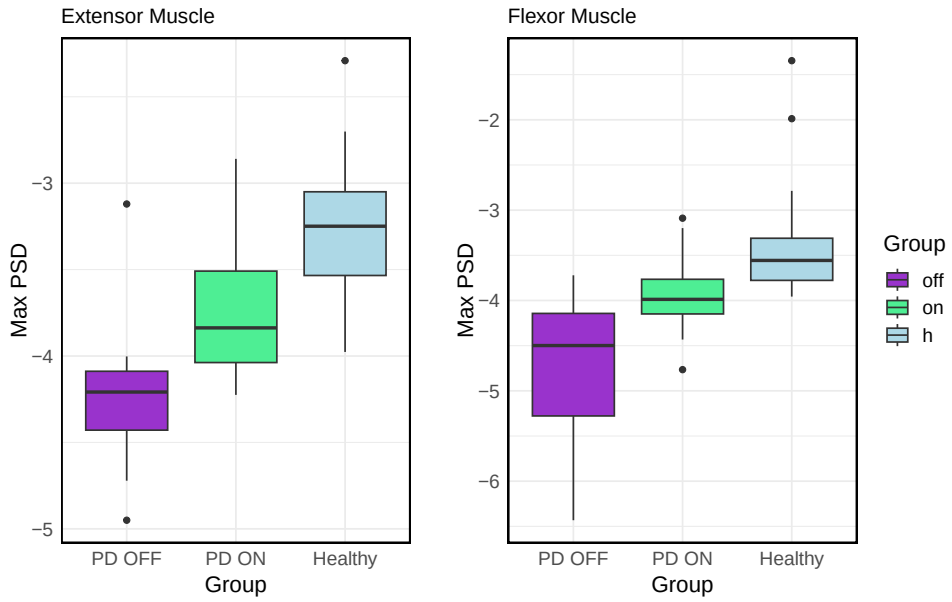


Figure 5.3 – Boxplot with the difference between the groups during phase 1.

natural motor activities, such as navigating virtual environments, there is more generalized and sustained muscle activation, compared to isolated and controlled movements (125). This is due to the need to maintain posture and balance while the body performs a variety of coordinated movements. Therefore, in phase 1 of the game, it is expected that there will be a constant muscle contraction, even in healthy individuals, due to the increased demand on the motor system during the performance of these more complex tasks.

Regarding the accelerometer signals, the results can be seen in Figure 5.4.

Analysis of accelerometer signals revealed significant differences between the groups studied. This association between game movements and the Z axis of the accelerometer can be explained by the biomechanics of flexion and extension movements, which tend to produce significant changes in the vertical acceleration recorded by the sensor. Furthermore, considering that the Z axis represents the vertical direction, it is reasonable to assume that the upward and downward movements of the hand during the game result in more pronounced variations along this axis.

Figure 5.5 show the results of maximum PSD for gyroscope data, during phase 1.

The gyroscope stood out in differentiating between groups, especially in the Z axis, indicating that faster movements may suggest greater flexibility in healthy individuals, while slow movements may be associated with rigidity in PD patients. Furthermore, the maximum PSD reflects the intensity of the gyroscope oscillations at different frequencies, being higher in healthy people and lower in PD patients, suggesting greater adaptability in healthy people and less adaptability in people with PD.

Magnetometer analysis can be seen in Figure 5.6, for phase 1. Although the mag-

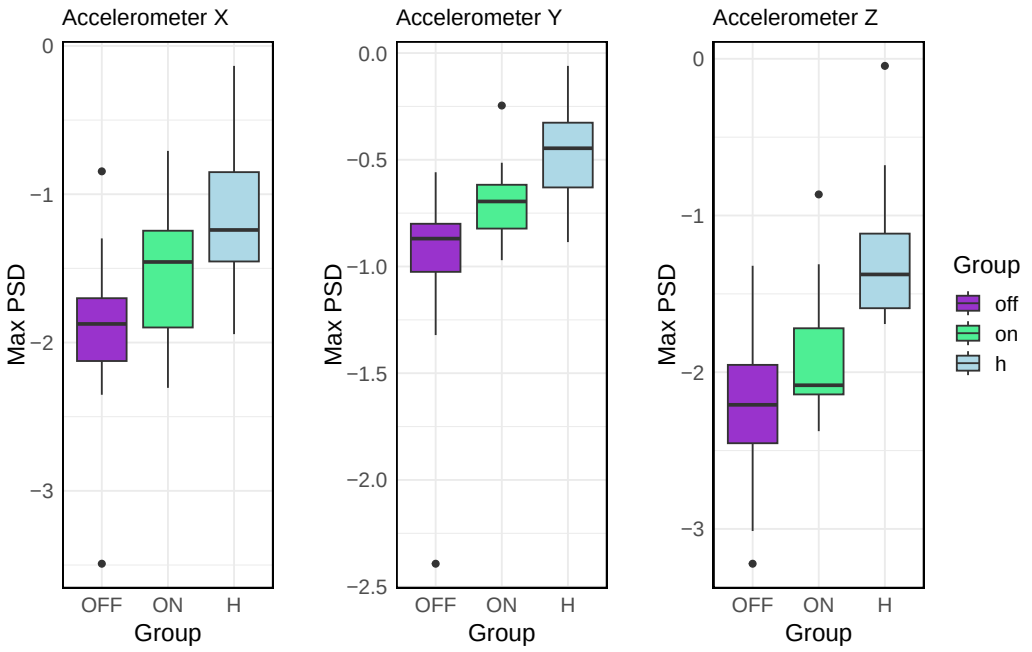


Figure 5.4 – Boxplot with the difference between the groups during phase 1.

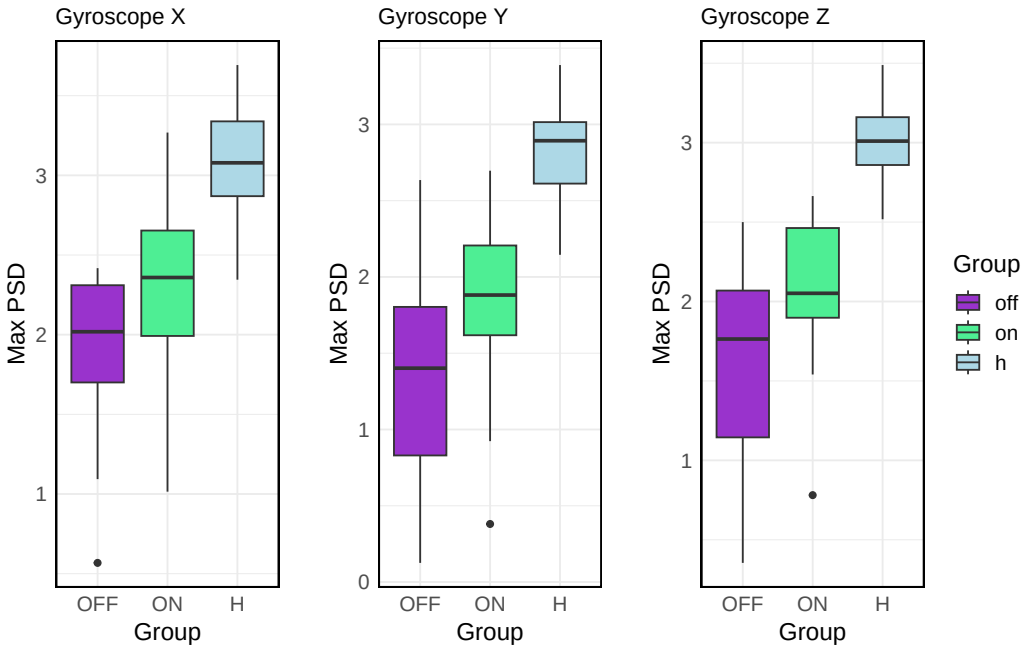


Figure 5.5 – Boxplot with the difference between the groups during phase 1.

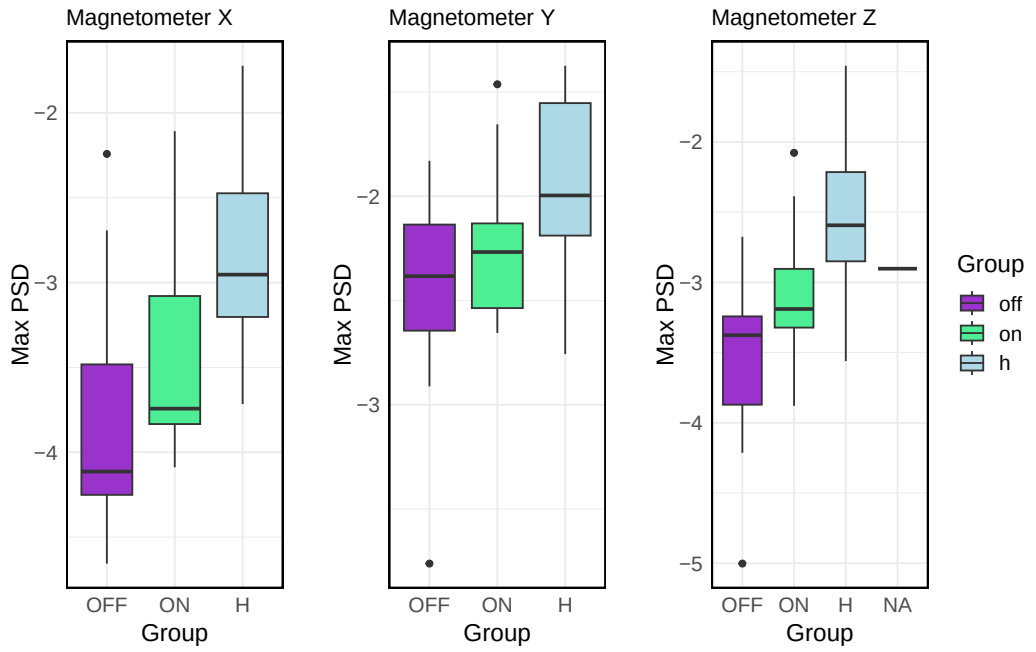


Figure 5.6 – Boxplot with the difference between the groups during phase 1.

netometer demonstrated the ability to distinguish between healthy groups and patients with PD, in phase 1, the differences observed between the "on" and "off" groups were not as pronounced. This finding highlights the complexity of the motor features of PD and the need to investigate multiple aspects of movement to fully understand the disease.

The Kruskal-Wallis test was applied to evaluate possible differences between groups. Correlation with the MDS-UPDRS values were also measured, regarding rigidity (Part III, items 3.3b and 3.3c). In Table 5.2 it is possible to see the results.

| | **Correlation** | **Statistical Difference (p value)** | | |
|---|---|---|---|---|
| **Sensor** | **UPDRS** | **OFF - H** | **ON - H** | **ON - OFF** |
| **AccX** | -0.55 | $< 0.001$ | 0.17 | 0.07 |
| **AccY** | -0.61 | $< 0.001$ | 0.12 | 0.03 |
| **AccZ** | -0.60 | $< 0.001$ | 0.002 | 0.17 |
| **GyroX** | -0.69 | $< 0.001$ | $< 0.001$ | 0.11 |
| **GyroY** | -0.64 | $< 0.001$ | $< 0.001$ | 0.05 |
| **GyroZ** | -0.80 | $< 0.001$ | $< 0.001$ | 0.02 |
| **MagX** | -0.64 | $< 0.001$ | 0.02 | 0.20 |
| **MagY** | -0.56 | 0.01 | 0.15 | 0.51 |
| **MagZ** | -0.63 | $< 0.001$ | 0.01 | 0.03 |
| **M. Extensor** | -0.66 | $< 0.001$ | 0.007 | 0.005 |
| **M. Flexor** | -0.64 | $< 0.001$ | 0.03 | 0.007 |

Table 5.2 – Statistics regarding phase 1 evaluations.

The results of phase 1 of the rehabilitation game reveal a significant correlation between sensor signals and the UPDRS scale. Notably, gyroscope sensors (GyroX, GyroY, GyroZ) showed the strongest correlations with UPDRS, indicating a robust association be-

tween rotational movements and muscle rigidity. This suggests that movements involving changes in body orientation are particularly relevant for assessing rigidity in PD patients during phase 1 of the rehabilitation SG. Furthermore, accelerometer sensors (AccX, AccY, AccZ) also exhibited significant correlations, although slightly lower than gyroscope sensors. This suggests that acceleration movements, such as raising and lowering the hand, also contribute to the assessment of rigidity during this phase of the game.

On the other hand, the magnetometer signals (MagX, MagY, MagZ) showed varied and less pronounced correlations with the UPDRS. Although there was still a significant association, the differences between the "on" and "off" medication groups were not as distinct. Regarding sEMG signals (M. Extensor, M. Flexor), both exhibited significant correlations with UPDRS, highlighting the importance of muscle activity in assessing rigidity. However, the magnitude of the differences between the medication "on" and "off" groups appears to be more prominent in the extensor muscle signals, suggesting a possible difference in the muscular response to movements performed during phase 1.

### 5.4.2 Phase 2

During phase 2, the movements of raising and lowering the closed hand were used (events 10 and 12 shown in Table 5.1.1). Since in this phase the person stays with the hand closed. Firstly, it is possible to observe the differences regarding the sEMG evaluations, shown in Figure 5.7.

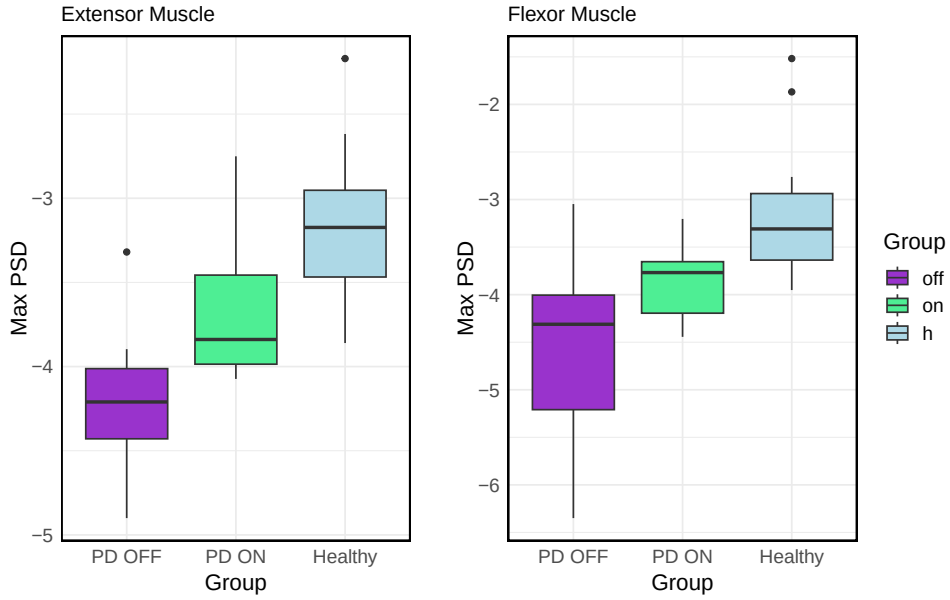


Figure 5.7 – Boxplot with the difference between the groups during phase 2. a) Extensor muscle. b) Flexor muscle.

In phase 2, there was a significant observation of differences between the groups, especially in relation to the flexor muscle. However, it is interesting to note that, despite

this distinction, the sEMG signals did not demonstrate such a pronounced difference between the groups when compared to previous analyses. This suggests that, during this phase of the game, other factors may be influencing muscle activity more, possibly due to the nature of the movements performed, such as keeping the hand closed. The smaller differentiation in sEMG signals may indicate a more homogeneous muscular response between the "on", "off" and healthy groups.

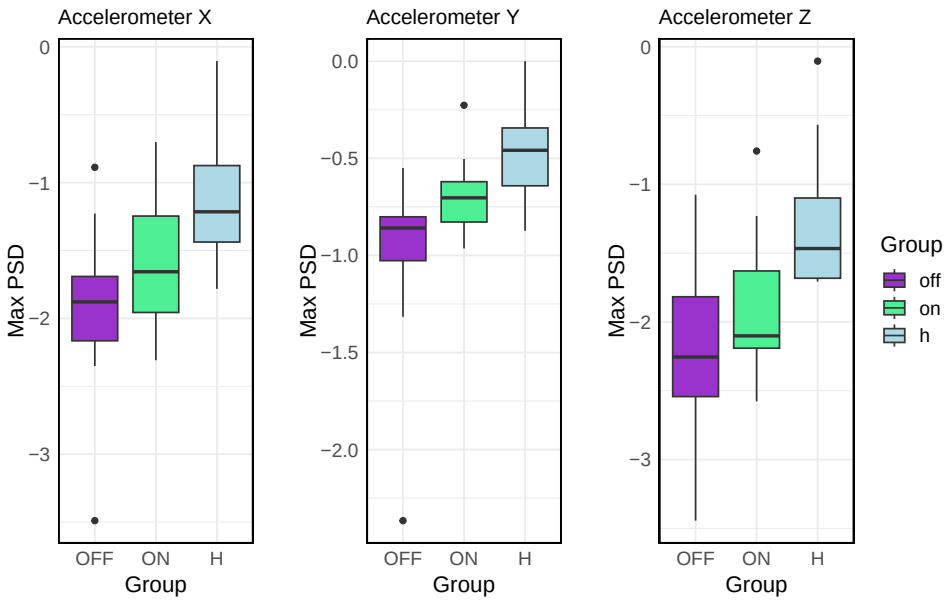


Figure 5.8 – Boxplot showing the differences between groups during phase 2.

In Figure 5.8 it is possible to observe the results regarding the accelerometer, for phase 2. The results indicate that the AccX sensor showed a moderate correlation with the MDS-UPDRS score, with statistically significant differences between the "off" and "h" groups, but not between the "on" and "h" groups, nor between the "on" and "off" groups. The AccY sensor also showed a moderate correlation with MDS-UPDRS, with statistically significant differences between the "off" and "h" groups, and between the "on" and "off" groups, but not between the "on" and "h" groups. Finally, the AccZ sensor showed a moderate correlation with the MDS-UPDRS, with statistically significant differences between the "off" and "h" groups, but not between the "on" and "h" groups, nor between the "on" and "off" groups. Indicating that in phase 2, the accelerometer was unable to differentiate the three groups so well.

Figure 5.9 indicates the results for gyroscope analysis in phase 2.

Regarding phase 2 of the RehaBEElitation game, the GyroX and GyroY sensors showed a moderate correlation with the UPDRS score, with statistically significant differences between the "off" and "h" groups, and between the "on" and "off" groups, but not between the "on" and "h" groups. The GiroZ sensor showed a strong correlation with UPDRS, with statistically significant differences between all groups.

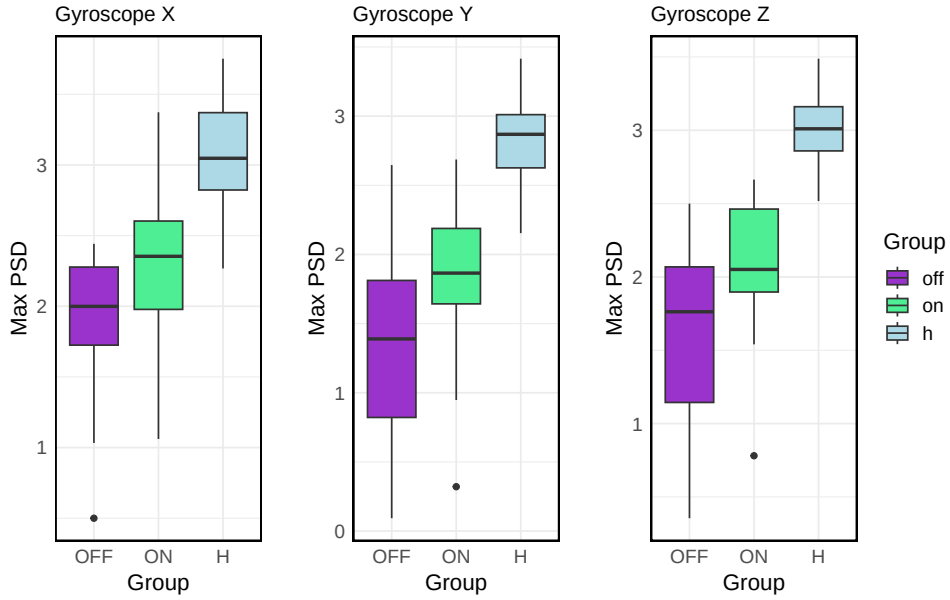


Figure 5.9 – Boxplot with the difference between the groups during phase 2.

Figure 5.10 indicates the results for gyroscope analysis in phase 2.

The results for the magnetometer showed a moderate correlation with the UPDRS and a statistical difference, mainly between the "off" and "h" groups, for the three axes.

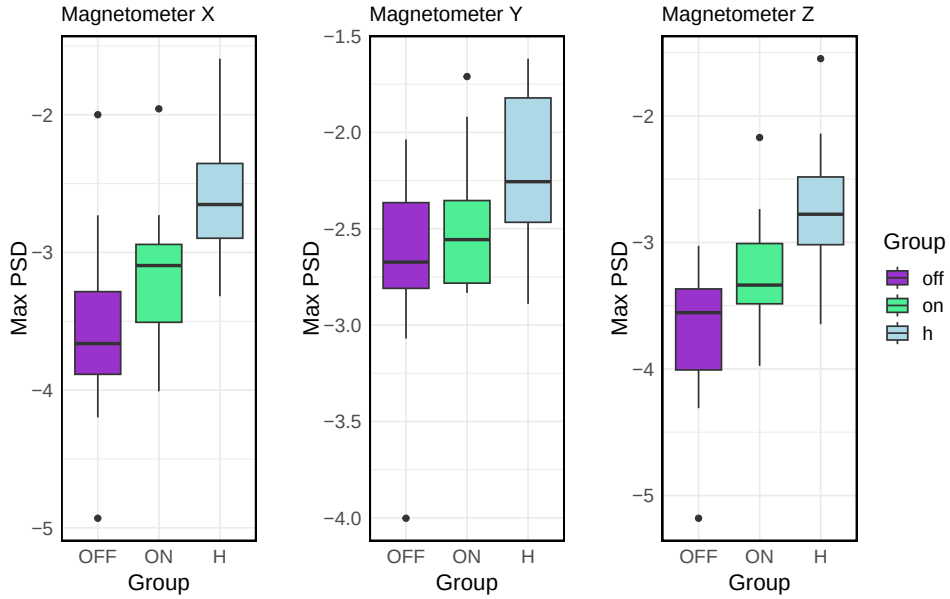


Figure 5.10 – Boxplot with the difference between the groups during phase 2.

The Kruskal-Wallis test was applied to evaluate possible differences between groups. The correlation with the MDS-UPDRS values were also measured regarding rigidity (Part III, items 3.3b and 3.3c). In Table 5.3 it is possible to see the results.

With the results found in phase 2 of RehaBEElitation, it can be observed that the

| Sensor | Correlation UPDRS | Statistical Difference (p value) OFF - H | ON -H | ON - OFF |
|---|---|---|---|---|
| **AccX** | -0.55 | $< 0.001$ | 0.07 | 0.16 |
| **AccY** | -0.59 | $< 0.001$ | 0.12 | 0.03 |
| **AccZ** | -0.57 | $< 0.001$ | 0.005 | 0.21 |
| **GyroX** | -0.67 | $< 0.001$ | $< 0.001$ | 0.08 |
| **GyroY** | -0.64 | $< 0.001$ | $< 0.001$ | 0.06 |
| **GyroZ** | -0.80 | $< 0.001$ | $< 0.001$ | 0.02 |
| **MagX** | -0.63 | $< 0.001$ | 0.01 | 0.11 |
| **MagY** | -0.56 | 0.01 | 0.15 | 0.47 |
| **MagZ** | -0.65 | $< 0.001$ | 0.01 | 0.03 |
| **M. Extensor** | -0.53 | $< 0.001$ | 0.16 | 0.15 |
| **M. Flexor** | -0.57 | $< 0.001$ | 0.01 | 0.02 |

Table 5.3 – Statistics regarding phase 2 evaluations.

GyroZ sensor stood out both in its ability to differentiate the "off" and "h", "on" and "h" and "on" and "off" groups, with significantly low p-values in all comparisons, and in correlation with the UPDRS score, exhibiting the highest absolute correlation of -0.80. This suggests that the GyroZ sensor may be a promising choice for assessing rigidity in these patients, due to its sensitivity in capturing the distinctive characteristics of different motor states and the strong association with symptom severity for this phase.

### 5.4.3 Phase 3

During phase 3, participants engaged in movements involving raising and lowering their hands, performed both in open and closed states (events 9, 10, 11, and 12, shown in Table 5.1.1). These movements closely mirrored those executed in phase 1 of the game. The results pertaining to (sEMG) are depicted in Figure 5.11.

These findings highlight the significant variability in sEMG activity between different medication states, clarifying the distinct muscular responses in individuals with PD compared to healthy controls. Notably, flexor muscles show a stronger correlation with medication states compared to extensor muscles. As in phase 1, this may occur due to a sustained contraction during the activity proposed in the game, which can interfere with the rigidity measurement.

The results regarding the accelerometer in phase 3 can be seen in Figure 5.12.

When investigating accelerometer signals, noticeable differences between groups emerge. Particularly notable are the disparities observed between various axes and among different groups. Notably, substantial variations are evident along the X axis, particularly when comparing the "h" and "off" groups. However, the distinctions observed on other axes are relatively subdued in comparison. Figure 5.13 shows the gyroscope results for phase 3.

It can be seen from the gyroscope results a greater difference between the groups for the Z axis, in the same way it is possible to observe significant differences between the

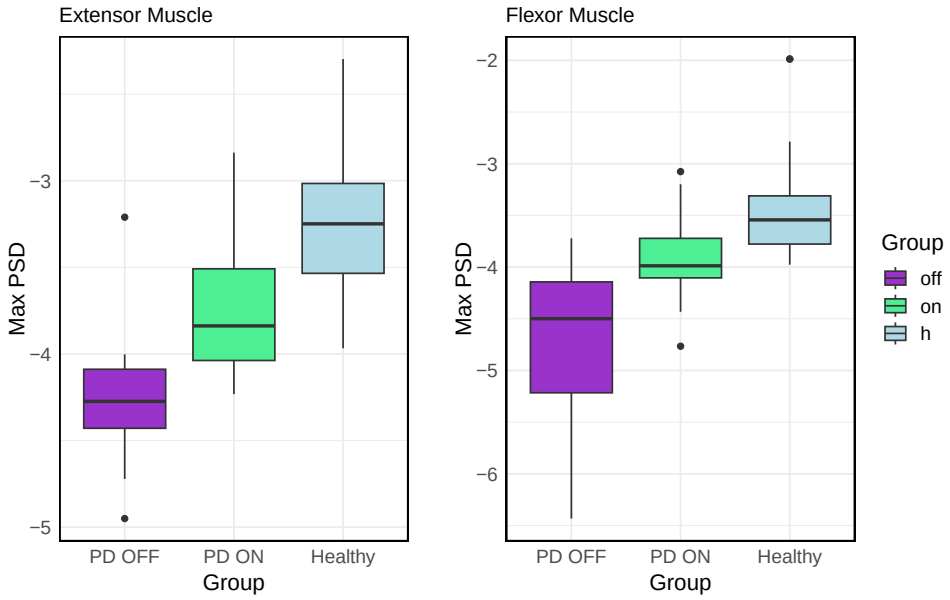


Figure 5.11 – Boxplot with the difference between the groups during phase 3.

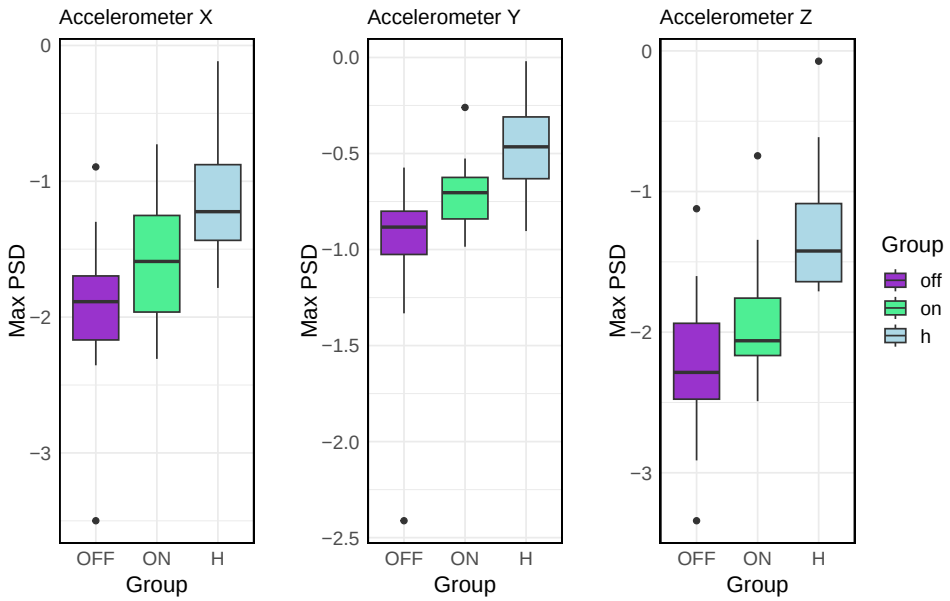


Figure 5.12 – Boxplot with the difference between the groups during phase 3.

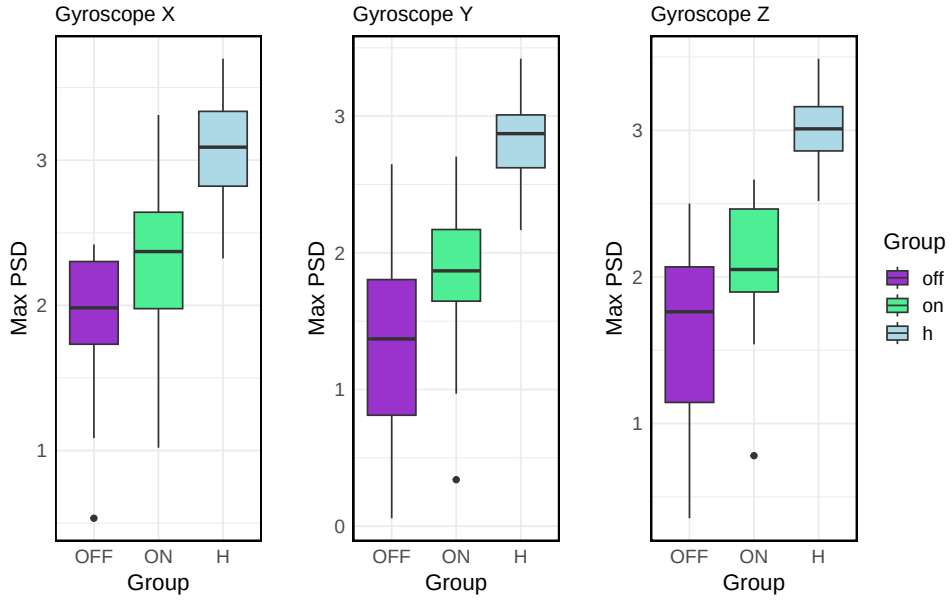


Figure 5.13 – Boxplot with the difference between the groups during phase 3.

groups, although to a lesser extent, for the other axes.

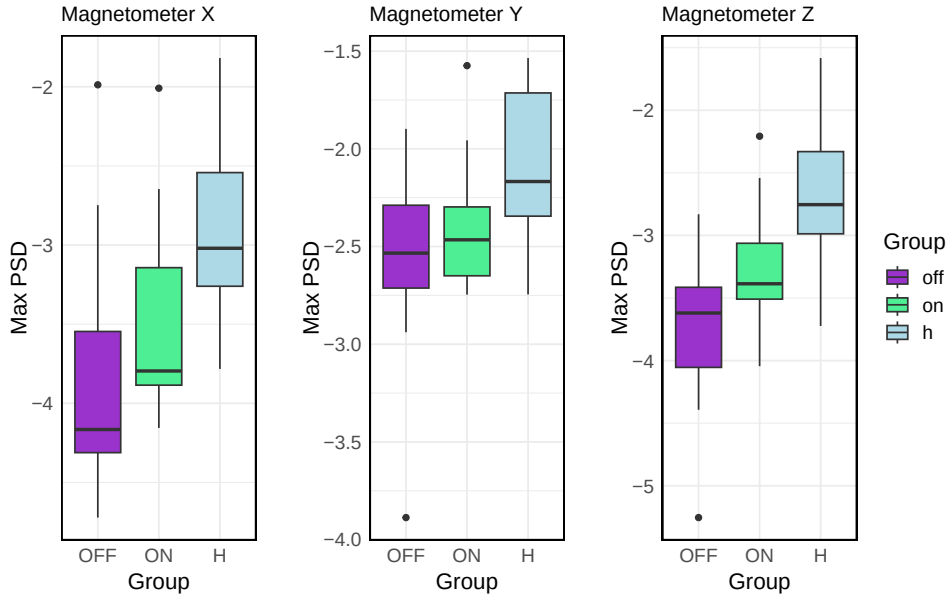


Figure 5.14 – Boxplot with the difference between the groups during phase 3. a) Magnetometer axis X. b) Magnetometer axis Y. c) Magnetometer axis Z.

The magnetometer results can be seen in 5.14. The magnetometer data reveal significant differences among the groups, particularly evident in the "h" and "off" comparison. However, regarding the "on" and "h" and "on" and "off" comparisons, the significance decreases, suggesting less pronounced differences among these groups.

The Kruskal-Wallis test was applied to evaluate possible differences between groups.

The correlation with the MDS-UPDRS values were also measured regarding rigidity (Part III, items 3.3b and 3.3c). In Table 5.4 it is possible to see the results.

| Sensor | Correlation UPDRS | Statistical Difference (p value) OFF - H | ON -H | ON - OFF |
|---|---|---|---|---|
| **AccX** | -0.55 | $< 0.001$ | 0.08 | 0.08 |
| **AccY** | -0.61 | $< 0.001$ | 0.11 | 0.03 |
| **AccZ** | -0.56 | $< 0.001$ | 0.003 | 0.20 |
| **GyroX** | -0.68 | $< 0.001$ | $< 0.001$ | 0.09 |
| **GyroY** | -0.64 | $< 0.001$ | $< 0.001$ | 0.06 |
| **GyroZ** | -0.80 | $< 0.001$ | $< 0.001$ | 0.02 |
| **MagX** | -0.62 | $< 0.001$ | 0.03 | 0.25 |
| **MagY** | -0.58 | 0.01 | 0.10 | 0.59 |
| **MagZ** | -0.63 | $< 0.001$ | 0.01 | 0.04 |
| **M. Extensor** | -0.67 | $< 0.001$ | 0.005 | 0.003 |
| **M. Flexor** | -0.68 | $< 0.001$ | 0.04 | 0.004 |

Table 5.4 – Statistics regarding phase 3 evaluations.

Analysing the results, it can be observed that the GyroZ sensor presented the highest correlation with UPDRS, reaching a value of -0.80, followed by GyroX and M. Flexor, both with correlations around -0.68. Regarding differences between groups, GyroZ also stood out, showing significant differences in all comparisons ("off" and "h", "on" and "h", "on" and "off"), with p values $< 0.001$. Furthermore, the M. Extensor sensor also demonstrated a strong ability to differentiate groups, especially in the "on" and "off" comparison, with a p-value of 0.003.

### 5.4.4 Phase 4

During phase 4, the movements of raising and lowering the open hand were considered (events 9 and 11, shown in Table 5.1.1). The movements were similar with the Phase 2, but here the participant stays all the time with the hand open. The sEMG results can be seen in Figure 5.15.

The sEMG results of phase 4 indicate significant differences between the groups for the two muscles analyzed, M. Extensor and M. Flexor. For M. Extensor, it can be observed greater differences for all groups. Similarly, for M. Flexor, it can be also observed significant differences in all comparisons among groups. These results highlight patterns of muscle activity during phase 4 of the study, with important implications for understanding rigidity. The results regarding the accelerometer sensors can be seen in Figure 5.16.

The accelerometer results in phase 4 reveal notable differences between the groups evaluated. When analyzing the differences between the groups, it can be observe that the X and Y axes showed significant differences in all groups.

Figure 5.17 represents the results regarding gyroscope data in phase 4.

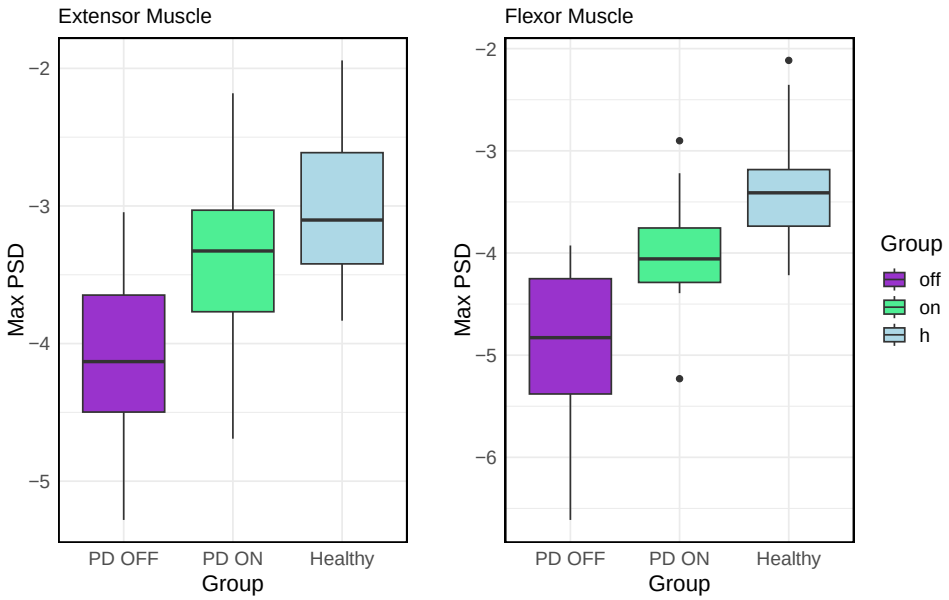


Figure 5.15 – Boxplot with the difference between the groups during phase 4. a) Extensor muscle. b) Flexor muscle.

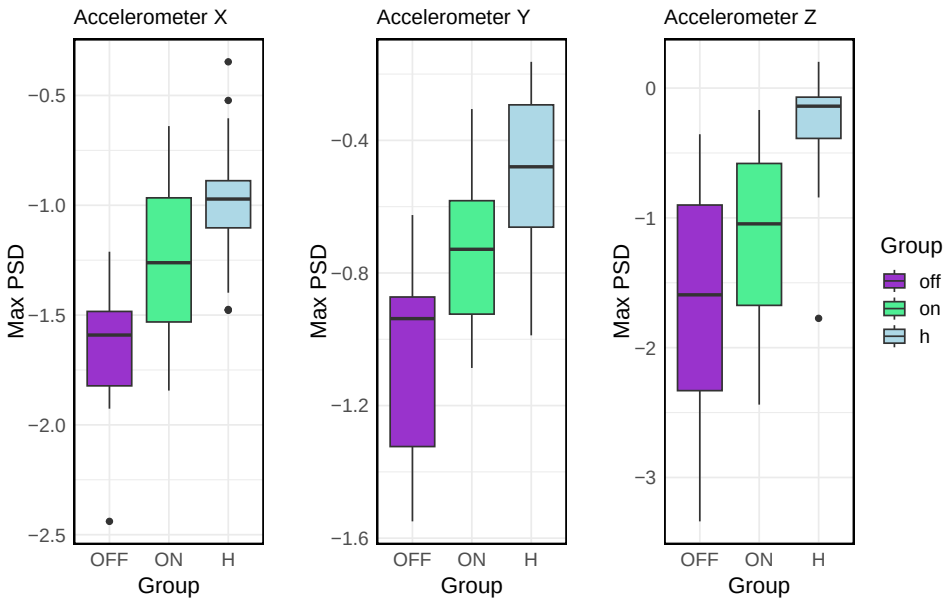


Figure 5.16 – Boxplot with the difference between the groups during phase 4.

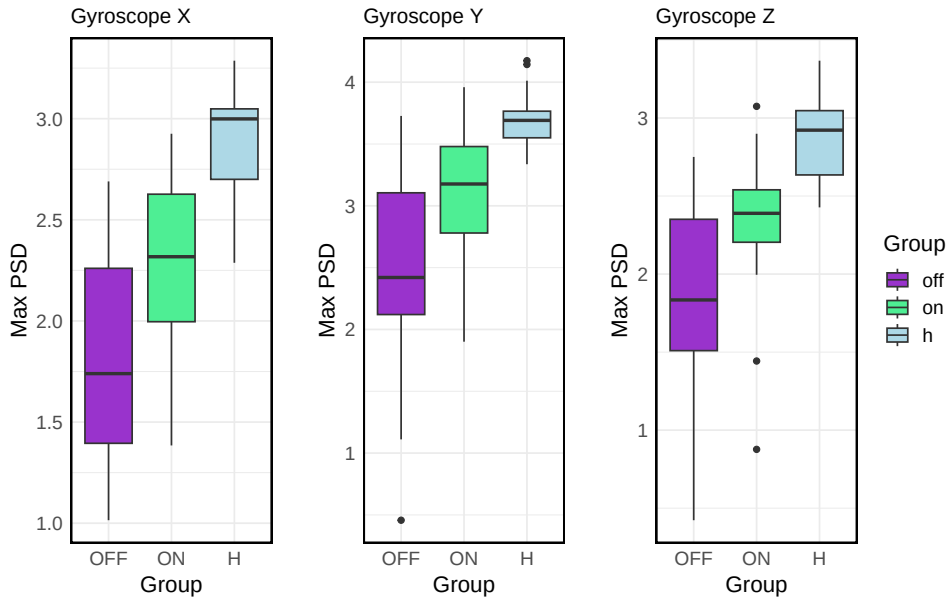


Figure 5.17 – Boxplot with the difference between the groups during phase 4.

In phase 4, it can be observed notable differences among groups when analyzing gyroscope data. From the graph it is possible to observe that there are significant differences between the "off" and "h", "on" and "h" and "on" and "off" groups. The X axis is the one that presents the greatest difference among the groups, since the signal evaluated is being carried out on this axis.

The results of magnetometer signals can be observed in Figure 5.18.

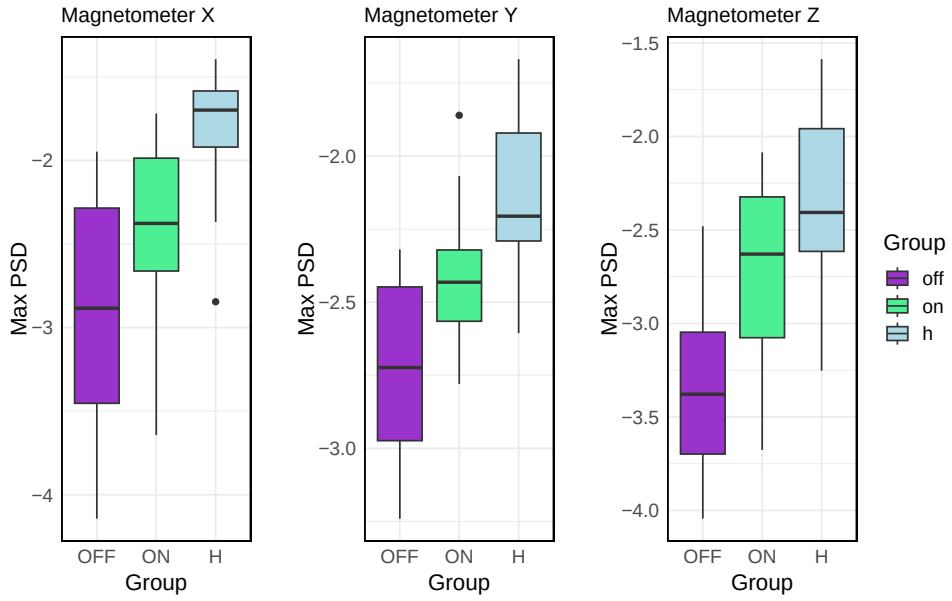


Figure 5.18 – Boxplot with the difference between the groups during phase 4.

When analyzing magnetometer data in phase 4, we also observed significant differences

among groups. It is possible to observe that there are differences in the magnetometer activity for all groups analyzed.

The Kruskal-Wallis test was applied to evaluate possible differences between groups. The correlation with the MDS-UPDRS values were also measured, regarding rigidity (Part III, items 3.3b and 3.3c). In Table 5.5 it is possible to see the results.

| Sensor | Correlation UPDRS | Statistical Difference (p value) OFF - H | ON -H | ON - OFF |
|---|---|---|---|---|
| **AccX** | -0.71 | $< 0.001$ | 0.05 | 0.01 |
| **AccY** | -0.69 | $< 0.001$ | 0.04 | 0.003 |
| **AccZ** | -0.59 | $< 0.001$ | 0.008 | 0.12 |
| **GyroX** | -0.68 | $< 0.001$ | 0.001 | 0.02 |
| **GyroY** | -0.58 | $< 0.001$ | 0.02 | 0.02 |
| **GyroZ** | -0.72 | $< 0.001$ | 0.009 | 0.05 |
| **MagX** | -0.66 | $< 0.001$ | 0.01 | 0.02 |
| **MagY** | -0.73 | $< 0.001$ | 0.01 | 0.006 |
| **MagZ** | -0.56 | $< 0.001$ | 0.04 | 0.001 |
| **M. Extensor** | -0.46 | $< 0.001$ | 0.33 | 0.01 |
| **M. Flexor** | -0.51 | $< 0.001$ | 0.06 | 0.002 |

Table 5.5 – Statistics regarding phase 4 evaluations.

The results in the table show the correlation between the sensors and the MDS-UPDRS, as well as the statistical differences between the "off" and "h", "on" and "h" and "on" and "off" groups. The GyroZ sensor showed the highest correlation with MDS-UPDRS (-0.72), followed by the MagY sensor (-0.73), indicating a stronger association between the activity recorded by these sensors and rigidity. Regarding the differences between the groups, it can be observed that the GyroZ, MagY and AccX sensors were able to significantly differentiate the three groups, with significant p values for all comparisons between "off" and "h", "on" and "h" and "on" and "off". This suggests that these sensors could be particularly useful in distinguishing among the three groups. However, it is important to note that the AccY and MagZ sensors also showed statistically significant differences between the groups, although at a lower magnitude compared to the other sensors. On the other hand, the M. Extensor and M. Flexor sensors showed lower correlations with the UPDRS and were not as effective in differentiating among groups, with higher p-values compared to the other sensors. This may be related to the fact that the muscle is frequently active during the game, making it impossible to observe large differences among the groups, regarding rigidity.

### 5.4.5 General Analysis

After analyzing the four phases of the study, it can be make an overview of the assessment of rigidity in people with PD, using the RehaBEElitation SG. In terms of

correlations with the UPDRS scale and differences between the "off" and "h", "on" and "h" and "on" and "off" groups, the phase that stood out was Phase 4.

In Phase 4, the accelerometer (AccX, AccY, AccZ) and gyroscope (GyroX, GyroY, GyroZ) sensors showed strong negative correlations with the UPDRS scale, suggesting a significant association with the severity of rigidity in PD. Furthermore, these sensors were able to effectively differentiate among the different groups analyzed.

Although magnetometer sensors (MagX, MagY, MagZ) showed moderate correlations with UPDRS and ability to differentiate among groups, they were not as robust as accelerometer and gyroscope sensors.

In terms of muscles analyzed, both the extensor and flexor muscles showed significant associations with severity of rigidity and differences between groups. However, motion sensors were more effective in assessing rigidity compared to sEMG sensors used to measure muscle activity.

Therefore, based on the results obtained, Phase 4 seems to be the most suitable for evaluating rigidity in PD patients, especially using the accelerometer and gyroscope sensors. These sensors proved to be more sensitive to variations in rigidity and more effective in differentiating between different groups. Therefore, it can be highlighted the sensors that were most relevant for the analysis of rigidity, during phase 4, in Figure 5.19.

## 5.5 Discussion

This chapter aimed to provide an objective assessment of rigidity in individuals with PD utilizing the RehaBEElitationSG. To our knowledge, no previous studies have utilized data recorded by inertial sensors during the interaction of PD patients with a SG to objectively assess rigidity. This innovative approach fills a significant gap in the literature, offering a novel method for evaluating motor symptoms in PD. By incorporating inertial sensors into the gaming experience, it was aimed to overcome the limitations of traditional assessment methods and provide a more accurate and objective evaluation of rigidity. This chapter explores the potential of SGs as a valuable tool for rigidity assessment in PD and lays the groundwork for future research in this area.

Improving the assessment of rigidity in PD is crucial for enhancing the management of this symptom. Utilizing innovative approaches, such as incorporating simple tasks and dynamic activities like SGs, this can revolutionize the evaluation process. By integrating sensor technologies and interactive gameplay, a more comprehensive and objective assessment of rigidity can be achieved.

In this sense, the development of SGs specifically designed to assess muscle rigidity in PD represents a new and promising area for exploration in the domain of SGs. Although existing SGs have primarily focused on rehabilitation and strengthening exercises for individuals with PD, direct assessment of muscle rigidity through gaming platforms remains

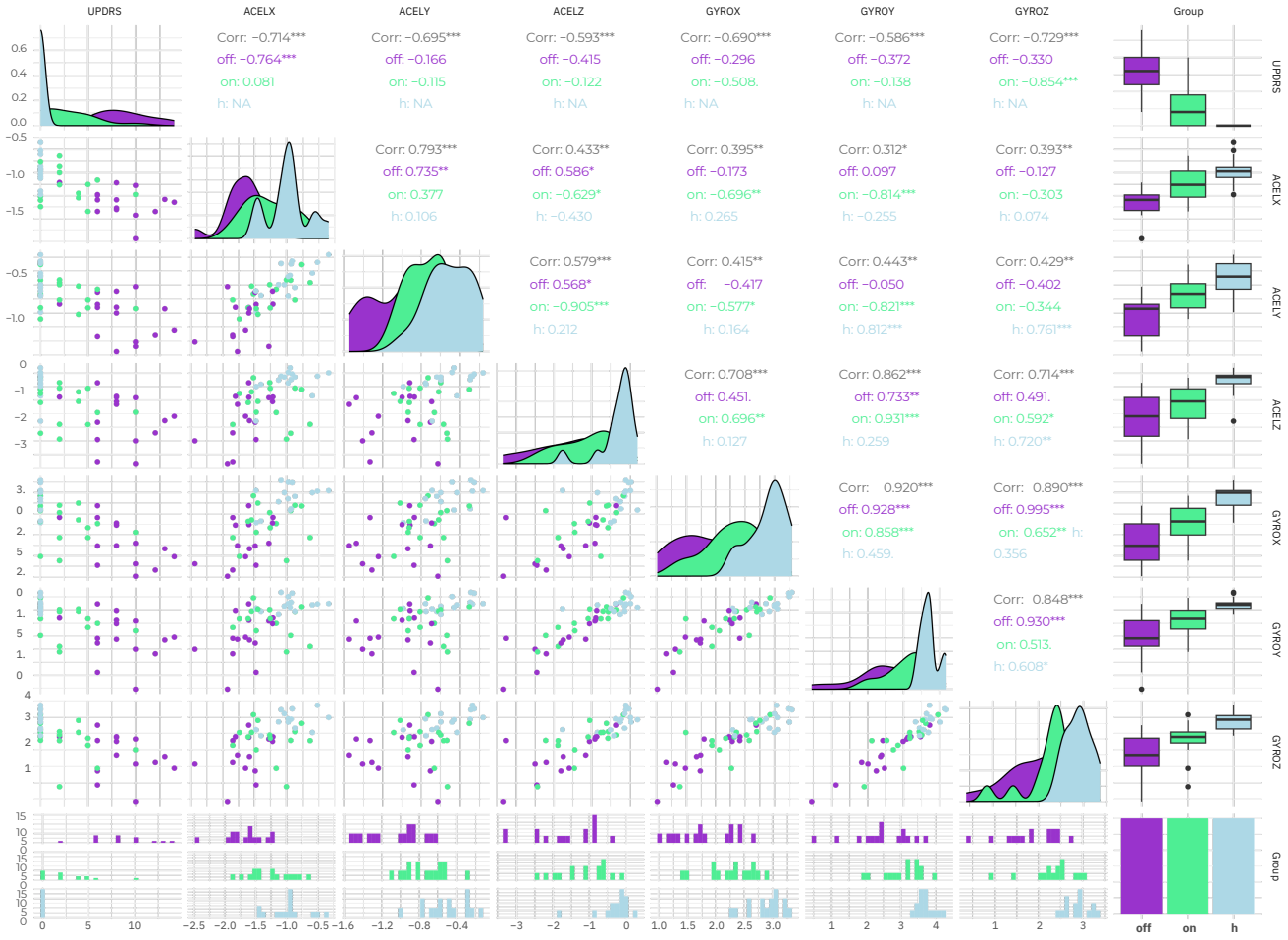


Figure 5.19 – Main differences for accelerometer and gyroscope sensors in phase 4.

an untapped opportunity. The RehaBEElitation SG was developed with the aim of being a tool for rehabilitation and measurement of the main symptoms of PD. Each phase was designed and developed based on the MDS-UPDRS movements, in order to obtain parameters that can be correlated with this assessment, which is still the gold standard for measuring the progression of PD. It has previously been tested and validated for the assessment of bradykinesia, obtaining favorable results for this type of assessment (78). In this context, it opens up avenues to assess additional symptoms, such as rigidity, thereby broadening the scope of evaluation within the research domain.

### Phase 1

During Phase 1 of the game, players manipulate a virtual representation of a bee as they go around a garden environment. This activity requires a more advanced degree of motor skills, since it entails coordinating muscles and joints to control the avatar's movements and interact with different components in the virtual environment. Studies have shown that engaging in complex and natural motor activities, such as exploring virtual worlds, results in increased and prolonged muscle activation compared to isolated

and controlled movements (120). The heightened demand on the motor system during the execution of complex tasks in Phase 1 is anticipated to lead to sustained muscle contraction, even in individuals without health issues, as they strive to maintain posture and balance while performing a range of coordinated movements. This explains why the difference between the "on" and "off" groups is not substantial, and also why there is a correlation with the UPDRS.

Analysis of inertial sensor data revealed significant insights. Accelerometer data showed notable differences, particularly in the Z axis, reflecting significant variations in movements. This is in accordance with previous research demonstrating the sensitivity of accelerometers in capturing vertical accelerations during dynamic tasks in PD evaluations (50, 60). Gyroscope data exhibited strong differentiation among groups, especially in the Z axis, suggesting possible differences in flexibility and range of motion between participants. Magnetometer data successfully distinguished among healthy individuals and those with PD, although differences between "on" and "off" medication states were less pronounced. Furthermore, correlation analysis revealed that gyroscope data exhibited the strongest association with the UPDRS, indicating a robust link with rigidity. This finding highlights the importance of gyroscopic measurements in assessing motor symptoms and disease severity in PD (43).

This suggests that movements involving changes in body orientation are particularly relevant for assessing rigidity in PD patients during this phase of play. Furthermore, accelerometer sensors (AccX, AccY, AccZ) also showed significant correlations, although slightly lower than gyroscope sensors. This suggests that acceleration movements also contribute to the assessment of rigidity during this phase of the game. In summary, the results from this phase highlight the importance of gyroscope and accelerometer sensors in assessing muscle rigidity in PD patients during rehaBEElitation phase 1.

### Phase 2

In phase 2, the participant remains with their hand closed, and it is possible to observe differences in the sEMG evaluations. The results indicate that there was a significant observation of differences among the groups, especially in relation to the flexor muscle. However, it is interesting to note that, despite this distinction, the sEMG signals did not demonstrate such a pronounced difference between the groups when compared to previous analyses. This suggests that, during this phase of the game, other factors may be influencing muscle activity more, possibly due to the nature of the movements performed, such as keeping the hand closed (17). The smaller differentiation in sEMG signals may indicate a more homogeneous muscular response between the "on", "off" and healthy groups.

Regarding the evaluation using inertial sensors, distinct results were observed regarding the ability of these devices to differentiate between different motor states and their correlation with symptom severity in patients with PD. The sensor that stood out in this

analysis was the gyroscope, which demonstrated a significant correlation with the MDS-UPDRS score, and statistically significant differences between the "off" and "h", "on" and "h", and "on" and "off" groups. Its absolute correlation of -0.80 suggests a strong association with rigidity severity. Other researches has shown the effectiveness of gyroscopes in wearable devices for monitoring and analyzing movement patterns in individuals with PD (45).

On the other hand, the accelerometer results were more varied. Although it demonstrated a moderate correlation with the MDS-UPDRS score, the accelerometer had difficulty differentiating groups during phase 2. The accelerometer sensors showed statistically significant differences among some groups but were unable to effectively distinguish between different motor states. The magnetometer results were similar to those of the accelerometer, with a moderate correlation with the MDS-UPDRS and statistically significant differences among the "off" and "h" groups, but not between the "on" and "h" and "on" and "off" groups.

Maintaining a closed hand may have limited the range and variety of movements performed during this phase of the game, impacting the ability of inertial sensors to capture relevant information about rigidity. The restriction of movement associated with the closed hand may have reduced the diversity of signals captured by inertial sensors, hindering their ability to differentiate between different motor states ("on" and "off") and correlate with the severity of symptoms. Furthermore, the more restricted nature of movements during phase 2 may have minimized differences in muscular responses between patient groups, thereby decreasing the sensors' ability to detect these variations.

### Phase 3

In phase 3, there was a continuity of the movements carried out in phase 1 of the game. The results obtained with the inertial sensors provided important insights into the muscular responses and movement patterns of participants with PD (PD) in different medication states.

Initially, sEMG results highlighted significant variability in muscle activity between different medication states, with a clear distinction in muscle responses in individuals with PD compared to healthy subjects. Specifically, flexor muscles demonstrated a stronger correlation compared to extensor muscles. During the phase in which the bee moves around the scenario, participants are likely to keep their flexor muscles tense for long periods to maintain the bee's positioning (26). This sustained contraction of the flexor muscles can result in greater muscular activity in these muscles, influencing the measurement of muscle rigidity, especially when compared to the activity of the extensor muscles (110). Therefore, the more significant results in flexor muscles may reflect the specific demand of these muscles during the execution of movements in the game.

With regard to inertial sensors, accelerometer results revealed notable differences be-

tween groups, especially along the X-axis, indicating an ability to discriminate between different medication states. However, the differences observed in the other axes were relatively less pronounced. The magnetometer results also revealed significant differences between the groups, with emphasis on the "off" and "h" comparison. However, the differences were less pronounced in the "on" and "h" and "on" and "off" comparisons, indicating less discrimination between these groups. Overall, the gyroscope sensor, especially along the Z-axis, demonstrated a strong correlation with UPDRS score and a significant ability to differentiate between different PD medication states.

It is interesting to note that, during the phase, the bee's stability may have reduced the need for quick and sudden movements on the part of the participants. This may have directly impacted the response of the inertial sensors, which may not have been as required as in previous phases of the game. The lack of intense movement of the inertial sensors may have contributed to a lower sensitivity in detecting variations in muscle rigidity (10). Therefore, it may have negatively influenced the accuracy of muscle rigidity measurements obtained through inertial sensors.

**Phase 4**

In phase 4 of the study, participants mainly performed flexion and extension movements of the open hand, which are very similar to those performed during the application of clinical scales to assess rigidity in patients with PD. This similarity is important, as it suggests that the movements performed in the game accurately reflect the actions performed during clinical rigidity assessment procedures. This increases the validity and relevance of the results obtained in the game, providing a more dynamic and potentially more sensitive tool for assessing rigidity in Parkinson's patients (19).

In phase 4 of the study, we observed significant results were observed regarding the assessment of rigidity in patients with PD, using the RehaBEElitation SG. Data collected during this phase indicated a strong correlation between accelerometer and gyroscope sensors and the UPDRS scale score, suggesting a significant association with the severity of rigidity in PD. Furthermore, these sensors were able to effectively differentiate among the different groups analyzed, including "off" and "h", "on" and "h" and "on" and "off".

The results also highlighted the effectiveness of magnetometer sensors in correlating with UPDRS scale scores and differentiating among groups. However, this association was less robust compared to accelerometer and gyroscope sensors.

As for the muscles analyzed, both extensor and flexor muscles showed significant associations with the severity of rigidity and differences between groups. However, motion sensors (accelerometer and gyroscope) were found to be more effective in assessing rigidity compared to sEMG sensors used to measure muscle activity.

Therefore, based on the results obtained, phase 4 emerged as the most suitable for evaluating rigidity in PD, especially using the accelerometer and gyroscope sensors. These

sensors have been shown to be more sensitive to variations in rigidity and more effective in differentiating between different groups. In Figure 5.19, it is possible to clearly differentiate the distribution of the three groups, in which the correlations between the sensors were strong.

In this sense, phase 4 of the game emerged as crucial for assessing rigidity due to the predominance of wrist flexion and extension movements. This emphasis provided an ideal opportunity to capture and analyze patterns of muscle activity and kinematics directly related to rigidity. Furthermore, the need for precision to hit the targets when drying the nectar added a layer of complexity and required more refined motor control on the part of the participants (68). This combination of specific movements and refined motor demands may have increased the game's sensitivity to detect subtle differences in rigidity between the groups studied.

**General analysis**

The utilization of advanced sensor technologies, including accelerometers, gyroscopes and magnetometers, in the assessment of rigidity in individuals with PD through the RehaBEElitation game has provided valuable insights. The comprehensive analysis conducted across the four phases of the game has shed light on the intricate patterns of rigidity and motor impairments experienced by individuals with PD. The correlation of sensor data with the MDS-UPDRS scores has enabled a quantitative evaluation of rigidity, offering a more objective and personalized approach to monitoring motor symptoms.

However, the use of sEMG was not as effective as expected, especially due to constantly performing the task during all phases of the game. This constant performance may have led to continuous muscular activity and therefore made it difficult to detect significant differences in rigidity between groups. This suggests that for future studies it may be necessary to consider strategies to minimize the influence of ongoing muscular activity.

The results from the study emphasize the importance of leveraging innovative methodologies, such as SGs combined with sensor technologies, for enhancing the assessment and understanding of rigidity in PD. The ability of sensors to differentiate between groups and correlate with disease severity underscores their potential in clinical practice and research settings.

## 5.6 Conclusions

In summary, this chapter's conclusion emphasizes the efficacy of the RehaBEElitation game in detecting rigidity patterns in individuals with PD. Phase 4 of the game, utilizing data from accelerometers and gyroscopes, was particularly successful in this regard. The results obtained during this phase offer crucial insights into the severity of rigidity experienced by PD patients, underscoring the significance of employing sensor technologies

for precise and personalized evaluations of the disease's motor manifestations. Moreover, the analysis of accelerometer and gyroscope data facilitated a clear differentiation among the various rigidity patterns observed in distinct groups of PD patients, indicating the substantial potential of these sensors in the identification and characterization of rigidity within clinical and research settings. These outcomes underscore the potential of RehaBEElitation as an innovative and efficient tool for evaluating critical symptoms in individuals with PD, opening avenues for future investigations to delve deeper into its clinical and therapeutic applications.

In addition to the RehaBEElitation game's ability to identify rigidity patterns, it is important to highlight the strong correlation found between the data obtained in the game and the MDS-UPDRS scores. This robust correlation suggests that measurements obtained during game interaction accurately and reliably reflect the severity of rigidity.

Furthermore, PSD analysis played a crucial role in extracting and interpreting sensor data. Through PSD analysis, it was possible to identify distinct patterns in the signals from accelerometers and gyroscopes, allowing for a more accurate correlation with rigidity. This refined analytical approach was instrumental in ensuring the quality and reliability of the results obtained, providing valuable insights into the relationship between movement patterns and rigidity in PD patients.

# 6

# Final Considerations and Future Perspectives

This work represented a comprehensive investigation into the assessment of rigidity in patients with PD, employing an innovative approach integrating advanced sensor technologies and a SG called RehaBEElitation.

The literature review revealed a number of significant efforts aimed at developing innovative and high-impact solutions for the assessment of rigidity, a challenging symptom to analyze in PD. The complexity of rigidity, which can vary in intensity and manifestation over time, has motivated researchers and health professionals to seek more precise, objective and sensitive approaches to its assessment. Among the main strategies identified, the use of advanced sensor technologies stands out, such as accelerometers, gyroscopes and magnetometers, which enable a more detailed and real-time analysis of movement patterns and muscle rigidity. These technologies allow for a more objective and quantitative assessment of rigidity, providing more accurate and reliable data for monitoring disease progression and response to treatment.

Furthermore, the literature often raises questions about whether rigidity is dependent on the speed of movement (43). Understanding this relationship is crucial for a more complete and accurate assessment of rigidity in patients with PD. In this sense, an experimental protocol was first developed, where movements were performed actively and passively at slow and fast speeds.

The protocol proposed in Chapter 3 emphasized the importance of the sEMG in assessing rigidity, with a particular emphasis on rapid active movements. During this protocol, participants performed a series of active and passive movements at slow and fast speeds, with the aim of evaluating muscle rigidity in different conditions. The results highlighted that fast active movements were more effective in detecting rigidity compared to other types of movements. This suggests that speed of movement plays a crucial role in the manifestation and detection of muscle rigidity in patients with PD. The speed of movement can amplify signs of rigidity, making them more evident and measurable using techniques such as sEMG. The results obtained in Chapter 3 also highlighted the accelerometer and the gyroscope as relevant sensors for analyzing the rigidity.

In Chapter 5, the protocol was developed using the RehaBEElitation SG as a tool to assess rigidity. One of the main conclusions of this study is the feasibility and effectiveness of using inertial sensors, especially gyroscopes and accelerometers, in assessing rigidity in patients with PD. These sensors demonstrated a strong correlation with MDS-UPDRS scores, suggesting a significant association with the severity of motor symptoms. Furthermore, they were able to adequately differentiate between different patient groups ("off" and "h", "on" and "h", and "on" and "off"), indicating their sensitivity to capture variations in rigidity across different medication states.

A relevant aspect of this study is the comparison between different types of sensors and their ability to assess rigidity. Although sEMG sensors have traditionally been used to measure muscle activity, it was observed that they were not as effective as inertial sensors in assessing rigidity during the performance of the tasks proposed in the game. This suggests that inertial sensors may offer a more practical and accurate alternative for rigidity assessment, especially in environments where the use of sEMG may be impractical or inconvenient. In the context of controlled environments, such as the protocol carried out in Chapter 3, sEMG emerges as a viable and valuable tool for assessing rigidity. However, it is important to recognize that sEMG alone may not be sufficient to differentiate all aspects of rigidity, especially during prolonged periods of muscle activation. While sEMG is capable of detecting muscle activity, it may not fully capture the complexity and variability of rigidity, which can involve aspects such as range and speed of movement.

On the other hand, the great advantage of using only gyroscope and accelerometer sensors to assess rigidity is the practicality and possibility of miniaturization of the devices. With these sensors, it is feasible to develop smaller and lighter devices, which can be easily integrated into wearables or even gaming accessories, such as the RehaBEElitation itself. This allows rigidity measurements to be taken continuously and non-intrusively while the person engages in everyday or leisure activities such as gaming. Furthermore, this approach eliminates the need for bulky and expensive equipment, making it more accessible and convenient for use in different contexts, including clinical and home environments.

In this context, the integration of SG-based assessment methods such as RehaBEElitation represents an innovative and promising approach to rigidity assessment in a more naturalistic and valid environment. These games combine specific motor tasks with playful and interactive elements, providing a more engaging and motivating experience for patients, while allowing a dynamic and objective assessment of rigidity.

Overall, the findings highlight the importance of utilizing advanced sensor technologies for objective and accurate rigidity assessments in PD. The strong correlations between sensor data and clinical assessments emphasize the potential of these tools to improve monitoring and understanding of motor symptoms in individuals with PD. In this sense, there are several directions for future research and development that can further improve the robustness and applicability of these methods.

## 6.1 Future Perspectives

One of the future directions is the integration of multimodal data. To achieve a more comprehensive and robust assessment of rigidity, future research should focus on fusing data from different sensors, sEMG and IMU. Advanced data fusion techniques, including machine learning algorithms, could be employed to integrate these signals effectively and extract meaningful insights.

Furthermore, conducting longitudinal studies to monitor rigidity in PD patients over prolonged periods is important. This would help understand the progression of the disease and the long-term effects of treatments on rigidity. Continuous monitoring, using wearable devices equipped with inertial sensors, can provide valuable data on how rigidity varies with daily activities and over time, offering deeper insight into the dynamics of the condition.

Improving the user experience of the RehaBEElitation SG can also contribute to greater patient engagement and adherence. Incorporating elements such as adaptive difficulty levels, real-time feedback, and personalized goals can make the game more motivating and enjoyable for patients. This, in turn, can lead to more consistent use and higher quality of the data collected.

Furthermore, the methodologies developed in this work could be adapted and applied to other neurological conditions where rigidity and motor symptoms are prevalent. Extending research to conditions such as multiple sclerosis, cerebral palsy, or stroke could help develop comprehensive tools to assess and manage motor impairments in a broader patient population.

In conclusion, although this thesis marks a significant advance in the assessment of rigidity in PD, it also opens up several possibilities for future research and development. By following these directions, we can strive to create more accurate, reliable, and user-friendly tools for monitoring and managing rigidity, ultimately improving the quality of life for people with PD.

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# Glossary

**e.g.**

an abbreviation of the latin expression *exempli gratia*, meaning "for example"..

**i.e.**

it means *id est*, which is the latin expression for "this is"..

**UFU**

Federal University of Uberlandia.

**UL**

University of Lorraine.

A

# Appendix 1 - RehaBEElitation data availability

## A.1 RehaBEElitation Serious Game:

The following data can be accessed:

1. Source Code

- CARDOSO MENDES, Luanne; ALVES MARQUES, Isabela; ABREU ROSA DE SÁ, Angela; RAMOS ROSA, Rodrigo; MARQUES ALVES, Camille; RODRIGUES LIMA, Kennedy; AFONSO LAMOUNIER JÚNIOR, Edgard; LÁZARO MARTINS NAVES, Eduardo; FRAGA VIEIRA, Marcus; MONTEIRO DE OLIVEIRA, Fábio Henrique; PINO, Pierre; BOURHIS, Guy; ALVES PEREIRA, Adriano; TOBIAS MACHADO, Carlos; MORÈRE, Yann; OLIVEIRA ANDRADE, Adriano de. **RehaBEElitation - Source code**. Zenodo, 2022. DOI: 10.5281/ZENODO.6985977

2. Setup

- CARDOSO MENDES, Luanne; ALVES MARQUES, Isabela; ABREU ROSA DE SÁ, Angela; RAMOS ROSA, Rodrigo; MARQUES ALVES, Camille; RODRIGUES LIMA, Kennedy; AFONSO LAMOUNIER JÚNIOR, Edgard; LÁZARO MARTINS NAVES, Eduardo; FRAGA VIEIRA, Marcus; MONTEIRO DE OLIVEIRA, Fábio Henrique; PINO, Pierre; BOURHIS, Guy; ALVES PEREIRA, Adriano; TOBIAS MACHADO, Carlos; MORÈRE, Yann; OLIVEIRA ANDRADE, Adriano de. **RehaBEElitation serious game**. Zenodo, 2022. DOI: 10.5281/ZENODO.6988572