Biomechanical analysis of an upper limb rehabilitation process using optoelectronic cameras in patients with Parkinson's disease

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Abstract

Parkinson's disease (PD) is the second most common neurodegenerative disease in North America and Europe. PD is a degenerative disease that affects these systems: central, peripheral, and enteric nervous, and has a significant impact on society, families and the quality of life of the patients. Patients with PD have a variety of motor symptoms such as resting tremors, rigidity, akinesia or bradykinesia and postural instability. Therefore, patients with PD need to have a rehabilitation program to preserve current function, improve range of motion (RoM), posture, strength and endurance, prevent disabling complications, and family training. This work presents a biomechanical assessment of 12 patients with PD evaluated with the Hoehn and Yahr scale before and after rehabilitation therapy for two months with robotic therapy (Armeo®Spring exoskeleton). Patients performed three tests (Maximum Forward Reach, Apley Scratching and Box and Block) where maximum angles, range of motion, angular velocities, and execution times were measured. Nexus software (Oxford Metrics, Oxford, UK) was used to track the trial data, and Polygon software (Oxford Metrics, Oxford, UK) provided the kinematic outcomes of each user. Also, game scores are calculated with the Armeo therapy report because it performs a quantitative analysis regarding the patient's score in performing the therapeutic games. A Wilcoxon test ($p = 0.05$) was performed to compare the variables before and after the therapy for the more and less affected upper limbs. Also, averages and standard deviations of game scores are calculated to compare the more and less affected upper limbs before and after rehabilitation therapy. Significant differences were found in the shoulder, elbow and wrist joints. The increase found was 15.89% for adduction-abduction of the shoulder, 6.8% for flexion-extension of the elbow, and 26.82% for flexion-extension of the wrist joint in the more affected upper limb before and after rehabilitation therapy in the maximum forward reach test.

Regarding the minor affected upper limb, the increase found was 9.57% for flexion-extension of the shoulder. On the other hand, in the Apley Scratching Test, the increase found was 12.65% for flexion-extension of the elbow joint in the more affected upper limb before and after rehabilitation therapy. Concerning the less affected upper limb, the increase found was 14.79% for flexion-extension of the elbow joint. Finally, concerning the Box and Block Test, the increase found was 9.13% for the flexion-extension of the elbow joint in the more affected upper limb before and after rehabilitation therapy. In the less affected upper limb, the increase found was 17.13% for the flexion-extension of the elbow joint. In conclusion, the Armeo therapy has been shown to improve motor skills reacquisition in upper limbs through the performance of high intensity, high dose, and is repeatable, reliable and flexible.

Keywords: Parkinson's Disease, Kinematics, Biomechanics, Motion capture system, Upper limb, Robotic rehabilitation, Maximum forward Reach, Apley Scratching, Box and Block.

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Chapter 1

Introduction

This chapter describes the problem concerning the lack of rehabilitation studies with the Armeo Spring ® exoskeleton, as there are few articles objectively measuring the effect of this therapy on patients with Parkinson's disease (PD). This introduction describes PD, the motor consequences in the upper limb, conventional rehabilitation, and robotics. The general and specific objectives of this study, the contributions, and the organization of the document are also presented.

1.1 Motivation

PD is a degenerative disease that affects the central, peripheral and enteric nervous systems of the human being [1], and it has a significant impact on society, individuals and families [2]. PD is the second most common neurodegenerative disease in North America and Europe [2] and affects 2-3% of the population over 65 years of age [3]. Patients with PD have disorders in the organization and control of movement [4]. The deficits are in the initiation and speed of movement during simple movements [4]. These problems increase when complex sequential and bimanual upper limb movements have to be performed [4], [5]. Handwriting is a complex motor skill that requires a sequence of upper limb movements. Patients with PD have micrographia, i.e. they fail to maintain the stroke size of the characters as the writing progresses [4], [6].

Patients with PD have a variety of motor symptoms caused by the relentless and progressive loss of neurons in the brain stem and cerebral cortex [2]. The most common motor symptoms are rest, rigidity, bradykinesia and postural instability. Other motor symptoms are flexed posture and motor blocks [7]. Rehabilitation is a set of technologies and is a person-centred process [8]. The rehabilitation program's goals are to preserve present function, improve the range of motion (RoM), posture, strength, and endurance, prevent disabling complications, family training, and maintain the patient's independence as long as possible [9]. Conventional rehabilitation aims to increase functional capacity and decrease secondary complications through movement [10]. Conventional rehabilitation positively impacts endurance, balance, and global motor function in patients with PD [10]. On the other hand, the non-conventional rehabilitation interventions in PD patients found in the literature are motor imagery (MI), action observation therapy (AOT), virtual reality, exergaming, and robot-assisted training [11]. Upper limb robotic rehabilitation is innovative because it is based on an interaction between the patient and a robotic device, and provides high intensity, high dose, and is repeatable, reliable, and flexible [12]. Armeo Spring ® (Hocoma AG, Switzerland) is an arm rehabilitation exoskeleton with the advantage that it has self-initiated movement. Thus, by providing weight-bearing support for the arm, the exoskeleton allows patients to utilize any remaining motor function [13].

The study of upper extremity motion analysis with 3D kinematic analysis can be an important tool for clinical decision making [14]. 3D kinematic analysis has several difficulties: (1) Upper extremities do not only perform a single relevant functional activity; (2) Functional activities of the upper extremity vary too much in the general population; (3) Upper extremities, especially the shoulder joint, have a wide RoM. Thus, these factors make the study of the upper extremities complex [14]. In the literature, few rehabilitation studies with the Armeo Spring® exoskeleton were found with an objective measure of the effect of this therapy. The results obtained in this study serve to understand which joint is most affected before rehabilitation therapy in patients with PD and evaluate the effectiveness of robotic rehabilitation therapy.

1.2 Project Objectives

1.2.1 General Objective

To perform a biomechanical analysis of an upper limb before and after of rehabilitation process with Armeo Spring ® Exoskeleton in patients with PD using a motion capture system.

1.2.2 Specific Objectives

1. To extract clinical parameters of interest such as maximum angles, angular velocities, execution times and joint range of motion from motion capture data.
2. To compare the results obtained in kinematics with the literature on upper limb rehabilitation in PD.
3. To evaluate the efficacy of robotic rehabilitation therapy in a group of patients with PD by performing a statistical analysis.
4. To understand which joint and degree of freedom are most affected in patients with PD.

1.3 Contributions

The contributions obtained with the development of the work are: A group of 12 volunteer Parkinson's patients, each with informed consent and supervised by professionals; Occupational therapist with official training in the Armeo device; a Professional with expertise in Vicon and Polygon software who guided me through the trials process; Professionals in biomedical engineering who guided me through the process of kinematic and statistical analysis; and Professionals in biomedical engineering who helps to write preparation of the original draft. Also, an article published as first author, entitled 'Biomechanical Assessment of Post-Stroke Patients' Upper Limb before and after Rehabilitation Therapy Based on FES and VR' [15]

1.4 Document Organization

In this section, it is described how the document organization is distributed.

- Chapter 2: This chapter describes the state of the art of Parkinson's disease, diagnosis, treatment, motor and non-motor symptoms, conventional and non-conventional rehabilitation, and rehabilitation with robotics. Also, this chapter describes the motion capture system that is fundamental for the biomechanical and kinematic analysis study. Finally, this chapter describes work related to the biomechanical analysis of the upper limb in patients undergoing robotic rehabilitation therapy.
- Chapter 3: This chapter describes the methodology of this study. First, the population is described (i.e., number of persons, anthropometric characteristics, inclusion and exclusion criteria). Then, the equipment is described and the experimental procedure with a description about therapeutic games. After, described the movement analysis assessment with a description of each test: Maximum Forward Reach, Apley Scratching and Box and Block Test. After that, the definition of variables is presented: maximum angles, range of motion, execution time, and angular velocity. Finally, the data analysis with a description of the statistical tests to be used in the results of this study is shown.
- Chapter 4: This chapter describes the three Test results: Maximum forward reach Test, Apley Scratching Test, and Box and Block Test. First, the Wilcoxon test compares the least affected limb before and after rehabilitation therapy and the most affected limb before and after rehabilitation therapy. Also, a similarity test is performed to compare the least and most affected limbs before and after treatment. This statistical analysis is performed for the four clinical variables: maximum angles, RoM, execution time, and angular velocity.
- Chapter 5: This chapter describes the discussion of the results of this study. Each table in Chapter 5 is discussed here and compared with the literature to determine if the results are consistent with other studies. Also, the limitations and importance of this kind of study are described.
- Chapter 6: This chapter describes the conclusion of this study. This chapter describes if the rehabilitation therapy was effective.
- Chapter 7: This chapter describes the recommendations and future work based on the results obtained and the project's planning.

Chapter 2

State-of-the-art

This chapter initially describes Parkinson's disease, its aetiology, epidemiology, symptoms, diagnosis, treatment and conventional and non-conventional rehabilitation. Also, emphasis is made on rehabilitation with robots because it is a complementary therapy that improves motor symptoms and provides motivation for the patient. Subsequently, the work related to the biomechanical analysis of the upper limb in patients with Parkinson's disease using a motion capture system is described.

2.1 Description of the Parkinson's disease

PD has initially described by James Parkinson in ”Essay on Paralysis Tremenstrans” of 1817, describing in detail the main motor signs of the disease, which are still considered the hallmarks of PD, namely bradykinesia, rigidity and tremor [16]. PD is a disorder of the neural cytoskeleton that affects movement and gait function in the early and middle stages of the disease and cognitive function in the later years of the disease [1], [2].

The characteristic features of Parkinson's disease are neuronal loss in specific areas of the substantia nigra and intracellular protein (alpha -synuclein) accumulation [3], [17], [18]. These two main neuropathologies are essential for diagnosis PD [3]. Neuronal degeneration occurs in certain types of neurons within particular brain regions. In the early stage of the disease, the loss of dopaminergic neurons is restricted to the ventrolateral substantia nigra with other midbrain neurons [3], [19]. When there is a drastic loss of these dopaminergic neurons, degeneration occurs before the onset of motor symptoms [3], [20].

Another neuropathology is the abnormal deposition of alpha-synuclein in the cytoplasm of some neurons in different brain regions [21]. Lewy bodies are composed of various aggregated alpha-synuclein, and their pathology occurs initially in cholinergic and monoaminergic neurons of the brainstem and neurons of the olfactory system. With the progression of PD, it is found in limbic and neocortical brain regions [3].

2.1.1 Epidemiology of Parkinson's disease

PD is the second most common neurodegenerative disease in North America and Europe [2]. PD affects 2-3% of the population over 65 years of age [3]. According to Minnesota (USA) population base, the incidence of PD was 21 cases per 100,000 people per year [3]. In the United Kingdom (UK), a 6% annual decrease in PD was reported between 1999 and 2009 due to better diagnosis of different parkinsonian syndromes [22], [23]. In general, in high-income countries, the incidence of PD is 14 cases per 100,000 persons in the total population and 160 cases per 100,000 persons aged 65 years and older [22], [24]. In 2010, approximately 1.1 million people in the USA had PD. By 2030, PD in the United States is expected to increase to 1.8 million and 2.5 million by 2050 [2].

The average age of diagnosis of PD is between 50 and 60 years, and the incidence increases with age, with less than 10% for people with PD before the age of 40 [2]. As for mortality, people with PD increase slightly unless complications such as dementia occur. Thus, most people who develop PD will die from causes other than PD [2]. PD is twice as typical in men as in women in most populations [3] because women have a protective effect from female sex hormones [3]. The frequency of developing PD is the lifetime risk, which was presented as 2% for men and 1.3% for women for people aged 40 years in the USA, taking into account competing risks (death from other causes such as cardiovascular disease or cancer) [22], [25]. Data on incidence by race or ethnicity are scarce and inconsistent [22].

In the literature, environmental and behavioural factors have been shown to affect the pathogenesis and progression of the disease [22]. 90% of PD cases are not genetically caused [22], [26]. Factors that have a higher risk for PD are consumption of dairy products, exposure to pesticides, history of melanoma, and traumatic brain injury. In contrast, factors with a lower risk of PD are smoking, caffeine consumption, higher serum uric acid concentrations, physical activity, ibuprofen and other common medications [22].

2.1.2 Diagnosis of Parkinson's disease

The diagnosis of PD is exclusively clinical and is made by post-mortem pathological analysis. The diagnosis must be accurate in order to provide prudent patient management. Early diagnosis is essential, but it is not always possible at the first clinical visit because patients may present with mild signs that may involve confounding factors [2]. Therefore, it is important to continually re-evaluate diagnoses and follow up on signs and symptoms [2].

The diagnostic criteria for PD require that the individual has bradykinesia with resting tremor, rigidity, or both. Also, individuals must meet at least two of the four criteria: (1) resting tremor, (2) dramatic enhancement of dopaminergic therapy, (3) presence of levodopa-induced dyskinesias, and (4) presence of olfactory loss or cardiac sympathetic denervation. Dyskinesia is an involuntary choreoathetotic movement that occurs with dopaminergic therapy [27].

2.1.3 Motor and non-motor symptoms in patients with Parkinson's disease

The symptoms of PD are mainly divided into the motor and non-motor symptoms. The motor symptoms are, in general: tremor, rigidity, akinesia and postural instability. On the other hand, the non-motor symptoms are, in general: neuropsychiatric, dysautonomia, sleep disorders, and sensory abnormalities.

2.1.3.1 Motor Symptoms

The main neuropathological feature of patients with PD is the relentless and progressive loss of neurons that starts in the brain stem towards the cerebral cortex [2]. This generates resting tremor, rigidity, akinesia or bradykinesia and postural instability that can be grouped under the acronym (TRAP) [7]. Other typical motor symptoms of PD are flexed posture and motor blocks. PD's secondary motor manifestations include akathisia, decreased arm swing during walking, freezing phenomenon, and ophthalmologic abnormalities [7].

The first presenting symptom when developing PD is tremor. It is reported that 69% of patients with PD have resting tremors at the onset of the disease and 75% during the condition [7]. Resting tremor may initially be stress-induced and affects the contralateral limbs over time, thus usually not to the same extent as in the original limb. Also, patients with PD may have a 'reemergent' tremor when they are asked to stretch their arms in a horizontal plane [7]. In the upper limb, tremor parkinsonism is a resting tremor that affects thumb flexion-extension against the index finger, wrist flexion-extension and forearm pronation-supination [9]. Jain et al. found that in PD, all movements are involved, including initiation, execution, and the ability to stop a movement once initiated [28]. Elbe et al. found that in many patients with PD, resting tremor persists during posture and movement [29]. The tremor frequency band due to PD ranges from 3-6 Hz [28]. Other studies claim that resting tremor ranges from 4-6 Hz [29].

Another common symptom is bradykinesia which is probably due to insufficient recruitment of muscle strength at the onset of movement. Bradykinesia was first described by James Parkinson and indicates a pathology of the basal ganglia that generate decreased arm swing and mask-like facial expressions. Secondary motor symptoms of bradykinesia are micrographia, gait disturbance and dysarthria. Therefore, it is considered the most disabling motor symptom affecting the development of activities of daily living (ADLs) [7].

Another common motor symptom is stiffness, a uniform and increased resistance in recruited agonist and antagonist muscles throughout the movement. When stiffness or muscle tone increases, it affects the trunk, neck, shoulder, hip, wrist, and ankle. Clinically, stiffness is confirmed by observing passive flexion-extension or rotation of the affected muscles. It is usually misdiagnosed as other forms of rheumatologic or skeletal injury [7].

Postural instability is another motor symptom that manifests in the later stages of PD by experiencing persistent instability when the patient is standing. This is detected by the 'Pull Test', which consists of pulling the shoulders backwards or forwards and observing the patient's response to the change in position. Body instability is the most common cause of falls and increases hip fractures. A study of 100 patients with PD was found in the literature stating that 38% of patients suffered falls, and 13% reported one fall per week [7].

2.1.3.2 Non-Motor Symptoms

Most patients with PD have non-motor symptoms that impact their quality of life [7]. Non-motor symptom recognition has improved in recent years, with studies focusing on the development and validation of non-motor symptoms (NMS) complex assessment tools, such as the Non-Motor Symptom Questionnaire (NMS Quest) and the Non-Motor Symptom Scale (NMS Scale) [30]. These non-motor symptoms are neuropsychiatric such as depression, anxiety, apathy, psychosis, impulsive behaviour, addiction and dementia; Dysautonomia such as orthostatic hypotension, sexual dysfunction, constipation, sialorrhea, dyshidrosis, urinary incontinence; Sleep disorders such as insomnia, excessive daytime sleepiness (EDS), sleep attacks, restless legs syndrome, REM sleep behaviour disorder (RBD); Sensory abnormalities such as olfactory loss, pain, dyspnea, fatigue [7].

The Neuropsychiatric symptoms are persistent in PD patients and have a high impact on quality of life [30]. Dysautonomia symptoms such as orthostatic hypotension affect 60% of patients with PD and are the best-known aspect of cardiovascular dysfunction [31]. Sleep disorders affect up to 90% of patients with PD [30], [32]. This disorder causes disability, reduced daytime functioning and poor quality of life. Finally, Sensory abnormalities such as hyposmia affect 90% of patients with PD [30].

2.1.3.3 Treatment of Parkinson's disease

Pharmacological treatments for PD are mainly based on dopamine. Initial therapies are levodopa preparations, dopamine agonists and monoamine oxidase B (MAO-B) inhibitors. In young patients with prominent tremors, anticholinergic agents (e.g., trihexyphenidyl) are used [27], [33]. Drugs to treat non-motor symptoms act through neurotransmitters other than dopamine. For dementia in PD patients, the International Parkinson and Movement Disorders Society designates rivastigmine as clinically helpful and its appropriate dose at 3-12 mg daily. To treat depression, the following are used serotonin reuptake inhibitors, selective serotonin-norepinephrine reuptake inhibitors, and tricyclic antidepressants. There is no adequate pharmacological treatment for the symptom of apathy in PD. For the symptom of psychosis, MAO- B inhibitors and sometimes levodopa are used. When psychosis is persistent, pimavanserin, clozapine and quetiapine are used. Finally, insomnia, fatigue, and daytime sleepiness are common in Parkinson's disease, but no pharmacological treatments for these symptoms have established efficacy [27], [34], [35].

2.1.4 General description of the rehabilitation

Rehabilitation is a goal-directed process that aims to reduce the impact of the disease for the most part [8]. A crucial point of rehabilitation is that it has a specific goal and a care package is designed to meet the need for ongoing care or support [8]. Rehabilitation is a set of technologies similar to pharmacological treatment and is a person-centred process [8]. Rehabilitation processes must be based on an understanding of the impairments, which can be described from a biomechanical, neurophysiological, cognitive, and behavioural point of view [8]. The goals of the rehabilitation program include preservation of present function, improving range of motion (RoM), posture, strength, and endurance; prevention of disabling complications; family training; and maintenance of the patient's independence as long as possible [9].

2.1.4.1 Conventional Rehabilitation in patients with Parkinson's disease

Conventional rehabilitation aims to increase functional capacity and decrease secondary complications through movement [10]. Conventional rehabilitation has been shown to impact endurance, balance positively, and global motor function in patients with PD [10], [36]. But, the effects of exercise diminish after follow-up periods without training [37]. Therefore, sustained effort and engaging patients in long-term exercise programs are essential but challenging [10]. So, having exercise technology interventions can improve adherence by encouraging patients to exercise in a motivating, fun and engaging way [10].

Crizzle and Newhouse [38] reviewed the literature and concluded that, through exercise, patients with PD improve their physical performance and the execution of activities of daily living. Conventional rehabilitation programs for PD patients focus on improving functional ability and mobility, depending on the type of activity proposed, duration of the program, length and frequency of weekly sessions, and type of evaluation [38]. Conventional rehabilitation programs include aerobic, stretching, and resistance exercise [39].

Aerobic exercise improves physical fitness, executive functions, fatigue, depression and quality of life in PD patients [40]. Also, aerobic exercise promotes brain health by reducing inflammation, suppressing oxidative stress and stabilizing calcium homeostasis [41], [42]. Some studies have shown that aerobic exercise may be beneficial in improving balance, gait, physical function, and quality of life in patients with PD [41]–[43]. Other studies have shown that aerobic exercise can improve memory and executive dysfunction and reduce the severity of depression. Exercise-induced changes help increase white and grey matter volume, increase hippocampal volume, and improve connectivity [44]. Ergun et al. demonstrated significant improvements in 43 patients with PD who performed aerobic exercise for six months. Improvements were seen in speed, depression and a measure of executive function [40].

2.1.4.2 Non-Conventional Rehabilitation in patients with Parkinson's disease

Some rehabilitation innovations in PD patients found in the literature are motor imagery (MI) and action observation therapy (AOT), virtual reality (VR) and exergaming, and robot-assisted training [11].

Recently, MI has been a promising additional rehabilitation method for patients with neurological disorders. Most evidence is in post-stroke patients that MI rehabilitation improved upper limb function and ADLs [45]. MI is the mental representation of actions in the absence of overt movements. MI aims to improve motor skills as it enhances the one signals that are usually generated during movement [46]. Other studies, such as Samuel et al. [46], asked patients to imagine movements while recording brain activity. Still, it remains unclear to what extent the inability of PD patients to solve the task is reflected. To reliably attribute brain activity patterns to compensatory mechanisms, one needs to use tasks that the patient can perform to objectively measure the patient's performance and strategies [47].

On the other hand, AOT is a technique based on the activation of the mirror neuron system that consists of observing different actions combined with the repetition of the observed actions [11]. MI and AOT should be considered promising approaches for rehabilitation patients with PD. These two techniques facilitate movement execution by matching the imagined or observed action with the internal representation. Thus, it enhances the learning of new tasks and improves motor performance [11], [48].

VR is the interaction of the person with a virtual environment to improve motor learning by employing perceptions such as visual, auditory and haptic inputs [11]. VR can be incorporated into gaming consoles and benefits in that it is low cost, user friendly and can be used in the home to promote physical activity. Exergaming is an exercise-based computer game and is a rehabilitation tool for patients with PD [11]. VR is a rehabilitation tool that engages patients in long-term exercise as it provides training in a challenging and motivating environment [10]. The literature found that a sense of control, challenge, and success are critical components of patient enjoyment of VR rehabilitation [10], [49]. Also, it not only provides real-life scenarios but offers more significant potential in ADLs [10].

2.1.5 Robotic rehabilitation for Parkinson's disease

Rehabilitation robotics is the combination of industrial robotics and medical rehabilitation and encompasses the fields of mechanical and electrical engineering, biomedical engineering, artificial intelligence and sensor and actuator technology. The overall goal of rehabilitation robotics is to help the patient function with maximum autonomy. As other objectives are that the patient is autonomous in executing an assigned task, the patient can perform ADLs with less human assistance, and the patient recovers their physical or cognitive functions [9].

Upper limb robotic rehabilitation is innovative because it is based on an interaction between the patient and a robotic device. Robotic rehabilitation provides high intensity, high dose, and is repeatable, reliable and flexible [12]. Robotic rehabilitation improves motor control, reduces motor deficits, and increases the ability to perform ADLs [50]–[52]. Robotic devices can be classified as end-effectors or exoskeletons. These interfaces only align with the distal joint or with the proximal and distal joints [50], [53]. Generally, robotic devices assist in completing a desired movement or resistance to dampen or prevent unwanted movements [50].

End-effector robots grasp the patient's hand or forearm at one point and generate forces at the interface [54]. But, the joints of this type of robot co-match those of the human limb. Although this type of robot is easier to fabricate, determining the posture of the upper extremity can be complicated with a single interface, especially if the interface is on the patient's hand [54]. Also, it is not possible to control torque at specific upper limb joints, so uncontrolled load transfer between upper limb joints is generated. In conclusion, generating an isolated motion at a single upper limb joint is complex because the final effect motion may cause a combination of wrist, elbow and shoulder joint motions. The range of motion in end-effector robots is limited because end-effector robots can only produce a limited set of rehabilitation therapy exercises [54]. Shing et al. gave examples of rehabilitation robots with end-effectors: MIT-MANUS, the MIME and the GENTLE/s. Many clinical trials have been performed to evaluate their efficacy, which resulted in a decrease in upper limb motor impairment in patients who received the robotic therapy. So, these results justify those exoskeleton robots are more sophisticated as rehabilitation devices [54]–[56].

The exoskeleton is a wearable robot, and the kinematic chain conforms to the anatomy of the human limb [9]. This kinematic conformity is essential to achieving ergonomic human-robot interfaces [9]. The exoskeleton can be used as an input device, i.e. a posture correspondence is established between the human and slave manipulator. It can also be used as a feedback device, i.e. a haptic interaction is provided between the slave robot and its environment [9]. The advantage of exoskeleton robots for rehabilitation is that it is possible to target specific muscles for training by generating a calculated combination of torques at specific joints [54]. Also, you have a larger RoM that allows a greater variety of movements for rehabilitation exercises [54]. There are several commercially available rehabilitation devices on the market: among the most sophisticated available are the Armeo products (Hocoma AG, Switzerland); mPower arm brace (Myomo Inc., Cambridge, MA), Hand Mentor (Kinetic Muscles Inc., Tempe, AZ), Suit HAL-5 (CYBERDYNE Inc., Japan), among others [54].

The choice between effector and exoskeleton is vital in rehabilitation design since effectors are closely interacting with the patient [9]. In comparison, exoskeletons present a continuous, multipoint physical interaction mediated by the patient's soft tissues and are usually dizzying at several anatomic joints [9]. Another difference is that effectors are used for limb segment movements that require less than 45 degrees. The exoskeleton is more appropriate for more extensive joint excursions [9].

2.2 Upper limb description

An upper extremity is a functional unit of the upper part of the human body. It has three sections: arm, forearm and hand [57]. [56]. It extends from the shoulder joint to the fingers, with 30 bones. In addition, it consists of many nerves, blood vessels and muscles [57].

Neurodegenerative diseases such as multiple sclerosis, Alzheimer's, and Parkinson's, among others, result in upper extremity motor disabilities that drastically affect ADLs. ADLs refer to the daily self-care activities [58], such as eating, drinking or bathing, and instrumental tasks [58]. To evaluate the ability to do ADLs, the execution of the tests is observed, and the patient reports some questionnaires to understand the daily difficulties [59].

2.2.1 Degrees of freedom (DoF) of upper limb

The upper limb has 9 degrees of freedom (DoF), excluding the finger joints [60]. First, the glenohumeral joint of the shoulder complex allows the humerus to rotate about the glenohumeral head with 3 DOF: flexion-extension, abduction-adduction, medial-lateral rotation [54]. In addition, the sternoclavicular joint has 2 DoF: elevation-depression and retraction-protraction. Thus, the shoulder joint has a total of 5 DOF. The elbow complex has 2 DoF; flexion-extension of the elbow and pronation-supination of the forearm [54], [61]. Finally, the wrist joint has 2 DoF: flexion-extension and radial-ulnar deviation (see Table 2.1) [54].

Table 2.1: DoF of Upper Limb.

Joint	DoF	Movement
Shoulder(Glenohumeral)	3	Flex-Ext, Abd-Add, Medial-Lateral Rot.
Shoulder(sternoclavicular)	2	Elevation-Depression and Retraction-Protraction
Elbow	1	Flex-Ext
Wrist	2	Flex-Ext, Radial-Ulnar Deviation
Forearm	1	Prono-Supination

2.2.2 Upper Limb Kinematic Measurement

Upper limb motion can be rapid and complex, especially in the shoulder joint. Therefore, markers attached to rods are subject to inaccuracies due to soft tissue oscillations and inertial effects (see Table 2.2 and Fig. 2.1) [62]. The wrist and elbow joints have relatively simple motion modelling because both joints can be represented as two-degree-of-freedom joints [62], [63]. But, the shoulder joint consists of separate joints, thus defying simple kinematic description [62], [63].

The study of upper extremity motion analysis with 3D kinematic analysis can be an important tool for clinical decision making [14]. 3D kinematic analysis has several difficulties: Upper extremities do not only perform a single relevant functional activity; Functional activities of the upper extremity vary too much in the general population; Upper extremities, especially the shoulder joint, have a wide RoM [14]. Thus, these factors make the study of the upper extremities complex. Kinematic measures effectively capture the minor changes in movement performance and quality [64]. This can be ignored by traditional clinical scales [65]. Thus, it is suggested that kinematics should be implemented to distinguish between true recovery and the use of compensatory movement patterns during task performance [14].

Table 2.2: The anatomical position of the markers in upper Limb, following the Plug-in gait marker model [66].

Marker	Position
C7	7th Cervical Vertebra
T10	10th Thoracic Vertebra
CLAV	Clavicle
STRN	Sternum (Xiphoid Process)
RBACK	Right Back (Scapula)
RSHO/LSHO	Right/Left Shoulder
RUPA/LUPA	Right/Left Upper arm
RELB/LELB	Right/Left Elbow
RFRM/LFRM	Right/Left Forearm
RWRA/LWRA	Right/Left Wrist A
RWRB/LWRB	Right/Left Wrist B
RFIN/LFIN	Right/Left Finger (Middle Knuckle)

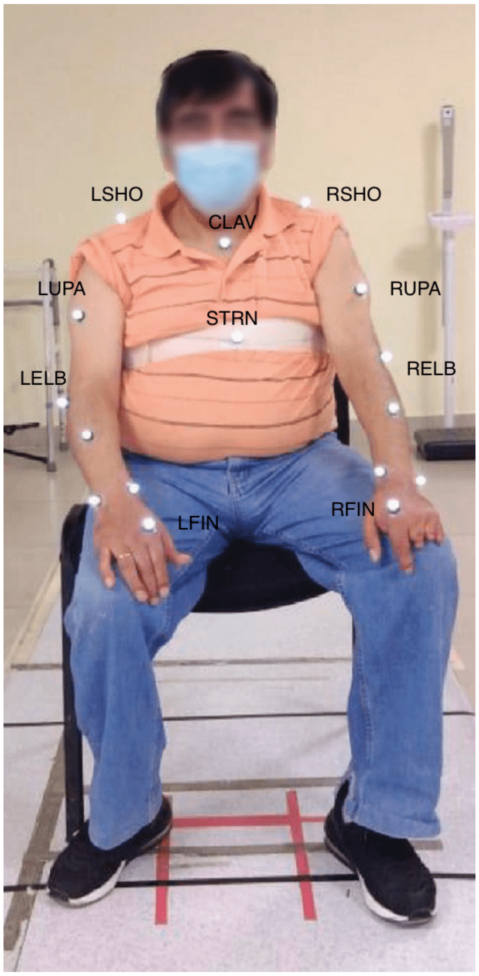


Figure 2.1: Anatomical position of the markers in upper Limb.

2.2.3 Motion Capture System for kinematic motion analysis

A motion capture system with an optoelectronic camera system is a gold standard for kinematic motion analysis. It is increasingly implemented as an outcome measure to assess performance and quality of movement after injury or disease involving upper extremity movements [14]. Optoelectronic motion capture systems use multiple high-speed cameras that send infrared light signals to capture reflections from passive markers placed on the body. These capture systems have high accuracy and flexibility in measuring various tasks [67]. VICON (Oxford Metrics, Oxford, UK) is a world leader in motion capture cameras, software and motion capture systems [68] and is implemented in the development of this study.

2.3 Robotic Devices for Rehabilitation of upper limb

2.3.1 Commercial exoskeletons for upper limb rehabilitation

In commerce, several researchers have developed exoskeletons that include the movements of the shoulder complex of the sternoclavicular joint: shoulder elevation depression. The exoskeletons are the Maryland-Georgetown-Army (MGA), the ARMin III and the IntelliArm [54].

The MGA Exoskeleton is a six-degree-of-freedom (DOF) device [54] used for assessing arm strength, speed, and ROM with onboard sensors. It can function as a resistance trainer and VR tool for rehabilitation [69], [70]. Carignan et al [69]. performed a game therapy with a virtual environment that consisted of dropping the ball, and the subject had to catch it. As a result, motor functions improved, upper extremity range of motion increased, and motor coordination increased.

ARmin III proposes a new ergonomic principle for the shoulder joint and provides movement of the humeral head [71]. Armin III has three DoF (2 DoF for the shoulder and one DoF for the elbow joint). In addition, it has an additional module that provides pronation-supination of the arm and phanto-extension of the wrist [71].

IntelliArm is a novel upper limb rehabilitation robot with an exoskeleton and handgrip training function. It is capable of shoulder, elbow, wrist and finger control. IntelliArm has 8+2 DoF, controls joints individually/simultaneously, and helps achieve effective rehabilitation in post-stroke patients or other neurological impairments [54], [72]. The IntelliArm has four active DoFs and two passive DoFs in the shoulder joint, two DoFs in the elbow joint, and one in the wrist joint. The four active DoFs of the shoulder are horizontal abduction/adduction, flexion/extension, internal/external rotation and vertical displacement of the glenohumeral joint. The two passive DoF of the shoulder are: anterior/posterior and medial/lateral [72].

The MAHI Exo-II upper extremity exoskeleton was first introduced in 2004 [73]. It has four active DoF: elbow and wrist flexion-extension, forearm pronation-supination, and radial-ulnar deviation. It has a passive DoF for shoulder abduction and adduction for user comfort [74]. French et al. [74] evaluated the performance of the MAHI Exo-II exoskeleton and concluded that it meets the requirements of high-performance rehabilitation exoskeletons. The characteristics are: it has working space, torque outputs and bandwidth that matches human capabilities, low inertia, static friction, viscous damping, low inertia, high friction, and viscous damping and the hardware capabilities to complement the implementation.

MyoPro (Myomo Inc., Cambridge, MA) is a motorized arm and hand orthosis designed to help restore function to the user's paralyzed or weakened upper extremity. This orthosis allows the person to perform ADLs that might otherwise be impossible. Also, MyoPro facilitates rehabilitation, muscle re-education and RoM [75]. The most common medical conditions are: Stroke, Arm Paralysis, Brachial Plexus Injury (BPI), Cerebral Palsy, and Multiple Sclerosis [75]. MyoPro works by reading myoelectric signals from the skin's surface and then activating small motors to move the limb as the user intends. The user then fully controls their hand, wrist, elbow and arm [75]. Then, the robotic arm support amplifies the myoelectric signals to help move the upper extremity [75]. MyoPro is the only portable robotic device on the market to help restore function for those who still have their arms and hands but are affected by motor symptoms [75]. Pundik et al. [76] investigated a case of a 42-year-old woman with traumatic brain injury and decreased motor control/coordination in the right extremity. She underwent motor learning-based therapy with the Myo orthosis. The patient improved their active range of motion and reduced tone. Also, significant improvements in motor function were observed, resulting from the high repetition of functional movement practice administered over a long duration.

The Hand Mentor (Kinetic Muscles Inc., Tempe, AZ) is a device that has a DoF that provides a controlled resistive force to the hand and wrist joints [77]. The force can oppose flexion or assist the extension of the hand [77]. In addition, the device incorporates sensors that monitor the position of the wrist and fingers in flexion-extension movements to measure the force applied to the hand by the system's actuator [77].

The Suit HAL-5 (CYBERDYNE Inc., Japan) is a wearable exoskeleton that uses sensors attached to the skin's surface that detects bioelectrical signals to perform desired movements with the user's voluntary commands [78]. HAL-5 is only available in Japan under a rental contract. The exoskeleton has several applications: improving physical function in the wellness and medical fields, supporting heavy work in other workplaces and supporting recovery activities at disaster sites [78].

The Armeo Power ® (Hocoma AG, Switzerland) is designed for arm and hand therapy at an early rehabilitation stage and therapy at an early stage of rehabilitation [79]. This exoskeleton has sensors and intelligent algorithms to detect when the patient cannot perform a movement to assist the patient's arm as much as necessary to reach the exercise goal successfully [71]. Armeo Power ® has six degrees of freedom that allow training in an extensive 3D workspace. In addition, it has an extensive library of game-like augmented feedback exercises that aim to train core movement patterns used in ADLs [79]. Staubli et al. [80], state that the Armeo Power ® allows even patients with severe movement impairments to perform high-intensity exercise. Klamroth-Marganska et al. [81] conducted a large controlled trial in stroke patients and found that the most severely affected patients benefited the most from robotic arm training.

Armeo Spring ® (Hocoma AG, Switzerland) is a widely used arm rehabilitation exoskeleton, with approximately 800 units for adults and children worldwide. Armeo®Spring is a spring-based weight compensating exoskeleton that allows virtual play in a three-dimensional workspace [13]. Armeo Spring ® has an upper arm module, a lower forearm module and a pressure-sensitive grip [13]. These models are adjustable in length to align the exoskeleton with the arm joints. Also, the exoskeleton is equipped with a spring to provide flexible weight compensation across nine configurations (A-I) [50].

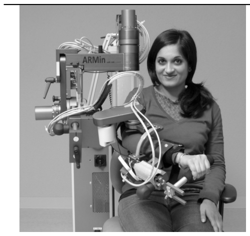
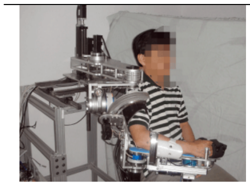
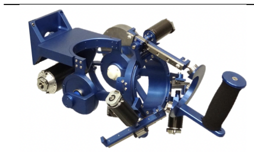
The advantages of ArmeoSpring therapy are that it has self-initiated movement. Thus, by providing weight-bearing support for the arm, the exoskeleton allows patients to utilize any remaining motor function. Also, it is motivating as patients are encouraged to achieve a more significant number of reaching and grasping movements based on specific therapy goals. Additionally, the ArmeoSpring exoskeleton focuses on the patient's movements and has repetitive movements that allow for better long-term results [13].

Rehabilitation of the arm and hand with ArmeoSpring is the preferred therapeutic option for the broadest range of patients. There are more than 130 studies on the Armeo Spring

®: Bartolo et al. [82], state that supplementing upper extremity therapy with ArmeoSpring therapy improves motor function; Sanchez et al. [83], state that ArmeoSpring creates a permissive environment to allow individuals to practice reaching and drawing movements; Rudhe et al. [84], state that the ArmeoSpring is designed as an ergonomic exoskeleton with integrated springs; Zimmerli et al. [85], state that with the ArmeoSpring the level of difficulty can be adapted to the patient's abilities. This allows the patient to be never frustrated or bored but constantly motivated; Zariffa et al. [86], state that in therapy with the ArmeoSpring, therapist involvement is reduced to one-quarter of the total session time.

Table 2.3 represents a summary of the names of the exoskeletons, the degrees of freedom and the objectives of each.

Table 2.3: Summary of commercial upper limb exoskeletons used for robotic rehabilitation.

Image	Name	DoF	Objectives
	MGA	6	Is used for assessing arm strength, speed, and ROM [69], [70].
	Armin III [71]	3	A new ergonomic principle of the shoulder joint provides movement of the humeral head [71].
	IntelliArm [72]	8+2	It is capable of shoulder, elbow, wrist and finger control [72].
	MAHI Exo-II [74]	4+1	Is a high-performance rehabilitation exoskeleton [74].

	MyoPro [75]		It is designed to help restore function to the user' paralyzed or weakened upper extremity [75].
	Hand Mentor [77]	1	Provides a controlled resistive force to the hand and wrist joints [77].
	Suit HAL-5 [78]	1	Detect bioelectrical signals to perform desired movements with the user's voluntary commands [78].
	Armeo Power ® [79]	6	Is designed for arm and hand therapy at an early stage of rehabilitation [79].
	Armeo Spring ®	5	Focuses on the patient's movements and also has repetitive movements that allow for better long-term results [13].

2.3.2 Commercial End-Effectors

The commercial End-Effectors are InMotion robots (Interactive Motion Technologies Inc., Boston, MA), Biodex System 4 dynamometer (Biodex Medical Systems Inc., New York), HUMAN NORM (SCMi, Stoughton, MA), and CON-TRES MJ (CMV AG, Switzerland) [54].

The InMotion monitors patients' movements during therapy while assisting you when the patient needs it to complete various motor therapy activities [87]. Therapy with this End-effector allows professionals to provide intensive motor therapy to help patients regain motor function [87]. InMotion® robots are used in more than 20 countries and are effective for motor impairments: Stroke, Cerebral Palsy, Spinal Cord Injury, Multiple Sclerosis, Parkinson's Disease, hemiplegic shoulder pain and muscle spasticity [87]. S. Levy-Tzedek et al. [88] studied the effects of motor performance stimulation and learning on the InMotion robot in five patients with PD. The authors concluded that InMotion provides a novel platform for studying the effects of neurological diseases and their treatments on motor performance and learning.

Biodex System 4 dynamometer is an End- Effector that delivers performance, accuracy, and safety [89]. They have a high correlation coefficient in reliability, accuracy, validity, and respectability [89]. Biodex System 4 has multiple applications, including neurorehabilitation. The system helps patients develop strength, endurance, and coordination [89]. Drouin et al. [90] quantitatively assessed the mechanical reliability and validity of the position, torque and velocity measurements of the Biodex system. The authors concluded that the results could only generalize the mechanical measurement capabilities of the dynamometer. Future studies should incorporate human participants to determine reliability and validity.

Humac Norm is the first choice of physical therapists, athletic trainers, orthopaedic surgeons and exercise scientists who demand the best results for their patients and their research [91]. HUMAC NORM aims to help take the guesswork out of documenting the need for treatment, patient progression and return to work/sports decisions [91]. Habets et al. [92] investigated the reliability of Humac NORM for concentric and eccentric strength tests of knee and shoulder muscles. This study was of clinical relevance as it shows excellent reliability values for concentric and eccentric strength of the knee extensors and flexors of the shoulder.

CON-TREX MJ is a versatile rotational testing, training and therapy system for testing and training all major joints of the upper and lower extremities in the open kinetic chain [93]. It allows analysis of static and dynamic strength of a joint and the resulting targeted functional muscle strength training and improves coordination skills with possible monitoring and correction during therapy [93].

Table 2.4 represents a summary of the names of the End-Effectors and the objectives of each.

Table 2.4: Summary of commercial upper limb End-Effectors used for robotic rehabilitation

Image	Name	Objectives
	InMotion® [87]	Helps patients regain motor function [87].
	Biodex System 4 dynamometer [89]	Helps patients develop strength, endurance, and coordination [89].
	Humac Norm [91]	Help take the guesswork out of documenting the need for treatment, patient progression and return to work/sport decisions [91].
	CON-TREX MJ [93]	Improves coordination skills with possible monitoring and correction during therapy [93].

2.3.3 Related Work

The search methodology employed databases: Pubmed, Google academic, Crai, Elsevier. Here we used keywords by boolean functions such as an upper limb, motion analysis, rehabilitation, Parkinson, kinematics, and robots. Also, Articles in Spanish, articles published before 2000, articles that did not evaluate any kinematic parameter, and articles that did not perform rehabilitation therapy with robots were excluded.

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Table 2.5: Related works to kinematic analysis with rehabilitation therapy with robotic devices in upper limb.

Authors	Objective	Methodology	Results
Brihmat et al. [94].	To evaluate the learning effect and reliability of selected parameters obtained with Armeo Spring ® in post-stroke patients during their routine clinical care.	Thirty post-stroke patients who participated in 3 evaluation sessions, each consisting of 10 repetitions of the "horizontal catch" exercise. Five kinematic parameters were calculated (task and movement time, hand trajectory ratio, maximum velocity, number of maximum velocities).	Significant inter- and intrasession learning effects were observed for most parameters, except for maximum speed.
Fundarò et al. [95].	To investigate changes in upper extremity motor performance in a patient with PD after non-weight-bearing training with a passive exoskeleton.	20 patients with Parkinson's disease who performed sessions five days/week for four weeks, 30 min for each arm; training was conducted with 12 exercises (monoarticular and multiarticular, horizontal and vertical movements). The percentage of target achieved, movement execution time and accuracy were analyzed.	The authors found a significant improvement of accuracy and speed for the simple movement in the dominant arm, of the achieved targets and speed for the complex movement on both sides.
Adans-Dester et al. [96].	To investigate the correlation between the kinematic parameters of range to the three-dimensional target and examine the degree of differences in the kinematic parameters.	Ten post-stroke patients participated in an intervention of 18 1-h sessions. Kinematic parameters were collected before and after the intervention. Kinematic parameters were cross-sectional and longitudinally (i.e., changes in response to the intervention).	The authors found that Subject analyses revealed moderate to significant effect size changes in the kinematics of 3D target reaching movements before and after the intervention. These changes in clinical outcomes and kinematic parameters varied greatly among participants.
Grimm et al. [97].	To evaluate the upper extremity of severely affected stroke patients with a multiarticular exoskeleton compared to the UE-FMA scale.	19 Post-stroke patients used the Armeo Spring exoskeleton and compared the sensor-based assessment with the Upper Extremity Fugl-Meyer Assessment (UE-FMA) clinical outcome assessment scale. The RoM of the shoulder, elbow, and wrist extremities were assessed.	The authors observed a strong correlation between wrist and elbow FE. UE-FMA was significantly predicted by a multiple regression model.

Picelli et al. [98].	To evaluate if robotic arm training might improve upper limb function in patients with PD.	Ten patients with Parkinson's disease received ten 45-minute treatment sessions, five days a week, for two consecutive weeks. Robot-assisted arm training was performed with the Bi-ManuTrack (Reha-Stim, Berlin, Germany).	The authors found that the results support the hypothesis that robot-assisted arm training could be a promising tool for improving upper extremity function in patients with PD.
Gijbels et al. [99].	To examine the feasibility of an 8-week assisted training program to improve upper extremity muscle strength and functional capacity in patients with multiple sclerosis.	Ten patients with a high level of disability MS actively performed task-oriented movements in a real-life-like virtual learning environment with the affected upper limb. Tests were administered before and after training and at a 2-month follow-up. The Armeo Spring was used a robotic device.	The authors found that muscle strength did not change significantly. Also, significant gains were seen in functional capacity tests. It is concluded that upper limb functionality is positively influenced after a rehabilitation program with robotic devices.
Dokkum et al. [100].	To identify the potential of kinematics in the assessment of early recovery of the upper limb after stroke.	Thirteen post-stroke patients and were assessed once a week for six weeks and at three months, and a performance-based kinematic analysis of a grasping reach-to-grasp task was performed.	The authors found that movement time, trajectory length, directness, smoothness, mean and maximum hand velocity were sensitive to change over time and distinguished between paretic, nonparetic and healthy control limb movements.
Kordelaar et al. [101].	To identify how pathological limb synergies between shoulder and elbow movements interact with compensatory trunk movements during a functional movement with the paretic upper limb after stroke.	Forty-six post-stroke patients were fitted with a 6-degree-of-freedom portable electromagnetic tracking device (Polhemus Liberty, Polhemus, Vermont, USA) for kinematic analysis. Patients performed a reach-to-grasp movement and a block-locating movement.	The authors found significant differences in the use of Forward Trunk Rotation, Axial Trunk Rotation, Upward Shoulder Rotation and Elbow Flexion, indicating that the contribution of these degrees of freedom to reach to grasp is modified.
Rand et al. [102]	To investigate how PD affects temporal coordination among the trunk, arm, and fingers during trunk-assisted reach-tograsp movements.	Participants were comfortably seated at a table. They could move the trunk comfortably back and forth in the sagittal plane, while still being able to grasp an object for all conditions quickly.	The authors found that for the transport component were significantly correlated with PD severity.

Table 2.5 shows several studies that have explored movement and upper limb rehabilitation for PD patients based on robotic rehabilitation strategies. Also, this table shows the methodology, the rehabilitation method and the results obtained from each study. This study is critical because few studies have been found in the literature that incorporates robotic rehabilitation in Parkinson's disease, making it novel. With the kinematic motion analysis, we can verify that the kinematic parameters have changed when compared before and after the rehabilitation therapy. Likewise, we can conclude if the rehabilitation therapy with the robotic device is effective.

One problem noted with the lack of information found in the literature is that the tests performed by patients are usually grasping and reaching exercises, which may be a problem when comparing the results of this study with the literature. This study is novel because it has a joint range of motion tests such as maximum forward reach test and apley scratch and manual dexterity tests such as box and block.

Chapter 3

Methodology

This chapter describes the methodology, initially describing the participants, defining the population, their anthropometric characteristics, their inclusion and exclusion criteria, and the ethics committee's approval. Subsequently, the type of study, equipment, rehabilitation, movement analysis, data analysis and definition of variables are described.

Rehabilitation therapy with the Armeo Spring ® exoskeleton was performed on 12 patients with Parkinson's disease. To evaluate the efficacy of Armeo®Spring exoskeleton therapy in PD patients, the upper extremities before and after (32.72±6.95) therapy sessions were compared in their joint motion. Motion analysis was performed with the VICON system (Oxford Metrics, Oxford, UK and Polygon software) while patients performed (i) the maximal forward reach test, (ii) the Apley scratch test, and (iii) the Box and Block test (BBT).

3.1 Participants

This study was carried out with 12 patients with PD (seven women and five men). The patients were between 40 and 80 (69.33±7.21) years old, weighed between 44 and 82 (63.66± 10.19) kg, and were between 1.44 and 1.70 (1.57±0.08) m tall. All patients had PD measured with the Hoehn and Yahr scale (HY) (see Table 3.1).

The HY scale is a widely used clinical scale that defines broad categories of motor function in PD [103]. The scale consists of a score of 1-5, where 1: only unilateral involvement, usually with minimal or no functional disability, 2: bilateral or midline involvement without impairment of balance, 3: bilateral disease: mild to the moderate disability with impaired postural reflexes; physically independent, 4: severely disabling disease; still able to walk or stand unassisted, 5: confinement to bed or wheelchair unless aided [104].

Inclusion criteria were: patients with PD stages I-III according to the Hoehn and Yahr scale, patients between 40 and 80 years of age, patients with partial independence to mobilize, patients under active medication (levodopa dose $\geq$ 300 mg per day) with a stable medical regimen for at least three weeks, decreased active upper extremity movement, upper extremity bradykinesia, upper extremity resting tremor.

Patients are excluded if they have a neurological disease and seizures, visual disorders, unstable medication, metallic or cardiac support implants (pacemakers and coronary stents),

Table 3.1: Anthropometric characteristics of patients with PD.

Pacient	Age (years)	Height (m)	Weight (kg)	Hoehn and Yahr
1	79	1.60	65	4
2	64	1.44	60	3
3	61	1.55	60	3
4	75	1.66	72	2
5	63	1.60	60	2
6	69	1.56	79	3
7	73	1.44	60	3.5
8	59	1.58	57	3
9	75	1.60	65	3
10	81	1.70	60	3
11	68	1.53	44	4*
12	65	1.68	82	3
	69.33±7.21	1.57±0.08	63.66± 10.19	

damaged skin or recent scars in the upper extremity area, pregnancy status, inability to walk 10 meters, history of deep brain stimulation, and cognitive disability that prevents them from reading, understanding and signing the informed consent for the test.

The Ethics Committee of the Club de Leones Cruz del Sur Rehabilitation Center (Chile) approved the intervention, and all the participants signed informed consent. At the beginning of each trial, the researchers explained each volunteer's experimental setup and device's functionality.

A single group pre and the post-experimental study was conducted to evaluate the effects of ArmeoSpring training in the Parkinson's disease patient population.

3.2 Equipment

The Hocoma Armeo Spring ® (Hocoma AG, Switzerland) device was used to train the movement of the affected upper extremities. The device consists of 6 degrees of freedom orthosis without actuators, with an elastic system for movement facilitation. It has an adjustable mechanical arm for variable levels of gravity support employing a spring mechanism, which allows patients to use the remaining function of the upper extremity to achieve a greater range of active movement within a three-dimensional workspace. The device is instrumented with position sensors in the joints and pressure sensors in the handle that allow the execution of graduated grip and release exercises. The device's software allows functional tasks to be performed and simulated in a virtual learning environment on a computer screen, delivering auditory and visual performance feedback during and after practice.

3.3 Experimental Procedure

In the first instance, the initial configuration of the equipment was performed individually for each patient before training, establishing the level of weight compensation, work space and level of difficulty. The level of gravity support provided by the device was defined according to the maintenance of the standardized position of 45° shoulder flexion and 90° elbow flexion in the affected arm. The setting functions were gradually adjusted in the first training session of each week. Sixty minutes of therapy for eight weeks, working individually with a therapist during the session. Participants used the most affected upper extremity to control and participate in therapeutic games (see Fig. 3.1). Delivering continuous supervision during training. An occupational therapist supervised therapy with formal training in the Armeo device. The training frequency was a total of 32.72±6.95 sessions for eight weeks, or nine weeks if the participant missed a training session. Each session lasted 40 minutes and consisted of repetitive execution of tasks in virtual reality added with one therapy game preferred by the patient (e.g., car racing or card games). Assisted mechanical training was supplemented with usual care consisting of physiotherapy and occupational therapy aimed at maintaining general functional status (e.g. mobilizations to prevent muscle contractures, breathing exercises, the practice of transfers, etc.; 2 to 3 times/week, 30 minutes/session).

Figure 3.1: Rehabilitation Therapy: Figure (a) patients are observed performing rehabilitation therapy, and figures (b) and (c) patients are observed performing the therapeutic games.

3.4 Therapeutic Games Used In Rehabilitation Therapy

The Armeo Spring ® training consists of multiple therapeutic games. The games are described as high flying, clean the ocean pirates. All games have different scores, but each has the same scale: The high flying game has a scale of 0-140, the clean the ocean game has a scale of 0-27, and the pirate game has a scale of 0-44.

The high flying game consists of a man flying over trees and collecting coins (see Fig. 3.2(a)). This game has a duration of 25 seconds:

The patients have to keep their posture to collect all the coins at the same height. The coins to collect are a little higher than before. The flying man descends to collect coins at the bottom of the screen.

As for the installation of the Armeo®Spring exoskeleton (for example, on the left upper extremity, so everything described below will be on the patient's left side):

- Second 1 to 12: The left arm in 80 degrees flexion and medial rotation of approx. 20 degrees. Forearm in 90 degrees flexion and neutral position. Hand affirms Armeo grasper with cylindrical grip. Posture is maintained until second 12, in which the same pose is observed only with greater shoulder flexion, reaching 90 degrees.
- Second 12 to 25: The left arm goes down to a position, maintaining a slight flexion of the shoulder (15 degrees) with medial rotation. Elbow in flexion of approx. 90 degrees and neutral position of the forearm. Hand asserts Armeo taker with cylindrical grip.

The clean the ocean game consists of observing the ocean with trash. Then, it has a net to collect trash in the middle of the screen (see Fig. 3.2(b)). This game has a duration of 30 seconds:

- Second 1 to 4: The patient collects trash with a net on the left side of the screen.
- Second 5 to 13: The patient returns to the middle of the screen with the net.
- Second 14 to 17: The patient picks up a piece of trash with the net on the left side of the screen.
- Second 18 to 23: The patient picks up a trash with the net on the right side of the screen.
- Second 24 to 30: The patient picks up a trash with the net on the left side of the screen.

Regarding the installation of the Armeo®Spring exoskeleton (for example, on the left upper extremity, so everything described below will be on the patient's left side):

- Initial position: Left-arm abducted at 30 degrees, slightly rotated medially. Forearm in 90 degrees flexion and neutral position. Hand asserts Armeo taker with cylindrical grip.
- Second 1 to 4: Arm abducts to 50 degrees, forearm and hand in the same position described above.
- Second 5 to 13: Return to initial shoulder position with medial rotation of the arm (approx. 15 degrees). Elbow in flexion of approx. 90 degrees and neutral forearm position. Hand asserts Armeo taker with cylindrical grip.
- Second 14 to 17: Arm abducts to 50 degrees, forearm now with greater extension than previously, approx. 110 degrees. Hand in the same position as described above.
- Second 18 to 23: Left-arm returns to the initial position, but without abduction.
- Second 24 to 30: Arm abducts to 70 degrees, forearm extends to 100 degrees—hand in the same position described above.

The pirates game lasts 30 seconds and consists of observing the sea with a pirate ship (see Fig 3.2(c)).

- Second 1 to 5: The patient shoots at the pirate while pressing the handle of the Armeo. When this succeeds, the ship sinks, and a new ship with a pirate appears.
- Second 5 to 10: The patient shoots at the pirate while pressing the handle of the Armeo. When this succeeds, the ship sinks, and a new ship with a pirate appears.
- Second 11 to 21: The patient shoots at the pirate while pressing the handle of the Armeo. When this succeeds, the ship sinks, and a new ship with a pirate appears.
- Second 22 to 30: The patient shoots at the pirate while pressing the handle of the Armeo. When this succeeds, the ship sinks, and a new ship with a pirate appears.

Regarding the installation of the Armeo®Spring exoskeleton (for example, on the left upper extremity, so everything described below will be on the patient's left side), slight tremors of the left upper extremity are observed during arm movements, and difficulty in maintaining the arm in a fixed position:

- Initial Position: Left-arm abducted at 40 degrees. Forearm in 90 degrees flexion and neutral position. Hand states Armeo taker with cylindrical grip.
- Second 1 to 5: Arm in the initial position. Hand movements are observed to squeeze and release the Armeo grasper and wrist movements of alternating abduction and adduction.
- Second 5 to 10: Arm in the initial position, only with slightly less abduction of the arm. Hand movements are observed to squeeze and release the Armeo grasper and wrist movements of alternating abduction and adduction.
- Second 11 to 21: Arm abducted at approx. Sixty degrees with the forearm in 90-degree flexion. Hand movements are observed to squeeze and release the Armeo grasper. Then lower the arm, becoming less abducted.
- Second 22 to 30: Arm is abducted to almost 90 degrees, with the elbow also in 90 degrees of flexion. Hand movements are observed to squeeze and release the Armeo grasper.

3.5 Movement Analysis Assessment of Upper Limb

Nexus software (Oxford Metrics, Oxford, UK) was used to track the trial data, and Polygon software (Oxford Metrics, Oxford, UK) provided the kinematic outcomes of each user. In this sense, the kinematic parameters such as maximum angles reached per joint, range of motion during the task per joint, time of execution of the task, and maximum angular velocity per joint of each limb was calculated. It is essential to mention that the movement was recorded at a sampling frequency of 100 Hz. This protocol included two modes (i.e., baseline and post-rehabilitation) to analyze the effects of the Armeo®Spring rehabilitation program. Participants were instrumented with 19 markers under a full body Plug-in Gait marker model

Figure 3.2: Figure (a) shows the interface of the high flying game, (b) shows the interface of the clean the ocean game, and (c) shows the interface of the pirates game.

for both modes. Besides, trials were executed on a chair and a table in front of the patient. Ten cameras, VICON (Oxford Metrics, Oxford, UK), were distributed to acquire the user kinematics.

Patients performed the Maximum Forward Reach Test, Apley Scratching Test, and Box and Block Test. The first is the horizontal distance measured from the plane passing through the occipital, the scapulae and the glutes to the vertical axis that occur in hand with the fingers extended forward. The distance is measured to the tip of the fingers, and the extended arm should make a 90 angle as can be seen in Figure 3.3.

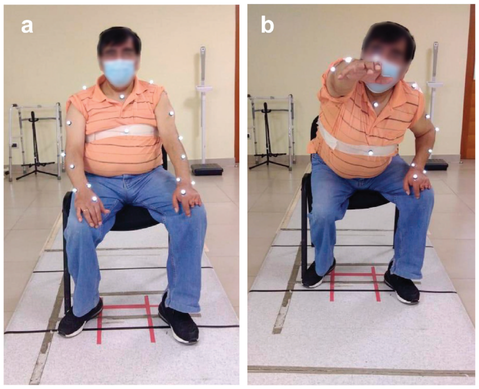

Figure 3.3: Maximum forward Reach Test sequence: Figure (a) shows the initial position, and figure (b) shows the final position [15].

The Apley Scratching Test consists of 3 main actions [105]:

- **Action 1:** The subject is instructed to touch the opposite shoulder with his hand. Here the Gloenohumeral Abduction, Internal Rotation, horizontal Abduction, and escape protraction are checked as shown in Fig. 3.4(a).
- **Action 2:** The subject is told to raise his arm above his head. Then bend his elbow and turn his arm out until it reaches behind his head with his palm to play with the medial edge of the counter lateral scapula or reach the column, that is, by touching the vertebrae. Here, the shoulder flexion, external rotation, and exhaust abduction are checked in Fig. 3.4(b).

- **Action 3:** The subject is told to reach an arm behind his back. Then, bend his elbow and turn his arm in with his palm out to touch the lower angle of the contralateral scapula or reach the column, that is, touch the vertebrae as far as possible. Here the shoulder extension, internal rotation and escape adjection are checked in Fig. 3.4(c).

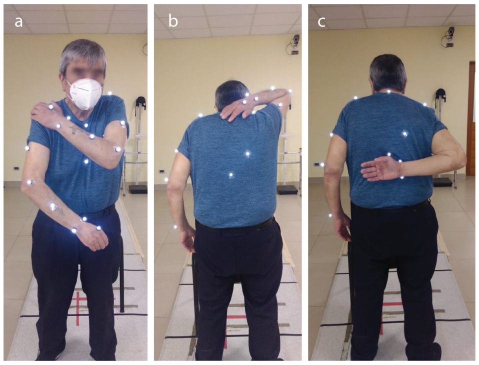

Figure 3.4: The Apley Scratching Test sequence: Figure (a) shows action 1 of the Apley scratch test. In figure (b), action 2 is observed. In the figure (c), action three is observed [15].

Finally, BBT measures gross manual dexterity, a frequently evaluated test in rehabilitation to estimate hand function [106]. BBT consists of moving one by one the maximum number of blocks from one box compartment to another (see Fig. 3.5) [107].

Figure 3.5: Third test: Box and Block.

3.6 Definition of variables

To evaluate the results of this study, the clinical parameters of interest are maximum angles, RoM, execution time, and angular velocity.

- **Maximum Angles:** Its unit is in degrees. Is the maximum angle reached by each upper limb joint: shoulder, elbow, wrist and forearm.
- **Range of Motion:** Its unit is in degrees. Is rotation about a joint. Measurement of ROM is a valuable part of the clinical assessment; therefore, it is essential that it is completed to provide accurate and reliable results [108], [109].

- **Execution Time:** Its unit is in seconds (s). It is the duration required to complete the exercise.
- **Angular Velocity:** Its unit is in (rad/s). It is derived from a position or angle data.

3.7 Data Analysis

The Wilcoxon test with a significance level of p = 0.05 was used for the upper limb joints to compare upper extremities before and after the rehabilitation process. This test is used after finding a non-normal distribution with a Shapiro-Wilk test.

Chapter 4

Results

This chapter shows the statistical analysis results and the extraction of clinical parameters of interest with their respective means and standard deviations. Also, this chapter shows the significant difference obtained in the Wilcoxon test, that are important to compare with the literature. The three tasks are described: Maximum Forward Reach Test, Apley Scratching Test and Box and Block Test. The four clinical parameters of interest are defined: maximum angles, RoM, execution time, and angular velocities.

4.1 Maximum Forward Reach Test

Table 4.1 presents the maximum angles obtained for the more and less affected upper limb in the Maximum Forward Reach Test before and after the rehabilitation therapy (RT). Regarding to more affected upper limb, significant difference was found in the abduction and external rotation of the shoulder joint, the elbow joint extension, and the wrist joint flexion. This corresponds to the increase of the maximum angle after the rehabilitation therapy compared to before. The increase found was 18.45% for the adduction of the shoulder, 36.33% for the external rotation of the shoulder, 18.69% for the extension of the wrist, and 43.47% for the flexion of the elbow. On the other hand, in the less affected upper limb, a significant difference was found in the elbow joint extension and flexion of the wrist joint. This corresponds to the increase of the maximum angle after the rehabilitation therapy compared to before. The increase found was 18.29% for the elbow extension and 42.21% for the flexion of the wrist.

When comparing the maximum angles reached between the more and less affected upper limbs, no significant differences were found. This is because both limbs are affected, and therefore, they develop motor symptoms that affect movement in both limbs (see Table 4.2).

In the analysis of RoM of the more and less affected upper limb before and after rehabilitation therapy presented in Table 4.3, a significant difference was found in the shoulders' adduction-abduction, flexion-extension of the elbow and wrist of the more affected upper limb. This corresponds to the increase of the RoM after the therapy compared to before. The increase found was 15.89% for adduction-abduction of the shoulder, 6.8% for flexion-extension

Table 4.1: Maximum angles obtained for the more and less affected upper limb in the Maximum Forward Reach Test before and after the rehabilitation therapy.

Joint	Movement	Maximum angle before RT(°) MA UL	Maximum angle after RT(°) MA UL	p-Value	Maximum angle before RT(°) LA UL	Maximum angle after RT(°) LA UL	p-Value
Shoulder	Flexion	60.42 ±9.00	66.08±10.84	0.27	61.02±10.02	66.17±7.60	0.13
	Extension	9.18±4.37	11.62±10.72	0.98	11.53±8.58	13.32±6.66	0.27
	Adduction	107.09±21.77	126.85±17.85	**$p \leq 0.05$**	109.57±26.06	119.30±13.99	0.27
	Abduction	15.16±8.70	14.82±7.34	0.62	11.81± 8.60	13.99±6.58	0.18
	Int. Rot.	35.79±12.40	44.27±13.85	0.23	38.72±15.38	43.35±12.60	0.27
	Ext. Rot.	60.33±19.58	82.25±40.63	**$p \leq 0.05$**	62.98±22.14	71.19±33.79	0.37
Elbow	Flexion	81.06±9.88	79.30±16.25	0.98	79.16±14.08	76.99±10.99	0.98
	Extension	32.14±9.66	26.13±5.13	**$p \leq 0.05$**	34.65±8.41	28.31±5.09	**$p \leq 0.05$**
Wrist	Flexion	30.75±10.68	44.12±12.67	**$p \leq 0.05$**	33.66±12.97	47.87±13.57	**$p \leq 0.05$**
	Extension	16.59±9.48	15.93±8.76	0.92	13.66±8.00	15.95±11.23	0.43
Forearm	Pronation	144.13±22.40	154.16±22.05	0.27	142.99±19.86	152.90±17.57	0.16
	Supination	117.59±20.08	114.26±23.40	0.92	117.20±19.25	123.25±14.80	0.32

of the elbow, and 26.82% for flexion-extension of the wrist. Regarding to less affected upper limb, a significant difference was found in the shoulders' flexion extension. This corresponds to the increase of the RoM after the therapy compared to before. The increase found was 9.57% for flexion-extension of the shoulder.

No significant differences were found when comparing the RoM reached between the more and less affected upper limbs (see Table 4.4). This is because both limbs are affected by PD, and consequently, when they perform the movement, they present difficulty in both limbs.

Regarding the execution of time, there was no significant difference before or after rehabilitation therapy for the less affected upper limb, as can be seen in the table 4.5. On the other hand, there was a significant difference before or after rehabilitation therapy for the more affected upper limb. It can be seen that the time after therapy is more extended than before rehabilitation therapy. The increase in the execution of time is 36.55% higher after therapy than before rehabilitation therapy. No significant differences are found when comparing the less and more affected upper limbs before and after rehabilitation therapy.

Table 4.6 shows the angular velocities of the more and less affected upper limb. Regarding to the more affected upper limb, a significant difference corresponed only to shoulder flexion-extension, given an increase in angular velocities of the more affected upper limb after the therapy compared to before. The increase found was 40.27% for flexion-extension. Also, in the less affected upper limb, a significant differences corresponded only to shoulder flexion-extension, given an increase in angular velocities of the less affected upper limb after the therapy compared to before. The increase found was 54.32% for flexion-extension.

Table 4.2: Maximum angles Wilcoxon test of the more and less affected limb in the Maximum Forward Reach Test before and after the rehabilitation therapy.

Joint	Variable	p-valor before RT	p-valor after RT
Shoulder	Flexion	0.92	0.96
	Extension	0.62	0.46
	Adduction	0.69	0.27
	Abduction	0.19	0.70
	Int. Rotation	0.69	0.98
	Ext. Rotation	0.62	0.32
Elbow	Flexion	0.92	0.70
	Extension	0.49	0.24
Wrist	Flexion	0.48	0.40
	Extension	0.32	0.96
Forearm	Pronation	0.83	0.89
	Supination	0.24	0.24

Table 4.3: RoM obtained for the more and less affected upper limb in the Maximum Forward Reach Test before and after the rehabilitation therapy.

Joint	Movement	RoM before RT(°) MA UL	RoM after RT(°) MA UL	p-Value	RoM before RT(°) LA UL	RoM after RT(°) LA UL	p-Value
Shoulder	Flex-Ext	69.61±9.98	77.71±17.57	0.20	72.55±13.29	79.50±11.13	**$p \leq 0.05$**
	Add-Abd	122.25±24.78	141.68±13.49	**$p \leq 0.05$**	121.38±31.17	133.30±12.01	0.41
	Int/Ext Rot	97.92±21.09	126.52±40.22	0.36	101.70±23.66	114.54±29.19	0.27
Elbow	Flex-Ext	113.20±15.27	105.43±17.92	**$p \leq 0.05$**	113.82±19.35	105.30±14.39	0.12
Wrist	Flex-Ext	47.35±18.48	60.05±17.35	**$p \leq 0.05$**	47.32±18.84	63.82±22.03	0.06
Forearm	Pron-Sup	261.73±39.43	268.42±38.66	0.96	260.20±37.46	276.16±29.09	0.2

Comparing the angular velocities reached between the more and less affected upper limb before and after rehabilitation therapy, no significant differences were found (see Table 4.7)

4.2 Apley Scratching Test

Table 4.8 presents the maximum angles obtained for the more and less affected upper limb in the Apley Scratching Test before and after the rehabilitation therapy. As shown, in the more affected upper limb a significant difference was found in the elbow joint extension. This corresponds to the increase of the maximum angle after the rehabilitation therapy compared to before. The increase found was 25.62%. By contrast, in the less affected upper limb, a significant difference was found in the extension of the shoulder joint and the elbow joint flexion. This corresponds to the increase of the maximum angle after the rehabilitation therapy compared to before. The increase found was 34.42% for the shoulder extension and

Table 4.4: RoM Wilcoxon test of the more and less affected limb in the Maximum Forward Reach Test before and after the rehabilitation therapy.

Joint	Variable	p-valor before RT	p-valor after RT
Shoulder	Flex-Ext	0.46	0.83
	Add-Abd	0.76	0.06
	Int/Ext Rot	0.27	0.51
Elbow	Flex-Ext	0.96	0.96
Wrist	Flex-Ext	0.83	0.27
Forearm	Pron-Sup	0.83	0.70

Table 4.5: Execution time of the Maximum Forward reach Test before and after the rehabilitation therapy.

Limb	Execution Time before RT (s)	Execution Time after RT (s)	p-Value
Less affected UL	8.45 ± 2.58	10.26 ± 2.70	0.20
More affected UL	8.18 ± 2.59	11.17 ± 3.19	**$p \leq 0.05$**
p-Value	0.57	0.14	

12.47% for the elbow flexion.

Some significant differences were found when comparing the maximum angles reached between the more and less affected upper limbs. There was an asymmetry between the more and less affected upper limb in two maximum angles that were not shown after the rehabilitation. In shoulder flexion, the more affected upper limb had a maximum angle of 13.47% higher than the less affected limb. In shoulder internal rotation, the difference before was 5.13%. These results show the potential of rehabilitation to decrease the motor symptoms after PD. These differences are observed in Table 4.9.

Table 4.6: Angular velocities obtained for the more and less affected upper limb in the Maximum Forward Reach Test before and after the rehabilitation therapy.

Joint	Movement	Ang vel. before RT(rad/s) MA UL	Ang vel. after RT(rad/s) MA UL	p-Value	Ang vel. before RT(rad/s) LA UL	Ang vel. after RT(rad/s) LA UL	p-Value
Shoulder	Flex-Ext	221.37±87.54	157.81±41.20	**$p \leq 0.05$**	268.97±162.06	174.29±58.35	**$p \leq 0.05$**
	Add-Abd	308.77±129.17	294.65±152.21	0.46	347.47±104.67	295.93±103.43	0.24
	Int/Ext Rot	343.75±136.10	298.41±167.40	0.36	363.40±61.78	336.57±137.63	0.63
Elbow	Flex-Ext	197.99±64.51	168.54±73.53	0.17	177.21±50.29	196.67±90.34	0.32
Wrist	Flex-Ext	146.13±83.44	170.19±111.23	0.63	157.89±66.48	188.05±109.39	0.83
Forearm	Pron-Sup	180.03±109.45	174.58±114.57	0.83	209.85±118.38	305.51±425.23	0.98

Table 4.7: Angular velocities Wilcoxon test of the more and less affected upper limb in the Maximum Forward Reach Test before and after the rehabilitation therapy.

Joint	Variable	p-valor before RT	p-valor after RT
Shoulder	Flex-Ext	0.23	0.96
	Add-Abd	0.98	0.18
	Int/Ext Rot	0.37	0.49
Elbow	Flex-Ext	0.41	0.10
Wrist	Flex-Ext	0.96	0.46
Forearm	Pron-Sup	0.96	0.96

Table 4.8: Maximum angles obtained for themore and less affected limb in the Apley Scratching Test before and after the rehabilitation therapy.

Joint	Movement	Maximum angle before RT(°) MA UL	Maximum angle after RT(°) MA UL	p-Value	Maximum angle before RT(°) LA UL	Maximum angle after RT(°) LA UL	p-Value
Shoulder	Flexion	67.47±10.57	62.58±11.28	0.23	58.39±7.46	63.97±9.49	0.27
	Extension	37.34±8.63	42.61±18.81	0.27	35.09±11.04	47.17±9.48	**$p \leq 0.05$**
	Adduction	96.89±20.79	90.25±26.19	0.62	103.94±21.75	86.30±20.49	0.06
	Abduction	17.16±9.85	19.74±19.31	0.98	17.95±13.07	14.04±14.68	0.55
	Int. Rot	104.58±12.91	94.18±27.36	0.32	99.21±22.31	99.13±13.59	0.76
	Ext. Rot	62.72±31.41	65.53±36.93	0.92	65.17±29.82	52.14±34.65	0.37
Elbow	Flexion	144.08±11.49	155.20±10.86	0.10	136.14±26.93	153.12±6.95	**$p \leq 0.05$**
	Extension	54.86±18.34	68.92±14.09	**$p \leq 0.05$**	54.23±17.50	65.42±13.77	0.10
Wrist	Flexion	49.42±13.84	41.08±23.20	0.16	48.42±11.74	39.17±10.53	0.13
	Extension	21.57±22.28	16.49±10.65	0.49	14.06±13.53	16.61±13.89	0.32
Forearm	Pronation	151.01±20.51	140.16±18.14	0.32	144.96±7.33	147.21±5.43	0.32
	Supination	65.57±46.82	55.01±51.99	0.55	65.96±39.96	75.63±46.62	0.49

Table 4.10 presented the RoM obtained for the more and less affected upper limb in the Apley Scratching Test before and after the rehabilitation therapy.In respect of more affected upper limb, a significant difference was found in the flexion-extension of the elbow joint. This corresponds to the increase of the RoM after the therapy compared to before. The increase found was 12.65% for flexion-extension of the elbow. On the other hand, in the analysis of the RoM in the less affected upper limb, a significant difference was found in the flexion-extension of the elbow joint. This corresponds to the increase of the RoM after the rehabilitation therapy compared to before. The increase found was 14.79%.

Some significant differences were found when comparing the RoM reached between the paretic and non-paretic limbs (see Table 4.11). It can be observed that the angles of the least and most affected upper extremities are similar for all movements before and after rehabilitation therapy.

Table 4.9: Maximum angles Wilcoxon test of the more and less affected limb in the Apley Scratching Test before and after the rehabilitation therapy.

Joint	Variable	p-valor before RT	p-valor after RT
Shoulder	Flexion	**$p \leq 0.05$**	0.76
	Extension	0.37	0.49
	Adduction	0.16	0.32
	Abduction	0.98	0.92
	Int. Rotation	**$p \leq 0.05$**	0.62
	Ext. Rotation	0.76	0.55
Elbow	Flexion	0.37	0.08
	Extension	0.98	0.99
Wrist	Flexion	0.69	0.84
	Extension	0.55	0.92
Forearm	Pronation	0.69	0.49
	Supination	0.84	0.37

Table 4.10: RoM obtained for the more and less affected upper limb in the Apley Scratching Test Test before and after the rehabilitation therapy.

Joint	Movement	RoM before RT(°) MA UL	RoM after RT(°) MA UL	p-Value	RoM before RT(°) LA UL	RoM after RT(°) LA UL	p-Value
Shoulder	Flex-Ext	99.92±14.98	110.08±26.29	0.23	99.06±12.56	105.56±12.02	0.27
	Add-Abd	113.35±20.25	109.99±33.35	0.84	119.40±28.64	101.25±25.86	0.23
	Int/Ext Rot	167.38±29.72	159.71±42.84	0.62	164.38±42.39	151.28±33.20	0.49
Elbow	Flex-Ext	198.95±24.73	224.12±14.71	**$p \leq 0.05$**	190.37±40.24	218.54±14.51	**$p \leq 0.05$**
Wrist	Flex-Ext	70.99±24.81	57.57±23.61	0.32	62.48±21.55	57.57±23.61	0.62
Forearm	Pron-Sup	216.58±62.53	195.17±59.54	0.37	210.93±40.93	222.84±49.72	0.49

Regarding the execution time, as shown in Table 4.12, no significant differences were found when comparing the most affected upper limb with the less affected upper limb before and after rehabilitation therapy, when comparing the most affected upper limb before and after rehabilitation therapy, and the less affected upper limb before and after rehabilitation therapy. Although there were no significant changes, it can be observed that the more affected upper limb has a longer time than the less affected limb before rehabilitation therapy. After rehabilitation therapy, the less affected upper limb has a longer time than the more affected upper limb.

Table 4.13 shows the angular velocities obtained for the more and less affected upper limb before and after the rehabilitation therapy. Regarding to angular velocities of the more affected upper limb, no significant differences were found. But, the angular velocity after therapy was higher in flexion-extension movements than before therapy. In the less affected upper limb, the angular velocity after therapy was higher in all movements, except for the

Table 4.11: RoM Wilcoxon test of the more and less affected limb in the Apley Scratching Test before and after the rehabilitation therapy.

Joint	Variable	p-valor before RT	p-valor after RT
Shoulder	Flex-Ext	0.84	0.19
	Add-Abd	0.27	0.16
	Int/Ext Rot	0.84	0.08
Elbow	Flex-Ext	0.83	0.10
Wrist	Flex-Ext	0.37	0.98
Forearm	Pron-Sup	0.92	0.06

Table 4.12: Execution time of the Apley Scratching Test before and after the rehabilitation therapy.

Limb	Execution Time before RT (s)	Execution Time after RT (s)	p-Value
Less affected UL	13.57 ±3.88	14.33 ± 3.54	0.92
More affected	14.15 ±4.73	13.69± 4.77	0.67
p-Value	0.76	0.84	

abduction-adduction movement, than before therapy.

Table 4.13: Angular velocities obtained for the more and less affected upper limb in the Apley Scratching Test before and after the rehabilitation therapy.

Joint	Movement	Ang vel. before RT (rad/s) MA UL	Ang vel. after RT (rad/s) MA UL	p-Value	Anr vel. before RT (rad/s) LA UL	Ang vel. after RT (rad/s) LA UL	p-Value
Shoulder	Flex-Ext	268.33±61.99	278.65±121.18	0.84	255.35±62.73	302.99±107.84	0.37
	Add-Abd	332.83±82.32	300.05±113.42	0.55	359.73±120.25	341.01±145.65	0.84
	Int/Ext Rot	481.65±123.19	423.46±167.68	0.37	495.89±106.61	526.74±193.02	0.76
Elbow	Flex-Ext	337.64±92.53	278.91±141.07	0.23	325.88±84.38	362.50±157.70	0.69
Wrist	Flex-Ext	389.91±231.02	235.95±181.37	0.23	345.60±152.16	361.73±208.15	0.98
Forearm	Pron-Sup	547.49±257.12	452.64±340.87	0.43	431.06±122.47	577.03±275.74	0.13

4.3 Box and Block Test

Table 4.15 presents the maximum angles obtained for the more and less affected upper limb in the Box and Block Test before and after the rehabilitation therapy. In the more affected upper limb, a significant difference was found in the flexion of the elbow joint and the flexion of the wrist joint. This corresponds to the increase of the maximum angle after the rehabilitation therapy compared to before. The increase found was 7.70% for the elbow extension and 31.87% for the wrist flexion. On the other hand, in the less affected upper limb a significant

Table 4.14: Angular Velocities Wilcoxon test of the more and less affected limb in the Apley Scratching Test before and after the rehabilitation therapy.

Joint	Variable	p-valor before RT	p-valor after RT
Shoulder	Flex-Ext	0.37	0.98
	Add-Abd	0.37	0.95
	Int/Ext Rot	0.55	0.10
Elbow	Flex-Ext	0.43	0.49
Wrist	Flex-Ext	0.76	0.27
Forearm	Pron-Sup	0.19	0.19

difference was found in the ext. rotation of the shoulder joint, in the flexion of the elbow joint, in the extension of the wrist joint, and the supination of the forearm joint. This corresponds to the increase of the maximum angle after rehabilitation therapy compared to before. The increase found was 88.75% for the shoulder ext. rotation, 15.05% for the elbow flexion, 10.97% for the wrist extension, and 28.31% for the forearm supination.

Table 4.15: Maximum angles obtained for the more and less affected limb in the Box and Block Test before and after the rehabilitation therapy.

Joint	Movement	Maximum angle before RT (°) MA UL	Maximum angle after RT (°) MA UL	p-Value	Maximum angle before RT (°) LA UL	Maximum angle after RT (°) LA UL	p-Value
Shoulder	Flexion	54.95±3.18	52.71±6.97	0.84	60.66±7.64	55.87±12.31	0.43
	Extension	21.35±5.74	23.66±8.43	0.31	30.52±8.17	25.16±5.74	0.15
	Adduction	50.20±14.58	54.39±18.57	0.84	50.48±10.98	60.93±26.23	0.68
	Abduction	18.60±6.00	13.09±3.66	0.15	19.75±8.74	17.35±6.63	0.56
	Int. Rot	18.40±9.56	20.45±8.63	0.68	28.97±5.88	21.60±7.88	0.21
	Ext. Rot	20.13±7.69	16.75±8.88	0.43	10.85±6.72	20.48±14.12	**$p \leq 0.05$**
Elbow	Flexion	100.64±2.26	108.39±6.87	**$p \leq 0.05$**	93.77±14.91	107.89±5.68	**$p \leq 0.05$**
	Extension	49.83±11.53	55.83±4.47	0.21	48.18±13.05	58.38±4.65	0.15
Wrist	Flexion	34.51±8.99	45.51±9.33	**$p \leq 0.05$**	34.47± 8.39	32.61±12.29	0.84
	Extension	7.72±7.26	8.91±13.28	0.31	11.66±8.53	10.38±10.52	**$p \leq 0.05$**
Forearm	Pronation	145.25±15.00	153.23±14.44	0.68	133.14±25.40	151.47±15.36	0.06
	Supination	105.05±9.00	104.93±7.61	0.95	82.40±28.92	105.73±6.23	**$p \leq 0.05$**

Some significant differences were found when comparing the maximum angles reached between the more and less affected upper limbs. There was an asymmetry between the most and less affected upper limb in two angular velocities, which was not shown after the rehabilitation. In shoulder extension, the less affected upper limb had a maximum angle 42.95% higher than the more affected upper limb. In the int. rotation of the shoulder, the less affected upper limb had a maximum angle of 55.47% higher than the more affected upper limb. Also, These results show the potential of the rehabilitation to decrease the motor

Table 4.16: Maximum angles Wilcoxon test of the more and less affected limb in the Box and Block Test before and after the rehabilitation therapy.

Joint	Variable	p-valor before RT	p-valor after RT
Shoulder	Flexion	0.21	0.43
	Extension	**$p \leq 0.05$**	0.06
	Adduction	0.84	0.15
	Abduction	0.67	0.16
	Int. Rotation	**$p \leq 0.05$**	0.98
	Ext. Rotation	0.15	0.56
Elbow	Flexion	0.56	0.84
	Extension	0.43	0.06
Wrist	Flexion	0.84	0.06
	Extension	0.43	0.84
Forearm	Pronation	0.56	0.84
	Supination	0.09	0.98

symptoms after PD. These differences are observed in Table 4.16.

Table 4.17: RoM obtained for the more and less affected upper limb in the Box and Block Test before and after the rehabilitation therapy.

Joint	Movement	RoM before RT(°) MA UL	RoM after RT(°) MA UL	p-Value	RoM before RT(°) LA UL	RoM after RT(°) LA UL	p-Value
Shoulder	Flex-Ext	76.31±5.99	76.37±14.03	0.98	91.18±13.65	81.03±16.66	0.31
	Add-Abd	68.80±19.79	67.49±21.17	0.98	70.24±16.67	78.28±29.29	0.84
	Int/Ext Rot	38.53±7.22	37.21±10.01	0.98	39.82±6.56	42.08±14.82	0.82
Elbow	Flex-Ext	150.48±12.43	164.22±9.23	**$p \leq 0.05$**	141.95±22.93	166.27±7.31	**$p \leq 0.05$**
Wrist	Flex-Ext	42.23±13.99	54.43±15.18	0.43	46.13±14.73	43.00±9.69	0.97
Forearm	Pron-Sup	250.31±20.86	258.17±13.44	0.84	215.54±52.58	257.20±18.86	**$p \leq 0.05$**

Analyzing the RoM presented in Table 4.17, a significant difference was only found in the elbow flexion extension in the more affected upper limb. RoM increases 9.13% after therapy. On the other hand, analyzing the RoM for the less affected upper limb, a significant difference was found in the flexion-extension of the elbow joint and the pronation-supination in the forearm joint. This corresponds to the increase of the RoM after rehabilitation therapy compared to before. The increase found was 17.13% for the flexion-extension of the elbow joint and 19.32% for the pronation-supination of the wrist joint.

Significant differences were found when comparing the RoM reached between the more and less affected upper limbs. There was an asymmetry between the most and less affected upper limb in an RoM, which was not shown after the rehabilitation. In shoulder flexion

Table 4.18: RoM Wilcoxon test of the more and less affected limb in the Box and Block Test before and after the rehabilitation therapy.

Joint	Variable	p-valor before RT	p-valor after RT
Shoulder	Flex-Ext	**$p \leq 0.05$**	0.68
	Add-Abd	0.84	0.06
	Int/Ext Rot	0.83	0.56
Elbow	Flex-Ext	0.56	0.21
Wrist	Flex-Ext	0.55	0.15
Forearm	Pron-Sup	0.15	0.98

extension, the less affected upper limb had a maximum angle 19.48% higher than the more affected upper limb. These differences are observed in Table 4.16.

Table 4.19 shows the angular velocities obtained for the more and less affected upper limb before and after the rehabilitation therapy. In the angular velocity of the more affected upper limb, significant differences corresponded to shoulder flexion-extension and wrist flexion-extension, given an increase in angular velocities of the more affected upper limb. The growth found was 52.53% for the shoulder flexion-extension and 34.46% for wrist flexion-extension (see Table 4.19). In the angular velocity of the less affected upper limb, a significant differences corresponded to shoulder flexion-extension, shoulder adduction-abduction and wrist flexion-extension, given an increase in angular velocities of the non-paretic limb compared to paretic limb. The growth found was 68.60% for the shoulder flexion-extension, 23.66% for the shoulder adduction-abduction, and 19.93% for the wrist flexion-extension.

Table 4.19: Angular velocities obtained for the more and less affected upper limb in the Box and Block Test before and after the rehabilitation therapy.

Joint	Movement	Ang vel. before RT (rad/s) MA UL	Ang vel. after RT (rad/s) MA UL	p-Value	Anr vel. before RT (rad/s) LA UL	Ang vel. after RT (rad/s) LA UL	p-Value
Shoulder	Flex-Ext	135.45±40.71	206.61±141.46	**$p \leq 0.05$**	147.05±39.42	247.93±179.12	**$p \leq 0.05$**
	Add-Abd	115.84±80.36	189.18±74.71	0.21	83.49±30.13	103.25±71.32	**$p \leq 0.05$**
	Int/Ext Rot	211.38±111.14	253.75±53.30	0.43	180.22±21.89	286.84±122.08	0.15
Elbow	Flex-Ext	343.89±150.72	313.36±53.03	0.68	246.03±76.08	302.31±84.69	0.21
Wrist	Flex-Ext	222.15±93.57	298.72±84.58	**$p \leq 0.05$**	170.95±65.59	213.51±65.64	**$p \leq 0.05$**
Forearm	Pron-Sup	310.21±157.56	372.47±133.96	0.68	336.27±189.87	286.43±133.76	0.84

Comparing the angular velocities reached between the more and less affected upper limb before and after rehabilitation therapy, no significant differences were found (see Table 4.20).

Table 4.20: RoM Wilcoxon test of the more and less affected limb in the Box and Block Test before and after the rehabilitation therapy.

Joint	Variable	p-valor before RT	p-valor after RT
Shoulder	Flex-Ext	0.21	0.09
	Add-Abd	0.15	0.84
	Int/Ext Rot	0.68	0.98
Elbow	Flex-Ext	0.15	0.56
Wrist	Flex-Ext	0.56	0.31
Forearm	Pron-Sup	0.56	0.43

4.4 Armeo Therapy Report

The Armeo Therapy report performs a quantitative analysis regarding the patient's score in performing the therapeutic games. These reports were made for the more affected upper limb and less affected upper limb (see Table 4.30). It can be observed that the scores for the more affected limb are lower than the scores for the less affected limbs, which was to be expected. The score in the High Flying game in the more affected upper limb is lower than, the less affected upper limb by 2.50%. The score in the Treasure island game in the more affected upper limb is lower than, the less affected upper limb by 28.65%. Finally, the score in the pirates' games in the more affected upper limb is lower than, the less affected upper limb by 19.39%.

Table 4.21: Scores of three Therapeutic Games: High flying, Clean the Ocean, and Pirates.

Games	Score More affected UL	Score Less affected UL
High Flying	127.36 ± 27.17	130.55 ± 27.17
Clean the Ocean	42.50± 26.50	54.68 ±26.41
Pirates	16.81±6.11	20.07±6.24

Chapter 5

Discussion

This chapter describes the discussion of each task: Maximum Forward reach, Apley Scratching and BB test. The significant difference is explained and compared with the literature. Also, this chapter describes the limitation of this study.

5.1 Maximum Forward Reach Test

First, patients with PD have a variety of motor disturbances that affect upper limb movement and lead to limitations in functionality and have a substantial impact on quality of life [110]. The first important fact to consider is that the movements in which maximum angles, RoM, and angular velocities exhibited significant differences when comparing the more and less affected upper limb before and after the rehabilitation therapy corresponded to an increase of those variables after the therapy. As presented in Tables 4.1, 4.3, and 4.6, values after the therapy were consistently higher than before the therapy when a p-value lower than 0.05 was obtained in the Wilcoxon test.

Another particular event to observe is that the movements in Table 4.1, the significant differences were found at the shoulder, elbow, and wrist level for the more affected upper limb. According to the nature of the test, differences could be expected at the elbow and shoulder joint levels. In contrast, the less affected upper limb coincided with these joints except for the shoulder joint. More significant changes were expected in the most affected limb since the motor symptoms are more advanced and affect the quality of life. Varalta et al. [111] reported that PD patients exhibit problems in balance skills when their extremity is more compromised.

Both findings are congruent also with the movement executed in the test. As described in Section 3, the Maximum Forward Reach Test includes a movement, mainly the shoulder joint. Hence, significant differences were found in movement that corresponded to the shoulder was expected.

There was a significant change in the execution of time compared to the more affected upper limb before and after the rehabilitation therapy (see Table 4.5). This is because it is the first control of rehabilitation therapy. Therefore, it is expected that at the end of the complete therapy, this significant difference will disappear. Also, it can be observed that before therapy, the more affected upper limb has a longer time than the less affected upper limb. The more affected upper limb has less fluidity in the movement. Also, PD patients have motor symptoms characteristic of Parkinson's disease that generate slowness of movement, so a long time is expected in the most affected limb. No articles related to the kinematic variable of running time in Parkinson's patients were found in the literature. However, some articles state that the execution time is longer in paretic vs non-paretic limb in post-stroke patients [100], [101].

The results obtained in this study serve to understand which joint is most affected before rehabilitation therapy in patients with PD and evaluate the effectiveness of robotic rehabilitation therapy. Also, some studies state that accurate and sophisticated analysis, i.e., kinematic analysis, is essential to assess changes after upper extremity rehabilitation [112].

5.2 Apley Scratching Test

The behaviour seen in the Apley Scratching Test is presented in Tables 4.8, 4.10, and 4.13. The values after the therapy were higher than before the therapy when a p-value lower than 0.05 was obtained in the Wilcoxon test.

In this case, no articles related to Apley scratching and kinematic analysis in Parkinson's patients were found in the literature. However, one study compared college students with a group of bodybuilders and found that internal rotation is lower in the bodybuilder group, resulting in less shoulder mobility [113]. Accordingly, in Tables 4.10, it can be observed that the more affected upper limb has less RoM than the less affected upper limb in the adduction-abduction movements. Therefore, the more affected limb has less abduction-adduction movement than the less affected limb.

Concerning comparing the more and less upper limb, the trend is maintained in Tables 4.9, 4.11, and 4.14. The number of variables with differences found before the therapy diminished after the therapy. No difference was found in the maximum angles, RoM, and angular velocities. Again, this is a display of the effectiveness of the therapy.

Regarding to angular velocities, as shown in Table 4.13, the angular velocities in the more affected upper limb are lower than, the less affected upper limb in adduction-abduction, and internal and external rotation movements. The literature states that the velocities of the subjects with PD were consistenly slower than those of normal subjects [114]. These results cannot be compared, because the group have both limbs affected, only one more affected than the other following the HY scale.

5.3 Box and Block Test

The first important fact to consider is that the movements in which maximum angles, RoM, and angular velocities exhibited significant differences when comparing the more and less affected upper limb before and after the rehabilitation therapy corresponded to an increase of those variables after the therapy. As presented in Tables 4.15, 4.17, and 4.19, values after the therapy were consistenly higher than before the therapy when a p-value lower than 0.05 was obtained in the Wilcoxon test.

BB is a test that involves reaching for several small objects. Alberts, J. et al. [115] found that this task involves the wrist trajectory to be significantly less smooth and less continuous, as one has more significant standard deviations. Therefore, they coincide with these results since there were substantial changes in the wrist in the maximum flexion angle, as shown in table 4.15. Also, there were substantial changes in the wrist in the angular velocity, as shown in table 4.19.

According to the literature, Rand et al. [102] state that the PD group produced significantly slower time and lower peak wrist velocity, and peak trunk velocity, than the control group. The authors concluded that Individuals with PD appear to prioritize control of the arm segment, which is directly related to the task goal, over the trunk segment. When comparing the angular velocity of the less-affected limb vs the most affected limb of the wrist, no significant difference was observed (see Table 4.20). Therefore, our results do not coincide. However, in the Table 4.19, it can be observed that there was a significant change in the speed of wrist flexo-extension before and after the rehabilitation therapy.

Other studies, such as Hebert et al. [116], aimed to quantify the observed improvements in movements in a subject using different prostheses before and after targeted muscle reinnervation (TMR) surgery. The authors found improved elbow flexion and less compensatory trunk movement. This study agrees with the results, because significant changes were also found in the elbow. So, our results that agree that there are substantial differences in elbow flexion when comparing before and after therapy, as shown in Table 4.15.

Additionally, these kinematic motion capture analysis methods can be incorporated into clinical practice as a gold standard for kinematic motion analysis and are increasingly implemented as an outcome measure to assess performance and quality of movement following injury or disease involving upper extremity movements [14]. Optoelectronic motion capture systems use multiple high-speed cameras that send infrared light signals to capture reflections from passive markers placed on the body. These capture systems have high accuracy and flexibility in measuring various tasks [14].

The limitations of this study are that in the literature, few studies were found that use robotic devices to improve upper limb mobility in patients with PD. Also, very few articles were found that performed a biomechanical analysis with kinematic variables, making comparison with the literature difficult.

5.4 Armeo Therapy Report

Although no article has been found in the literature that implements the Armeo Therapy report in patients with Parkinson's disease, there is one of other illnesses such as stroke there is one. It has been shown in the literature that Armeo Therapy has increased the quality of movement, arm function, muscle strength, RoM, pain and spasticity, ADLs, and cognitive function [117]. In the Table 4.21, it can be observed that all therapeutic games increased the score in the less affected limb. This was to be expected since they have more motor skills. Some articles have shown that rehabilitation with Armeo Therapy facilitates the recovery of arm motor function and cognitive skills [118]. Cognitive skills are important as they relate to information processing, and the training consists of a program of mixed games, which the patients select according to their understanding.

Chapter 6

Conclusion

This study performed a biomechanical analysis of the upper limb in 12 patients with Parkinson's disease before and after rehabilitation therapy with an 8-week intervention with the Armeo Spring ® exoskeleton. Each patient had written informed consent, and this study was approved by The Ethics Committee of the Club de Leones Cruz del Sur Rehabilitation Center (Chile). The kinematic variables evaluated were the maximum angle, RoM, execution times and angular velocities. Nexus software (Oxford Metrics, Oxford, UK) was used to track the trial data, and participants were instrumented with 19 markers under a full body Plug-in Gait marker model. Besides, trials were executed on a chair and a table in front of the patient. Ten cameras, VICON (Oxford Metrics, Oxford, UK), were distributed to acquire the user kinematics. Finally, the patients performed three activities: Maximum Forward Reach test, Apley Scratching, and Box and Block. The kinematic data were compared with the literature.

Armeo therapy has been shown to improve motor skills reacquisition in upper limbs through the performance of high intensity, high dose, and is repeatable, reliable and flexible [12]. However, rehabilitation conventional has proven insufficient for a rehabilitation process because even though it increases functional capacity, the effects of exercise diminish after follow-up periods without training [37]. In this study, the implementation of Armeo Spring ® Therapy as complementary tools in Parkinson's rehabilitation therapies has been shown to improve the range of motion, maximum angles, and angular velocities of more and less affected upper limbs when performing three well-known motion tests (Maximum Forward Reach Test, Apley Scratching Test, and Box and Block Test).

The results showed that the number of variables with differences found before the therapy diminishes after the therapy. As more minor differences are observed, the more affected upper limb gets back movement characteristics of the less affected upper limb and performed more similarly, which is a first step in assessing the effectiveness of the therapy. Armeo Therapy have proven its benefits in the rehabilitation of post-stroke patients, as it has improved joint range of motion and maximum angular velocity. Therefore, the results obtained in this study serve to understand which joint is most affected before rehabilitation therapy in PD patients and to evaluate the efficacy of robotic rehabilitation therapy.

In the Maximum Reach test, the most affected joints were the shoulder, elbow and wrist because, depending on the nature of the test, differences in the elbow and shoulder joints were to be expected. Also, this test includes a movement, mainly in the shoulder joint. Hence, significant differences were found in the movement about the shoulder joint was expected.

On the other hand, in the Apley Scratching Test, the most affected joints were the elbow joint. Still, no articles related to Apley scratching and kinematic analysis in Parkinson's patients were found in the literature. The nature of the test described in the Chapter 3 that the joints most involved in the development of the test are the shoulder and elbow, which is to be expected.

Regarding the Box and Block Test, the elbow's most affected joints were the elbow. However, it was expected that this test would have the wrist as the most affected extremity. The nature of the test involves reaching a series of small objects, which leads to the wrist being in constant movement.

Chapter 7

Recommendations and future work

It is expected to perform the biomechanical analysis on the estimated date of the end of the project in future work. It would be interesting to compare the beginning of the project with the end of the project. Also, to see what other significant differences are found in the upper limb, compare the first cut of the project with the end of the project. The rehabilitation therapy for these patients is expected to be 24 sessions per subject, of 60 minutes per session, with an intensity of 2 sessions per week. It is essential to highlight that this project started in July 2021 and is expected to end in the first week of June 2022.

Also, it would be interesting to perform a graphical analysis of the averages and standard deviations of the joints where significant changes were found, and the change before and after rehab therapy could be observed graphically. For this purpose, Polygone or Matlab software would develop the graphs. The graphical analysis would have a graph of the joint of the most affected upper limb before and after therapy, and another graph of the joint of the least affected upper limb.

It would also be interesting to carry out this study by performing biomechanical analysis in the development of activities of daily living, such as opening a bottle, and pouring a glass of water, among others because the activities of daily living are essential for the quality of life of patients. Finally, also in this study, the upper extremity dynamometry, Nine Hole, abbreviated Minimental, physical examination (goniometry and muscle strength according to Daniel's) were evaluated. It would also be interesting to perform an analysis with these evaluations.

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