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"GAIT ANALYSIS BEFORE AND AFTER DIFFERENT REHABILITATION TREATMENTS IN PARKINSON'S DISEASE"

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Abstract

The research thesis focuses on the evaluation of rehabilitative treatments for Parkinson's disease, in particular through gait analysis. Parkinson's disease is a neurodegenerative disease that affects motor function, including gait and mobility. The study aims to assess how interventions such as exoskeletons and physical kinesiotherapy can mitigate gait impairments in Parkinson's patients. Gait analysis techniques are utilized to measure improvements in parameters such as spatio-temporal, kinematics, and kinetics. The pathophysiology of Parkinson's disease involves dopaminergic neuron degeneration, abnormal protein accumulation, mitochondrial dysfunction, impaired protein clearance, neuroinflammation, and genetic factors. Treatments for Parkinson's disease include medications such as carbidopa-levodopa, dopamine agonists, MAOB inhibitors, surgical procedures such as deep brain stimulation, and rehabilitative treatments such as physiotherapy and exoskeleton-assisted therapy. Gait analysis is a method used to evaluate human movement during walking or running, employing observational or instrumented techniques. Observational analysis involves visual evaluation of gait, while instrumental analysis uses advanced equipment such as motion analysis systems, force platforms, and electromyography to measure various variables related to movement and muscle activity.

The gait cycle can be analyzed in its principal phases: stance and swing. The stance phase involves the foot being in contact with the ground and bearing weight, while the swing phase sees the foot moving forward for the next contact. Each phase has subphases with specific functions like load acceptance, single-limb support, and limb advancement. Parameters such as stride length, step width, cadence, and velocity are crucial in gait analysis. These metrics are used to quantify different aspects of walking patterns in order to understand and diagnose movement abnormalities associated with the pathology. Stereophotogrammetry is a technique used in gait analysis to precisely capture and analyze three-dimensional motion. It involves optoelectronic systems, markers, and cameras to track movement and reconstruct positions accurately. Various protocols such as the Davis-Hellen Hayes, CAST, and IORgait provide standardized methods for marker placement, data collection, and joint angle calculations during gait analysis. IORgait is the protocol used in this study. Results of this study show that the two treatments have an effect on the Parkinson's disease patient.

Significant differences were observed between T0 and T1 measurements for both the Fkt and Ekso groups, as well as compared to the control group. These differences encompassed various parameters such as lower limb angles, EMG activity, joint forces, torques, and spatiotemporal

parameters. Both Ekso and Fkt therapies resulted in significant improvements in gait parameters compared to initial measurements.

Sommario

La presente tesi si concentra sulla valutazione dei trattamenti riabilitativi per la malattia di Parkinson, in particolare attraverso la "Gait Analysis". Il morbo di Parkinson è una malattia neurodegenerativa che colpisce la funzione motoria, compresa l'andatura e la mobilità. Lo studio mira a valutare come due interventi riabilitativi, l'esoscheletro e la kinesiterapia fisica, possano mitigare gli effetti sulla deambulazione nei pazienti affetti da Parkinson. Le tecniche di analisi del cammino vengono utilizzate per misurare i miglioramenti di parametri quali gli spazio-tempo , la cinematica e la cinetica articolari. La fisiopatologia della malattia di Parkinson coinvolge la degenerazione dei neuroni dopaminergici, l'accumulo anomalo di proteine, la disfunzione mitocondriale, la compromissione della clearance proteica, la neuro infiammazione e i fattori genetici. I trattamenti per il Parkinson includono farmaci come la carbidopa-levodopa, gli agonisti della dopamina, gli inibitori MAOB, procedure chirurgiche come la stimolazione cerebrale profonda e trattamenti riabilitativi come la fisioterapia e la terapia assistita da esoscheletro. L'analisi del cammino è un metodo utilizzato per valutare il movimento umano durante il cammino e può essere effettuato tramite tecniche osservazionali o strumentali. L'analisi osservazionale prevede la valutazione visiva dell'andatura, mentre l'analisi strumentale utilizza apparecchiature avanzate come sistemi di analisi del movimento, piattaforme di forza ed elettromiografia di superficie per misurare varie variabili legate al movimento e all'attività muscolare. Il ciclo del passo è caratterizzato da due fai principali: appoggio e oscillazione. La fase di appoggio prevede che il piede sia a contatto con il suolo e porti il peso, mentre la fase di oscillazione vede il piede muoversi in avanti per il contatto successivo. Ogni fase ha delle sottofasi con funzioni specifiche come l'accettazione del carico, il supporto di un arto singolo e l'avanzamento dell'arto. Parametri come la lunghezza del passo, la larghezza del passo, la cadenza e la velocità sono cruciali nell'analisi del passo. Queste metriche aiutano a comprendere e diagnosticare anomalie o patologie del movimento legate alla patologia. La stereofotogrammetria è una tecnica utilizzata nell'analisi del cammino per catturare e analizzare con precisione il movimento tridimensionale. Si tratta di sistemi optoelettronici, marcatori e telecamere per tracciare il movimento e ricostruire le posizioni in modo accurato. Vari protocolli, come i protocolli Davis-Hellen Hayes, CAST e IORgait, forniscono metodi standardizzati per il posizionamento dei marcatori, la raccolta dei dati e i calcoli degli angoli articolare durante l'analisi del cammino. IORgait è il protocollo utilizzato in questo studio. Sono state osservate differenze significative tra le misurazioni T0 e T1 sia per i gruppi Fkt che per Ekso, nonché rispetto al gruppo di controllo. Queste differenze comprendevano vari parametri come gli angoli degli arti inferiori, l'attività EMG, le forze articolari, le coppie e i parametri

spaziotemporali. Entrambe le terapie Ekso e Fkt hanno portato a miglioramenti significativi nei parametri dell'andatura rispetto alle misurazioni iniziali.

Chapter 1

1.1 Introduction

The current research thesis aims to assess the results of rehabilitative treatments for Parkinson’s. disease, particularly their impact on gait patterns. Parkinson's disease is known to influence gait, and this study seeks to analyze how rehabilitation interventions may mitigate these effects. Parkinson's disease is a neurodegenerative condition characterized by a range of motor symptoms, including altered gait patterns and mobility. These motor symptoms can significantly affect the quality of life of a person. Using gait analysis techniques, we evaluate the results of rehabilitative treatments and determine which treatment yields the best results. Gait analysis, which involves the precise measurement and assessment of walking patterns and movements, serves as an important tool in this research. It allows to quantify improvements in gait parameters, such as spatio-temporal parameters, kinematics, and kinetics resulting from the rehabilitative treatments. By comprehensively examining these gait-related outcomes, the aim is to provide valuable insights into the effectiveness of rehabilitative treatments for Parkinson's disease.

In this study, two specific rehabilitation treatments for Parkinson's disease were selected: Exoskeleton and Physical Kinesitherapy:

• Exoskeletons are wearable robotic devices designed to help individuals with motor disorders improve their mobility and quality of life.

• Physical kinesitherapy (also known as physical therapy or physiotherapy) plays a significant role in the treatment of symptoms of Parkinson's disease. It involves a variety of therapeutic exercises, movement therapies, and techniques designed to improve mobility, balance, strength, and overall quality of life for people with Parkinson's disease.

Although numerous rehabilitation approaches are available, the choice was made to focus on these two treatments to assess their effectiveness in improving the condition of people with Parkinson's disease. These treatments were selected based on their potential to address motor symptoms, particularly their impact on gait patterns, which are common in Parkinson's disease. The current research will evaluate and compare the results of these two rehabilitation treatments.

In this research, a variety of techniques and tools are employed to comprehensively analyze walking patterns and assess their impact on individuals. These include stereophotogrammetry, force plates, and electromyography. Through the application of these diverse techniques and tools, current research strives to deliver a comprehensive analysis of walking patterns in individuals with Parkinson's disease following rehabilitative treatments.

Thesis outline

Chapter 2: Parkinson's Disease

- Discusses PD's chronic degenerative nature, pathophysiology, demographics, symptoms, and treatment modalities.

Chapter 3: Gait Analysis

- Explores the multidisciplinary field of gait analysis, including biomechanical principles, technologies, and techniques used to study human walking patterns.

Chapter 4: Rehabilitation Treatments

- Focuses on exoskeletons, detailing their structure, development, applications in rehabilitation, and potential to improve mobility and quality of life.

Chapter 5: Materials and Methods

- Describes the collaborative project assessing the comparative effectiveness of exoskeleton-based therapy for PD patients, including data collection, preprocessing, and statistical analysis methods.

Chapter 6: Results and Discussion

- Analyzes the effects of Ekso exoskeleton and Fkt interventions on gait parameters in PD patients, presenting findings from kinematic, kinetic, and EMG data analysis.

Chapter 7: Conclusion

- Summarizes significant improvements in both Ekso and traditional therapy groups post-treatment, highlighting the importance of individual preferences and further research for personalized rehabilitation strategies.

Chapter 2

Parkinson's Disease

Parkinson's disease, often abbreviated as PD, is a chronic degenerative disorder that affects the central nervous system and affects motor and nonmotor functions. Typically, its symptoms manifest gradually, and as the condition progresses, nonmotor symptoms become more prevalent. Initial signs include tremors, stiffness, slowed movements, and difficulty walking. In addition, challenges may arise in cognitive abilities, behavior, sleep patterns, and sensory perception.

Progressive degeneration of dopaminergic neurons in a brain region called the substantia nigra is at the heart of PD. These neurons play an important role in the production of dopamine, a neurotransmitter essential for the regulation of movement.

2.1 Pathophysiology of the disease

PD, a multifaceted neurological disorder, originates from intricate processes within the brain. Its fundamental essence lies in the progressive degeneration of specific neurons, particularly dopaminergic neurons located in the substantia nigra region of the brain. These neurons play a pivotal role in the production of dopamine, a crucial neurotransmitter for orchestrating seamless and coordinated motor movements. As these dopaminergic neurons gradually degenerate and succumb to cell death, dopamine levels within the brain decrease markedly. This dopamine deficit gives rise to the hallmark motor symptoms associated with PD, encompassing tremors, muscle rigidity, bradykinesia (slowed movements), and difficulty maintaining balance.

Adding complexity to the pathophysiology of PD is the accumulation of abnormal proteins, notably alpha-synuclein, within neurons. Alpha-synuclein has an inherent propensity to aggregate and form insoluble clumps, known as Lewy bodies, which constitute a defining pathological feature of PD. These protein aggregates disrupt regular cellular functions, notably neurotransmitter regulation, and are closely associated with the degeneration of dopaminergic neurons.

Furthermore, mitochondrial dysfunction has become a significant contributor to PD. The mitochondria, the cellular powerhouses, play a pivotal role in maintaining cellular health. In PD,

mitochondrial dysfunction can lead to increased oxidative stress and compromised energy supply to neurons, making them more susceptible to damage and eventually death.

The brain ordinarily employs mechanisms to remove damaged or misfolded proteins. However, in PD, these protein clearance mechanisms may falter, allowing toxic protein aggregates, such as alpha-synuclein, to accumulate and further disrupt cellular functions.

Neuroinflammation within the brain, a condition termed neuroinflammation, has also been implicated in PD. Microglial cells, the immune agents of the brain, are activated and release inflammatory molecules in response to the presence of abnormal protein aggregates. This inflammatory response can inflict damage on neurons, exacerbating the disease's progression.

Although most PD cases are sporadic, certain individuals carry specific genetic mutations that increase their vulnerability to the disease. Mutations in genes such as LRRK2, PARK7 (DJ-1) and PINK1 can alter various cellular processes, making these individuals more susceptible to PD.

In summary, PD emerges as a multifaceted neurodegenerative condition, characterized by gradual loss of dopaminergic neurons, accumulation of abnormal protein aggregates, mitochondrial dysfunction, impaired protein clearance mechanisms, neuroinflammation, and genetic factors. These complex factors collectively contribute to the nuanced pathophysiology of PD.

PD is a neurodegenerative disease with a prevalence that increases primarily with age, making it more common among the elderly population. Although it can affect people of various ages, it is most frequently diagnosed in those over 60 years of age, with the risk increasing significantly as one advances over the years. PD exhibits gender bias, with men approximately 1.5 times more likely to develop the disease than women, although the precise reasons for this difference are unclear. In addition, there are some reported variations in the prevalence of PD among different racial and ethnic groups, with individuals of European ancestry often showing greater susceptibility. While most PD cases are sporadic, meaning that they occur without a clear family history, genetic factors play a role, particularly in familial forms of the disease. Additionally, there are geographical variations in the prevalence of PD, possibly due to environmental factors such as exposure to pesticides. As the global population continues to age, the demographic impact of PD is expected to increase, highlighting the importance of ongoing research and healthcare initiatives to address the complexities of this neurodegenerative disorder in diverse demographics. The prevalence of PD has doubled in the past 25 years. Global estimates in 2019 showed more than 8.5 million people with PD. Current estimates suggest that in 2019, PD resulted in 5.8 million disability adjusted life years (DALYs), an increase of 81% since 2000, and caused 329 000 deaths, an increase of over 100% since 2000.

2.2 Symptoms

The primary manifestations of PD become evident when nerve cells within the basal ganglia, a region of the brain responsible for coordinating movement, experience impairment or degeneration. Typically, these neurons play a crucial role in the production of dopamine, a vital neurotransmitter. However, in the presence of neuronal death or dysfunction, dopamine production decreases, leading to the characteristic movement difficulties characteristic of this condition. Despite ongoing research, scientists remain unaware of the exact cause behind the demise of these neurons.

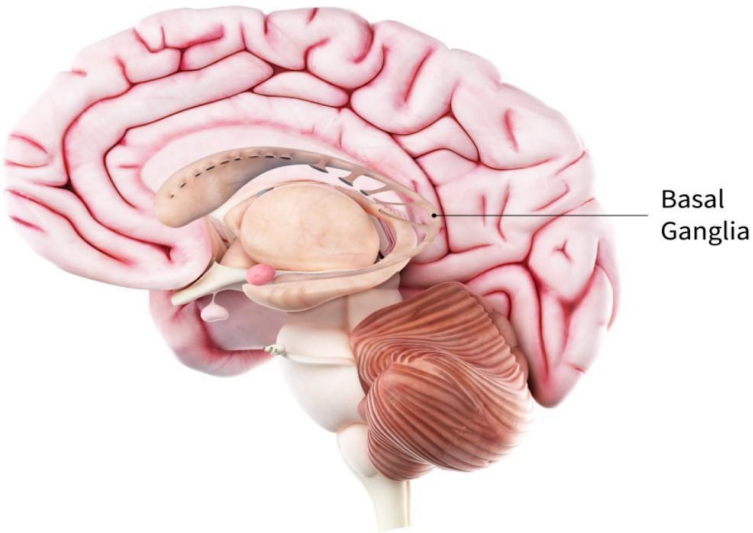

Figure 1 The basal ganglia are a group of nuclei located deep within the brain that play an important role in motor control, cognition, and emotions.[30]

People with PD also experience a loss of nerve endings that produce norepinephrine, a primary chemical messenger of the sympathetic nervous system, which governs various bodily functions, such as the regulation of heart rate and blood pressure. This depletion of norepinephrine may contribute to some of the nonmotor symptoms associated with Parkinson's, including fatigue, irregular blood pressure, sluggish digestive tract movement, and abrupt drops in blood pressure when standing from a seated or lying position.

Furthermore, many individuals with PD exhibit the presence of Lewy bodies, abnormal clumps of protein composed of alpha-synuclein, within their brain cells. Scientists are actively researching to gain a deeper understanding of both the normal and abnormal functions of alpha-synuclein and its

connections to genetic variations that influence the development of Parkinson's disease and related conditions such as Lewy body dementia.

PD encompasses a wide array of symptoms, which can be categorized into three distinct groups: primary motor symptoms, secondary motor symptoms, and nonmotor symptoms.

The primary motor symptoms are the most recognizable and are typically attributed to the degeneration of dopamine-producing neurons in the brain. These include tremors, characterized by involuntary shaking, especially during rest; bradykinesia, which results in slow movement and difficulty in performing daily tasks; rigidity, leading to stiffness and muscle pain; and postural instability, which makes maintaining balance difficult.

Secondary motor symptoms often appear as the PD progresses or as a consequence of primary motor symptoms. These can include freezing of gait, changes in posture, slow movement (bradykinesia) and a shortened stride, causing sudden difficulty in starting walking; dystonia, which involves involuntary muscle contractions and abnormal postures; hypomimia, a reduced range of facial expressions often referred to as a "masked face"; and micrographia, where handwriting becomes smaller and cramped.

The nonmotor symptoms of PD are equally significant and diverse, affecting various body systems. Cognitive changes such as memory problems, attention deficits, and impaired executive function are common. Autonomic dysfunction can cause problems such as constipation, urinary problems, and fluctuations in blood pressure. Mood and psychiatric symptoms such as depression, anxiety, and apathy can arise, sometimes accompanied by hallucinations or delusions. Sleep disturbances such as insomnia, restless leg syndrome, and rapid eye movement sleep behavior disorder (RBD) are also prevalent. Sensory symptoms, fatigue, speech difficulties, and swallowing problems further contribute to the multifaceted nature of PD.

2.3 Treatments

2.3.1 Medications

Medications can be prescribed to help manage the symptoms of PD, including problems walking, movement, and tremors. These medications work by increasing dopamine levels in the brain or mimicking dopamine's effects. PD is characterized by low levels of dopamine in the brain, but dopamine itself cannot be administered directly because it cannot penetrate the brain.

Carbidopa-Levodopa (Rytary, Sinemet, Duopa, others)

Levodopa, the most effective drug for PD, is a natural chemical that can enter the brain and converts to dopamine. Carbidopa is often combined with levodopa (Lodosyn) to prevent early conversion to dopamine outside the brain and reduce side effects such as nausea. However, as the disease progresses, the benefits of levodopa may fluctuate, and involuntary movements (dyskinesia) can occur with higher doses. Inbrija is a brand name drug that delivers carbidopa-levodopa in inhaled form, which can help manage the symptoms that occur when oral medications suddenly stop working during the day. Duopa is a brand-name drug that combines carbidopa and levodopa, administered through a feeding tube to deliver the medication in gel form directly to the small intestine. It is used for advanced Parkinson patients who have significant fluctuations in their response to carbidopa-levodopa.

Dopamine Agonists

These medications do not convert to dopamine but mimic its effects in the brain. They may not be as effective as levodopa but have a longer duration of action. Examples include pramipexole (Mirapex ER) and rotigotine (Neupro).

Monoamine oxidase B (MAO B) inhibitors

Medications such as selegiline (Zelapar), rasagiline (Azilect) and safinamide (Xadago) inhibit the brain enzyme monoamine oxidase B (MAO B), which breaks down brain dopamine. These medications can be used to prevent the wear-off effect when taken with levodopa but can increase the risk of hallucinations.

Catechol O-methyltransferase (COMT) Inhibitors

Entacapone (Comtan) and opicapone (Ongentys) mildly prolong the effects of levodopa by blocking an enzyme that breaks down dopamine. They may cause side effects such as dyskinesia, diarrhoea, nausea, or vomiting.

Anticholinergics

These medications have been used for centuries to control tremors but have modest benefits and can lead to side effects such as memory impairment, confusion, hallucinations, constipation, dry mouth, and urination difficulties.

Amantadine

Amantadine (Gocovri) can be prescribed alone in the early stages of PD or with carbidopa-levodopa in the later stages to treat dyskinesia. Side effects can include changes in skin colour, swelling of the ankle, or hallucinations.

Adenosine receptor antagonists (A2A Receptor Antagonists)

Drugs like istradefylline (Nourianz) target areas of the brain that regulate the dopamine response, allowing more dopamine to be released.

Nuplazid (Pimavanserin)

This medication is used to treat hallucinations and delusions that can occur with PD, although its exact mechanism of action is not fully understood. Each individual's treatment plan may vary, and it is essential to work closely with a healthcare team to determine the most suitable medications and doses for the treatment of PD symptoms.

2.3.2 Surgical procedures

Deep brain stimulation (DBS) is a surgical procedure that is used to alleviate the symptoms of PD. In this procedure, surgeons implant electrodes in a specific region of the brain and these electrodes are connected to a generator implanted near the collarbone. The generator sends electrical pulses to the brain, which can help reduce the symptoms of PD. DBS is typically considered for people with advanced PD who experience unpredictable responses to levodopa medications. It can be particularly effective in stabilizing fluctuations in the effectiveness of medications, reducing or stopping involuntary movements (dyskinesia), reducing tremors, and improving overall motor function.

It is important to note that DBS does not stop the progression of PD itself. Instead, it focusses on the management of symptoms. DBS can be especially beneficial when dealing with problems related to levodopa therapy, including motor fluctuations and dyskinesia.

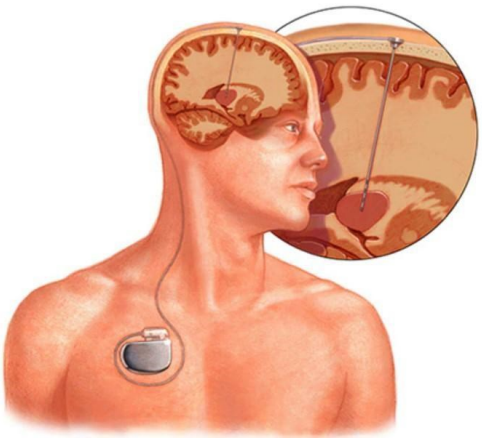

Figure 2 electrodes implanted into the brain during deep brain stimulation (DBS).[31]

Magnetic resonance focused ultrasound (MRgFUS) is a minimally invasive treatment that has shown promise in the management of tremors associated with PD and essential tremors. During this procedure, high-intensity focused ultrasound (HIFU) waves are precisely directed to the brain region responsible for tremors, guided by real-time magnetic resonance imaging. Focused ultrasound generates heat, allowing controlled ablation of targeted neural circuits, effectively reducing or alleviating tremors. MRgFUS provides immediate relief for many patients and represents a promising alternative to traditional surgical interventions for the treatment of tremors in PD.

2.3.3 Rehabilitative treatments

Physiotherapy, also known as physical therapy, is an important component of rehabilitative treatment for people with PD. Physiotherapy involves exercises, manual techniques, and other interventions to improve mobility, balance, strength, and general physical function. In PD, physical therapy can help address specific motor symptoms, such as bradykinesia (slowness of movement), rigidity, and balance impairments, which are common challenges faced by people with the disease. Exoskeletons are innovative rehabilitation tools that can greatly benefit people with mobility challenges, including those with PD. These wearable robotic devices provide external support to the limbs, particularly the legs, helping to walk, stand, and gait training. Exoskeleton-assisted rehabilitation can help individuals improve mobility, regain functional independence, and improve quality of life.

Chapter 3

Gait Analysis

3.1 Definition

Gait analysis is a method for evaluating how people move when walking or running, and it can be performed using observational or instrumented techniques. Observational analysis involves a more subjective assessment where an observer visually examines a person's gait and forms hypotheses about whether their movements deviate from the typical pattern. In contrast, instrumental analysis relies on advanced equipment, such as computerized motion analysis systems, force platforms, cinematography, and electromyography, to precisely measure spatial, temporal, and kinematic variables. These variables include aspects such as the movement and positions of the limbs, joint angles, motion paths, speeds, generated forces, and muscle activity in specific body segments during different phases of the walking or running cycle.

A gait analysis laboratory is a facility dedicated to systematic assessment of human locomotion. It employs a range of advanced tools and techniques, including motion capture systems that use cameras, markers placed on specific anatomical landmarks), and force platforms embedded in the floor. When analyzing gait, the process involves a subject walking on a designated pathway while being recorded by cameras, which capture the three-dimensional trajectories of the markers affixed to their body. These collected data are subjected to biomechanical modelling to determine the underlying movement of skeletal structures, thus enabling a comprehensive understanding of joint kinematics. Kinetic aspects of gait patterns are assessed using force platforms that measure reaction forces and moments on the ground. These platforms provide valuable information on the magnitude, direction, and spatial distribution of the forces generated during each step. However, this kinetic analysis does not provide insight into individual muscle contributions. To address this, surface electromyography (EMG) electrodes are often used to record muscle electrical activity. Anomalies in kinematic, kinetic, or EMG patterns can be indicative of specific pathologies, predict treatment outcomes, or gauge the efficacy of rehabilitation programs, making gait analysis an important tool in clinical diagnostics and biomechanical research.

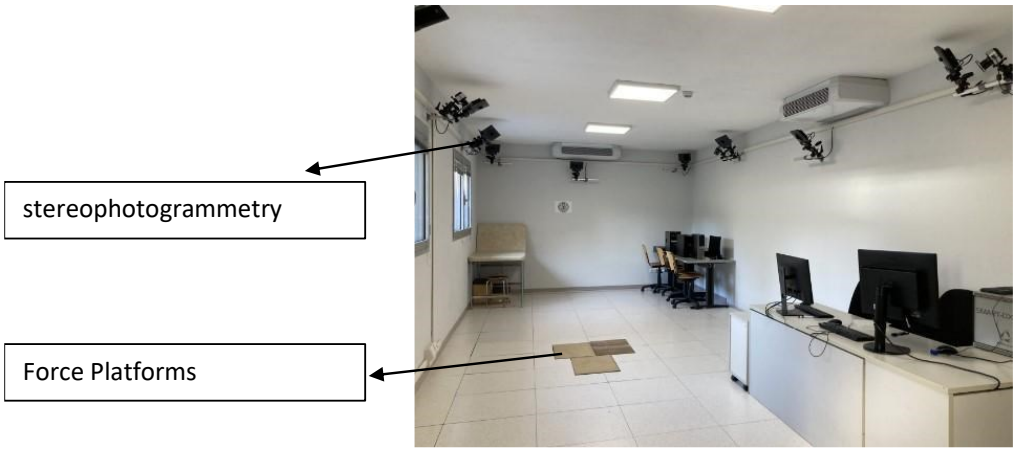

Figure 3.1 Padova University BiomovLab

Gait analysis involves mainly the measurement of three distinct types of data: kinematic data, which capture body movements through motion capture systems; dynamic data (kinetics), which encompass forces and angular moments measured with force platforms and sensors; and EMG data, which record muscle activation signals through surface electrodes.

3.2 Gait cycle

The gait cycle, also known as the walking cycle, is a fundamental concept in biomechanics and human locomotion. It refers to the sequence of events that occur from the initial contact of one foot with the ground to the subsequent contact of the same foot. The gait cycle is divided into two phases: the stance phase and the swing phase.

It is necessary to distinguish between two concepts:

Stride: This is defined as the equivalent of the gait cycle and serves as the fundamental unit of reference in gait analysis. It is defined by the time interval between two successive initial contacts of the same foot and serves as a temporal reference for describing all other biomechanical events and muscle activities during walking.

step: On the other hand, the step refers to the distance between the initial contact of one foot (usually the heel) and the initial contact of the same part of the contralateral foot. It represents a spatial measurement and is typically used to assess step width or other spatial aspects of walking patterns.

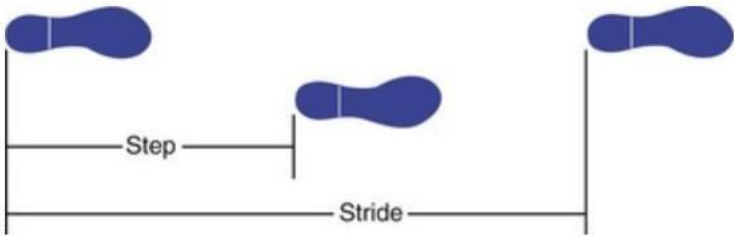

Figure 3.2 The distinction between step and stride

In the context of the gait cycle, several spatio-temporal reference parameters are defined:

Stride length: The length of the strike is determined by the length of the foot in addition to the distance covered during the swing phase.

Step width: The width of the step measures the lateral distance from the heel to the midline of forward progression in the frontal plane.

Cadence: Cadence refers to the number of steps taken within a unit of time, typically measured in steps per minute. Quantifies the speed with which a person walks.

Velocity: Velocity, in the context of gait analysis, represents the speed at which a person is walking. It is often measured in meters per second.

3.2.1 Phases of the gait cycle

As mentioned above, the gait cycle is divided into two phases: the stance phase and the swing phase. During the stance phase, one foot is in contact with the ground, bearing the body weight, while the other foot is in the swing phase, moving forward in preparation for its next contact. The gait cycle is a highly coordinated and repetitive process that is crucial to stable and efficient walking. It serves as a framework for analyzing and understanding various aspects of human movement, including walking patterns, stride length, step timing, and the interaction between different body segments and joints.

The typical time distribution is roughly 60% for the stance phase and 40% for the swing phase. Specifically, within the stance phase, the time is divided as follows: 10% for each of the initial double support and terminal double support intervals and 40% for the single support phase.

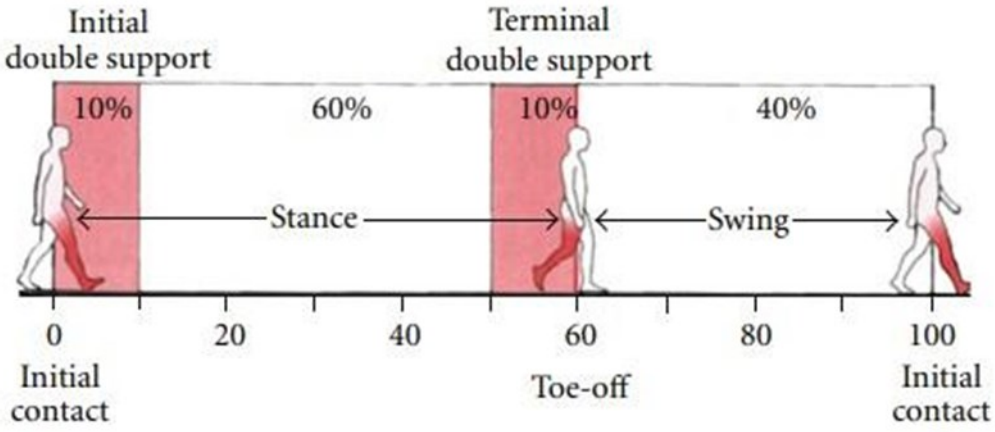

Figure 3.3 Stance and Swing phases [29]

The stance phase can be divided into five distinct phases:

Initial contact (heel strike): This is a very brief phase during which the heel of the forward-projecting foot contacts the ground.

Loading response: It marks the initial period of double support, during which the body begins to respond to the load placed on the leg.

Mid-Stance: This phase covers the first half of the single-support interval. It is the longest phase and begins with the lifting of the contralateral foot. It ends when the foot is fully planted on the ground, with the heel (metatarsus, and toes in contact with the ground)

Terminal Stance: This phase ends the single-support period. It begins with lifting the heel and continues until the other foot encounters the ground. During this phase, body weight is transferred to the forefoot.

Pre-Swing: This final phase of the stance represents the second period of double support in the gait cycle. Here, the transfer of body weight rapidly unloads the limb that is not actively contributing, but instead prepares for the upcoming swing phase.

These five phases collectively describe the intricate sequence of movements that occur during the stance phase of the gait cycle.

On the other hand, the swing phase can be divided into three stages.

Initial Swing: It starts when the foot is lifted off the ground and ends when the swinging limb is parallel to the supporting foot.

Mid-Swing: This phase begins when the swinging limb is directly opposite the supporting limb and ends when the swinging limb advances further, causing the corresponding tibia to become vertical.

Terminal Swing: It begins when the tibia is in a vertical position and ends when the foot is in contact with the ground.

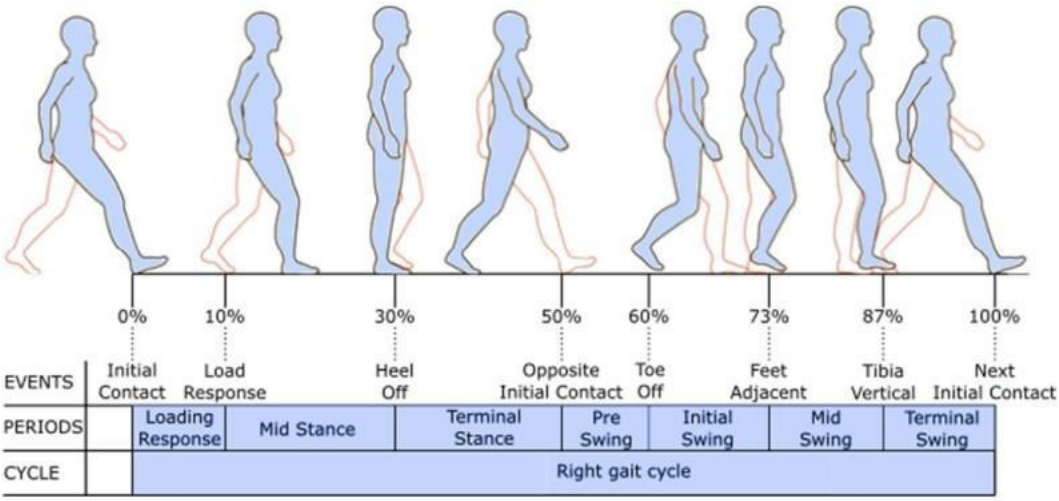

Figure 3.4 The subdivision of the stance and swing phase [5]

3.2.2 The functions of the entire lower extremity during walking

As mentioned above, each of the eight phases of the step serves a distinct functional purpose and is defined by a coordinated movement pattern designed to fulfil that purpose. Furthermore, sequential progression through these phases allows the limb to perform three fundamental tasks: load acceptance, single-limb support, and limb advancement.

- **Load Acceptance**

The load acceptance marks the beginning of the support phase and encompasses the initial two phases of the step.

Phase 1: Heel contact

The interval is 0-2% of the gait cycle.

Event: Positioning of the limb to initiate support with rolling of the heel. The contact with the ground, executed by the heel, generates a sudden and momentary vertical reaction force, as there is a brief free fall of the body by approximately 1 cm. The alignment of the force line with the joints introduces instability in the ankle and hip, while the knee remains stable.

Purpose: Preparation for heel support.

Phase 2: Load Response

The interval is 0-10% of the gait cycle.

Events: Rollover of the heel and transfer of body weight to the supporting limb, which brings the forefoot closer to the ground, resulting in ankle plantarflexion (the toes point downward) and knee flexion (the knee bending). The ankle plantarflexion, driven by the force applied to the heel, helps absorb the impact. Knee flexion, initiated by the action of the pretibial muscles, is sufficient to contribute to impact absorption while maintaining the necessary stability to support the load.

Purpose: Impact absorption, stability under load, and preservation of forward progression.

- **Single Support**

The detachment of the foot against the lateral side for the swing phase marks the beginning of a single support for the limb in contact with the ground. This continues until the lateral side of the foot contacts the ground again. It includes the phases:

Phase 3: Intermediate Support

The interval is 10-30% of the gait cycle.

Events: This phase marks the point at which the vector changes its alignment at each joint. As the limb swings forward over the supporting foot, the key factor of dynamic stability shifts from the knee joint to the ankle joint. The vector becomes orientated anteriorly relative to the ankle and knee joints, while it becomes posteriorly relative to the hip joint.

Purpose: The primary objectives in this phase are to promote the progression of body weight over the supporting foot and maintain stability of the limb and trunk.

The moment generated by the progression, which arises from the lateral swing of the limb and the rolling motion of the heel, results in dorsiflexion of the ankle joint and, in the final phase, extension of the knee joint.

Phase 4: Terminal Support

The interval is 30-50 % of the gait cycle.

Events: During this phase, as the body moves forward onto the forefoot, the ankle joint undergoes dorsal flexion and the heel lifts as the knee finishes its extension. The forward movement of the trunk shifts the vector more towards the front of the ankle joint. Toward the end of the terminal support phase, rotation of the ankle joint/foot complex on the toes moves the knee forward, past the vector, unlocking it and initiating knee flexion.

Purpose: To facilitate the forward movement of the body beyond the supporting foot.

- **Advancement of the Limb**

It begins during the final stage of support (pre-swing), which is essential for correctly positioning the limb. Then it encompasses three distinct movements: lifting, advancing, and preparing for the upcoming support phase as the limb swings through.

Phase 5: Pre-Swing

The interval is 50-60 % of the gait cycle.

Events: During this double support phase, a substantial range of knee flexion begins as the plantar flexes of the ankle joint. As the vector moves forward beyond the metatarsophalangeal joints and the weight is transferred from one limb to the other, it releases the foot to pivot, causing the heel to lift. This action repositions the knee in front of the vector, inducing knee flexion and thigh advancement.

Purpose: To properly position the limb for the swinging phase.

Phase 6: Initial Swing

The interval is 60-73% of the gait cycle.

Events: The initial lifting of the toes signifies the forward movement of the lifted limb. Knee flexion intensifies to detach the foot from the ground. There is a partial reduction in ankle dorsiflexion, while hip flexion causes the thigh to rotate forward.

Purpose: To raise the foot off the ground and advance the limb

Phase 7: Mid-Swing

The interval is 73-87% of the gait cycle.

Events: The detachment from the ground is now influenced by the positions of the ankle joint and the hip. The ankle dorsiflexes until it reaches a neutral position, the hip continues its flexion, and the knee starts to extend.

Purpose: Advancing the limb and lifting the foot off the ground.

Phase 8: Terminal Swing

The interval is 87-100% of the gait cycle.

Events: Hip flexion is stopped, and the knee continues to extend until it reaches a neutral position. The ankle joint remains in a neutral position.

Purpose: Achievement of complete limb advancement and preparation for the next support phase.

3.3 Stereophotogrammetry

Stereophotogrammetry is a technique that is used for precise three-dimensional motion analysis. It relies on optoelectronic systems, which combine optical and electronic components to capture and analyze the motion of objects or subjects. These systems are commonly used in biomechanics and gait analysis to understand how the human body moves during activities such as walking or running. Stereophotogrammetry is a technique that enables the determination of both the position and orientation of a local reference system in relation to a global reference system. When observing a point in motion within a laboratory space, stereophotogrammetry allows us to reconstruct the precise position of that point in the laboratory space at each sampled moment in time. In other words, it provides the x, y, and z coordinates of that point for each moment during the observation period, all with respect to a laboratory reference system. Stereoscopic vision, which is the ability to perceive the three-dimensional nature of objects in our surroundings, is based on the combined input from both of our eyes. In the context of stereophotogrammetry, this means that the use of two cameras is necessary to reproduce this principle and accurately capture the three-dimensional position and movement of objects or points within a given space.

The term rigid body refers to an object with a simple geometric shape in which the distance between pairs of points belonging to it remains constant, regardless of the forces or stresses applied to it. In other words, a rigid body does not deform or change shape when subjected to external forces, and the relative distances between its constituent points remain unchanged. This concept is often used in mechanics and physics to simplify the analysis of motion and forces in various physical systems. Bones are considered rigid bodies, and specific points called anatomical landmarks are used to describe them morphologically. This is done by creating a set of orthogonal Cartesian axes. To represent the movement of the bone, two reference systems are needed: one global reference system, typically the laboratory reference system, and one local on the bone. Six numbers are derived from these systems, where the first three indicate the vector connecting the laboratory reference system to the origin of the bone reference system and the other three indicate how the bone reference system is orientated relative to the laboratory reference system.

Stereophotogrammetry uses markers to track and capture the movement of objects or subjects. These markers are strategically placed on the object or subject of interest to allow cameras to track their positions in a three-dimensional space. Markers can be of two main types: Active and Passive Markers.

Active markers comprise LEDs that autonomously generate the light signal but still require a constant power supply. However, passive markers are typically spherical plastic supports coated

with a reflective material, which is highly visible to cameras due to the application of an optical filter. Optoelectronic systems use cameras operating within the visible or infrared spectrum (wavelength ranging from 780-820 nm). Cameras typically identify these markers as bright points in the scene, often in white. Each video camera, equipped with its lens, is characterised using a mathematical model, and the resulting captured image represents a two-dimensional projection of a three-dimensional scene.

Stereophotogrammetry's main aim is to accurately determine the 3D coordinates (x, y, z) of a point within a recording volume as it moves. This process considers the volume reference frame and the selected sampling frequency to achieve a precise position reconstruction over time.

3.3.1 Camera calibration

Calibration, the process of configuring camera parameters, is essential to ensure the collection of accurate and error-free data. Two distinct types of parameters come into play:

Internal parameters: These parameters are unique to each video camera and encompass characteristics such as focal length and distortion coefficients.

External Parameters: These parameters pertain to the position of the camera relative to the laboratory's reference system.

The initial step in calibrating within a laboratory is to position a set of perpendicular rods, all of which share a common origin. These rods are then captured by each camera, enabling the definition of a single relative system. Calibration using pinhole cameras, where the object's incident ray passes through the camera's optical axis, is the most common method for defining an efficient mathematical mode.

A beam of light from point P in space passes through a small hole and lands on the image plane, creating a point known as "p." Using a coordinate system centered at the camera's viewpoint, with one axis (z) aligned with the camera's lens, we establish the relationship between the coordinates (xp, yp) on the image plane and the coordinates (Xp, Yp, Zp) of points p and P in the camera's coordinate system (C, Xc, Yc, Zc). Then, taking into account the pixel dimensions and the central point of the image, we determine the coordinates (u, v) of point p on the sensor, which is typically located at the bottom right corner of the image plane. Finally, we calculate the coordinates of point Pp in the camera's coordinate system relative to an absolute reference system. Following this initial calibration, referred to as static calibration, we conduct a dynamic calibration to correct for any geometric distortions in the acquired measurements.

An operator moves throughout the entire acquisition volume, shifting an object with known dimensions (a wand), ensuring that the markers attached to it are captured by at least two cameras from different angles at each position. By doing this, the cameras record measurements that might either overstate or understate the actual size of the object. This deliberate setup allows for the calculation of the distortion error for each camera, which can then be corrected.

The images taken by the cameras are two-dimensional and are later analyzed using reconstruction algorithms to create a three-dimensional representation of the observed object. This process is known as triangulation.

In a laboratory environment, it is common for a minimum of six cameras to observe points. This ensures that each point is visible from at least two different angles, which is a necessary condition for successful triangulation.

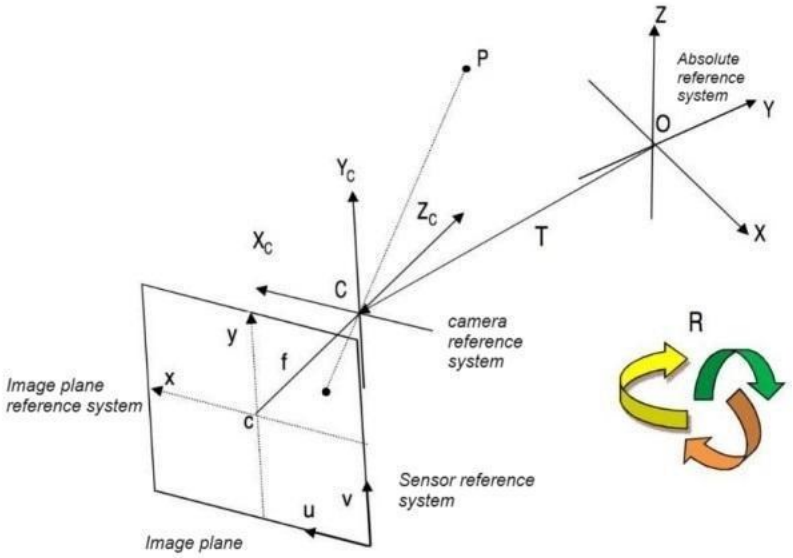

Figure 3. 5 Projecting a point P onto the image plane in the 3D space [6]

3.3.2 Reconstruction and tracking

After the camera calibration, the position of any marker within the working area can be determined. Following reconstruction, the marker recognition step, known as labelling, takes place, which can be performed either automatically or manually. This tracking process can be approached in two primary ways: one, by relying on the regularity of marker trajectories, using mathematical tools to

predict their future positions based on past data, and the other involves leveraging prior knowledge about the subject being studied, such as their shape or movement characteristics. The latter approach is less flexible and applies when specific information is available. In essence, the complexity of the tracking operation hinges on the number of markers used and the nature of the subject's movements under analysis.

3.3.3 Protocols

To ensure the effective functioning of various tracking systems over time, a series of protocols have been developed to capture the gait of specific individuals and process the associated data. When constructing a protocol, it is crucial to establish a set of markers to determine the optimal positioning of technical and anatomical reference systems, define conventions for representing joint angles, and outline methods for estimating inertial parameters.

- **Davis-Hellen Hayes protocol (Davis et al., 1991)**

  The protocol of Davis et al. serves as a reference standard and was developed in relation to gait analysis in children with cerebral palsy. The initial phase of the protocol involves gathering anthropometric parameters of the subject, such as body weight, height, tibia length, distance between the femoral condyles, or knee diameter, along with other parameters related to body segments.

  Marker placement

  - Trunk: Two markers positioned at the right and left sternoclavicular junctions and one at the same height in the spinous process of the sixth cervical vertebra C6.
  - Pelvis: At the level of the two anterior superior iliac spines (ASIS) and at the level of the sacrum, the three points are in the same plane that contains the ASIS and the posterior superior iliac spines (PSIS).
  - Thigh: Greater trochanter, femoral lateral epicondyle, and one on a wand placed 1/3 of the length of the thigh so that the plane containing the three points is parallel to the frontal plane.
  - Leg: Lateral malleolus, head of the fibula, and another on a wand similar to the thigh.
  - Foot: Calcaneus and head of the second metatarsal.

  The protocol includes a static phase in which the subject is still for a few seconds. This helps to establish the initial marker positions relative to the body. When these positions are combined with calculations based on anthropometric measurements, joint rotation centres can be estimated. Following static acquisition, the subject is instructed to walk at their self-perceived normal speed from a fixed starting point. Once a sufficient number of consistent acquisitions have been made, the

data collection session ends. Anthropometric measurements provide data on segment masses and moments of inertia, while marker trajectories obtained through the motion capture system yield information on relative body segment movement, joint angles, velocities, and accelerations. Finally, the joint rotation centres are calculated using equations that incorporate anthropometric measurements.

Helen Hayes, developed in 1990 by Kadaba et al., is quite similar to the Davis protocol, differing mainly in the choice of anatomical reference points, where Davis includes two additional reference points. The Helen Hayes protocol, established in 1990, remains a widely used approach to quantitatively assess differences in gait patterns between healthy and pathological subjects. It involves collecting data on the relative positions and orientations of body segments, ground reaction forces, inter-segment distances, and lower limb muscle activities. Joint angles are measured following the Euler convention's sequence of rotations on the x, z, and y axes. Markers are strategically placed on various body landmarks, but a notable challenge lies in marker alignment, particularly when sticks are used for placement, as they can introduce uncertainty due to potential movements during walking. However, this protocol continues to be a prominent tool for global gait analysis in medical and research fields.

Bone structure	**Description**	**Acronym**
Trunk	Right Sternoclavicular Junction	RS
	Left Sternoclavicular Junction	LS
	C6 Spinous Process	N
Pelvis	Right Anterior Superior Iliac Spine	R
	Left Anterior Superior Iliac Spine	B
	Sacrum	H
Thigh	Greater Trochanter	RH
	Femur	RF
	Femoral epicondyle	RK
Leg	Fibula Head	RP
	Tibia	RB
	Lateral Malleolus	RA
Foot	Second metatarsal head	RT
	Calcaneus	RQ

Table 3.1 Marker set of Davis protocol marker set marker set.

- **CAST protocol, Calibrated Anatomical System Technique (Cappozzo et al., 1995)**

The study by Cappozzo et al. aims to provide a precise quantitative description of joint dynamics and kinematics. This information serves practical purposes in both clinical applications and research studies. Cappozzo et al. investigated problems related to precisely monitoring the positions of bone segments in the pelvis and lower extremities during physical activities using stereophotogrammetry. Therefore, the objective was to provide an experimental protocol for estimating anatomical reference systems that align with adjacent bone segments. These systems are essential to define the orientation and position of a specific bone segment.

The first step in joint kinematics reconstruction involves creating a technical reference system for each body segment based on marker coordinates in the laboratory reference system. Cappozzo et al. quickly pointed out that every technical reference system, due to instrument errors and experimental artefacts, is essentially the result of an estimation calculation. This technical reference system can align with the anatomical reference system and can be determined based on the positions of three non-aligned markers, which are part of a cluster placed on the surface of the bone segment under analysis. This protocol specifies placing the cluster markers in regions where the movement of the soft tissue relative to bone is minimal. This is to minimize the errors caused by soft tissues. The next step involves identifying anatomical reference points without physically attaching markers to them. Instead, we reconstruct their positions over time in relation to the previously established technical reference systems. This procedure is termed anatomical calibration and can be conducted in two different approaches:

- In this procedure, a marker is strategically placed on a specific bony landmark of interest that serves as an anatomical reference point. Using the marker coordinates from the cluster positioned on the bone segment under examination, the marker's coordinates in the technical reference system are determined. The subject is then guided to assume a position that ensures visibility of both the markers within the technical system and the marker on the anatomical reference point by at least two cameras. This step is repeated for each anatomical reference point. Finally, once the positional data for these reference points is captured, the markers used for their identification are removed before the execution of the actual motor activity.
- A practical method involves using a wand with two spherical markers positioned at a known distance from its tip. This wand is carefully directed toward the specific bony landmark of interest, as shown in Figure 3.7. By measuring the separation distance between the markers on the wand and its endpoints, we can accurately determine the position of the anatomical reference point within the technical reference system. It is essential to ensure that both the rod markers and those within the cluster remain visible to at least two cameras during this procedure. This step is repeated for each anatomical reference point. This method is

typically more practical, especially when the anatomical reference point is located in an inconvenient or challenging location.

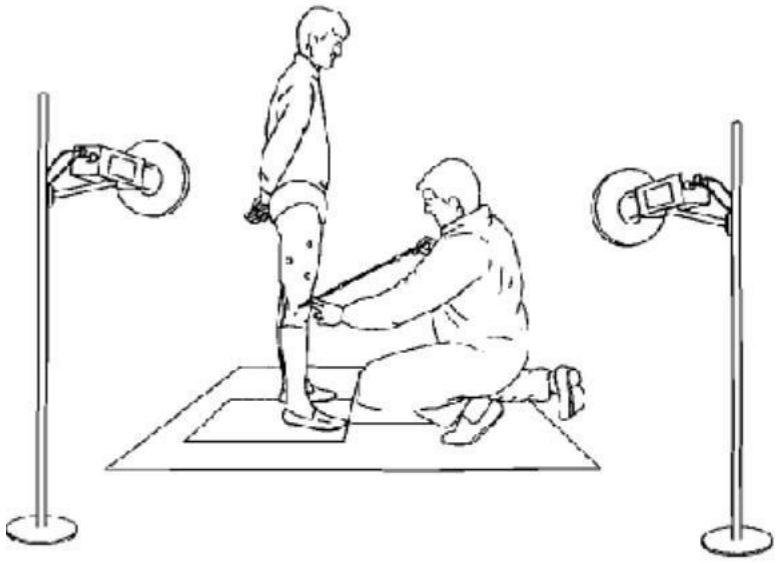

Figure 3.7 Calibration with a wand for anatomical landmarks in the femur [22]

Cappozzo et al. also emphasised that it is possible to determine the position of an anatomical reference point within its relative reference system by assuming that, during a particular posture, it aligns with another reference point that can be calibrated more easily.

Bone structure	**Description**	**Acronym**
Pelvis	Anterior superior iliac spine	ASIS
	Posterior superior iliac spine	PSIS
	Centre of the Acetabulum	AC
Femur	Centro della testa del femore	FH
	Prominenza del gran trocantere	GT
	Epicondilo mediale	ME
	Epicondilo laterale	LE
	Apice anterolaterale della superficie patellare	LP
	Apice antero-mediale della superficie patellare	MP
	Condilo laterale	LC
	Condilo mediale	MC

Leg	Intercondylar Eminence	IE
	Prominence of tibial tuberosity	TT
	Apex of the Head of the Fibula	HF
	Distal medial malleolus apex	MM
	Apex of the distal lateral malleolus	LM
	Medial point of the tibial surface	MMP
	Lateral Point of the Fibular Surface	MLP
Foot	External Calcaneal Prominence	CA
	Dorsal Surface of the First Metatarsal Head	FM
	Dorsal Surface of the Fifth Metatarsal Head	SM

Tabel 3.2 Anatomical points according to the CAST protocol

- **IORgait Protocol (Leardini, Sawacha et al., 2007)**

In 2007, a team of researchers led by Leardini introduced a protocol aimed at addressing the compromises inherent in previous methods. This protocol was developed to strike a balance between conflicting objectives. Its primary goal is to reduce measurement discrepancies between different operators and within the same operator while ensuring a precise definition of anatomical planes. Drawing inspiration from the CAST method for establishing anatomical reference systems, this protocol diverges from the CAST by utilizing an anatomical cluster. This choice sacrifices some precision in estimating anatomical points, in contrast to CAST's technical cluster designed to minimize errors arising from soft tissues. Furthermore, the protocol incorporates time-saving techniques borrowed from the Davis method. In this protocol, markers are placed on specific body landmarks. These landmarks are chosen because they are easily visible to cameras and help reduce measurement errors. Three of these landmarks are calibrated using an anatomical method with a wand, similar to the CAST protocol. This protocol follows the Grood & Suntay convention for calculating joint angles.

This protocol results in a significant reduction in the number of required calibrations, dropping from a total of thirty-three to just six. An interesting feature of this protocol is the absence of technical clusters, which makes it particularly suitable for specific applications. For example, it is ideal for analyzing the gait of pediatric patients, where there may be limited anatomical space available to place these technical groups.

In summary, the IORgait protocol strikes a balance between the Davis and CAST protocols, inheriting strengths and potential limitations from both. It shares the robustness of the Davis protocol but faces the same limitation of marker placement on anatomical landmarks and defining the technical cluster. However, it differs from the Davis protocol by not requiring wands and by utilizing anthropometric measurements, eliminating associated errors.

Bone structure	Description	Acronym
Pelvis	Anterior right iliac spine	RASIS
	Anterior left iliac spine	LASIS
	Posterior right iliac spine	RPSIS
	Posterior left iliac spine	LPSIS
	Centre of the femoral head	FH
Femur	Greater trochanter	GT
	Lateral epicondyle	LE
	Medial epicondyle	ME
Leg	Head of the Fibula	HF
	Prominence of the tibial tuberosity	TT
	Lateral malleolus	LM
	Medial malleolus	MM
Foot	Calcaneus	CA
	Fifth metatarsal head	Vm
	First metatarsal head	Fm

Table 3.3 Anatomical reference points as specified by the IORgait protocol.

3.3.4 Stereophotogrammetry errors

Stereophotogrammetric systems can be affected by inherent and external errors within the system, which can influence the precision and accuracy of kinematic variable estimation. The primary types of errors are as follows.

1. Vision system uncertainty:

Instrumental errors in stereophotogrammetric systems are introduced by all components of the system, especially cameras. The accuracy of reconstructing a marker's position is highly dependent

on the camera's resolution. The higher resolution allows for the correct definition of the marker shape, area, and position. This category encompasses systematic errors (low frequency), caused by inaccuracies in the measurement model or calibration, leading to poor estimation of parameters of interest, and random errors (high frequency), such as electrical noise, flickering, and sampling errors.

Instrumental errors can be calculated using calibration tools called "spot-checks". These tools involve measuring the known distances between markers to assess the extent of the error. Performing spot checks, which are straightforward tests, verifies the system's performance.

Marker distance measurement tests: These tests are designed to evaluate the performance of the system by monitoring the consistency of the relative distances between markers throughout the measurement volume. Notable examples include:

- Pendulum test: This test uses a rigid pendulum equipped with two markers. It involves capturing 3D data as the pendulum completes two oscillations (2D) in orthogonal planes.
- Full-Volume Test: In this test, a rigid wand with two markers is moved at a constant speed along each axis within the measurement space.
- Walking test: During this test, an operator walks while placing his feet on markings with a bar (a wand with two markers) at various orientations.
- Marker Alignment Line Test: This test acquires data from a stationary rod while it rotates around a known point in the laboratory reference frame. The tip of the rod serves as the pivot point for this evaluation.

Marker displacement measurement: This category involves assessing marker displacement within the measurement field, often employing a motorized device capable of applying known motions to the markers.

These tests play a crucial role in assessing the accuracy and reliability of the system by examining marker behaviour and displacement under controlled conditions. Precision and accuracy are based on setup parameters such as camera positions, number of cameras, measurement field size, calibration tools, and user attention. To minimize systematic errors, prioritise precise calibration and use available filtering methods. It is also good practice to assess any remaining experimental errors with spot checks before each session.

2. Uncertainty due to a mismatch between actual and expected marker placement:

Errors in marker localization can arise because markers are positioned on the body's surface rather than directly on an anatomical landmark. This type of error can be minimized by taking extra care in the anatomical calibration procedure but cannot be entirely eliminated.

Errors can also occur due to soft tissue artefacts. In motion analysis, it is often assumed that the cluster of markers on a body segment remains firmly attached to the underlying bone. However, during actual movement, the skin and soft tissues can cause markers to move relative to the

underlying bone. This type of error is challenging to correct because it has a frequency similar to joint motion, making filtering techniques ineffective. Markers are not fixed to the underlying bone. When performing a motor task, there is relative movement between the markers and the corresponding bone segment. In other words, the position of the anatomical reference point in the technical reference system varies over time. This type of error can be in the range of several centimeters. Marker coordinate errors affect both the technical and anatomical systems. The objective is to have minimal displacement and spread of errors. To achieve this, an optimal marker cluster design is introduced with the aim of minimizing error propagation from marker coordinates to bone-linked reference position and orientation.

Soft tissue artefacts have two main components:

Deformation: This can be easily eliminated using rigid plates (Solidification, Deformable Surface Modelling, and Point Cluster Technique).

Rigid displacement: Identifying this component is challenging and requires compensation methods such as dynamic calibration, global optimization (creating joint models where all joints are considered spherical, resolving all possible movements), and multiple calibration (processing dynamic calibration data).

3.4 Force platform

A force platform is a device consisting of an instrumented plate (typically rectangular) that measures the force exchanged between a subject's foot and the ground. Measure three components, namely, x, y, and z, of the resultant forces and applied moments. It is always possible to estimate the magnitude, direction, point of application (centre of pressure, COP), and orientation of the force.

A force plate uses load cells to measure forces, and these load cells can incorporate various technologies, such as piezoelectric elements, strain gauges, or beam load cells.

Electrical signals are processed to provide measurements of force and torque. Force transducers based on strain gauges have an elastic element or load cell to which the forces to be measured are applied. Under load, the elastic element generates deformation on its surface. The elastic element converts the forces to be measured into deformation in the most reproducible and linear manner possible. The actual sensing component is the strain gauge, which consists of an insulating layer (support) and the embedded measuring grid. The strain gauges are adhered to the elastic element. Typically, four strain gauges are used, arranged so that two are stretched and two are compressed by the applied force. These four strain gauges are connected in a circuit known as a Wheatstone

bridge, powered by the supply voltage, and it consistently produces an output voltage when the four resistances are different.

The 4 triaxial strain gauges (load cells) form a 12-channel system. The magnitude of the external force is obtained by adding the forces measured by the individual cells. The torque with respect to the centre of the platform is measured as follows:

$$\{C_x = \frac{\Delta y}{2}(-F_{1z} - F_{2z} + F_{3z} + F_{4z})\; C_y = \frac{\Delta x}{2}(F_{1z} - F_{2z} + F_{3z} - F_{4z})\; C_z$$

$$= \frac{\Delta x}{2}\left(-F_{1y} + F_{2y} - F_{3y} + F_{4y}\right) + \frac{\Delta y}{2}(F_{1x} + F_{2x} - F_{3x} - F_{4x})$$

For Fz 0, the point of application of force relative to the center of the platform (center of the force platform) is determined as follows: $\{x_F = \frac{Cx}{F_z}\; y_F = \frac{Cy}{F_z}$

The values of forces and moments, denoted Q, are derived from a calibration matrix A, which is obtained by experimental measurements of the various sensors (s). Q = As

Piezoelectric materials are a type of material that can generate an electric charge when subjected to mechanical stress or pressure. This electric charge is directly proportional to the amount of mechanical stress applied to the material. To make use of this effect in practical applications, a charge amplifier is often used to convert the generated electric charge into a voltage signal, typically within the range of 0 to 10 volts. The key relationship here is that the magnitude of the voltage produced is directly related to the magnitude of the applied mechanical stress: the greater the mechanical stress, the higher the voltage output. The advantage of using piezoelectric sensors is their versatility in covering a wide range of measurement requirements. They can be used to measure very small or extremely large forces simply by adjusting the sensitivity of the measurement equipment. However, one drawback to consider is that piezoelectric sensors may experience drift when subjected to prolonged static loads, which can affect their long-term accuracy and stability.

In summary, piezoelectric sensors convert mechanical stress into an electric charge, which is then further transformed into a voltage signal. The voltage output is directly proportional to the applied mechanical stress, which makes piezoelectric sensors valuable tools for measuring a wide range of forces and pressures.

3.5 Surface Electromyography

Electromyography measures the electric potentials that develop within the muscle during contractions. Recording electrodes can be either insertion electrodes (when in contact with the motor unit) or surface electrodes (on the skin). Surface electrodes are less precise as they measure multiple motor units but are also noninvasive.

Individual potential mirrors the activity of a single motor unit in the case of insertion electrodes or a group of motor units in the case of surface electrodes. These potentials are generated by the electrical depolarization of muscle fibers in response to a stimulus from the neuromuscular junction. The motor unit action potential (MUAP) represents the combined electrical activity of the motor unit, consisting of a motoneuron and its associated muscle fibers. More muscle fibers lead to more action potential. Consequently, MUAP is the sum of these actions.

3.5.1 Signal acquisition methods

Monopolar Configuration: In this setup, one electrode is placed on the muscle, and another electrode is placed indifferently on a non-muscle part of the body. This configuration has the disadvantage of recording all electrical signals, including noise in the vicinity of the measurement area, and is less specific when trying to record myoelectric signals from a small portion of the body.

Bipolar Configuration: Two electrodes are placed on the muscle and the potential between them is recorded. The two recording surfaces detect two potentials relative to a common reference point. The two signals are subtracted from each other and amplified.

Double-Differential Configuration: This set-up employs three equally spaced electrodes, resulting in two differential signals and one double-differential signal. This technique is used to achieve higher spatial resolution (greater precision) or to estimate the conduction velocity. An advantage is that it attenuates signals due to artefacts.

Multiple Differential Channel Configuration: Three or more equally spaced electrodes are used, providing at least two differential channels. This technique is used to estimate the conduction velocity and observe the propagation of the signal along the fibers.

3.5.2 Signal Processing in Electromyography

Signal processing in EMG mainly involves amplification and filtering. The goal is to identify muscle activity, duration, and intensity from raw EMG data. Other processes include rectification (converting to absolute values) and techniques such as averaging or root-mean square, which represents the square root of signal power over a specific time interval. Linear envelopes and integration are also used. During sustained isometric contractions, myoelectric signals, whether voluntary or electrically induced, exhibit time-varying characteristics (non-stationary signals). These signal variations reflect physiological and pathological events that characterize the muscle of interest. One of the key forms of non-stationarity is signal slowing, with other variations related to amplitude and shape. It is important to define indices that can describe the properties of signals and their time-dependent variations, including the descriptors of amplitude, spectrum, and shape.

Chapter 4

Rehabilitation Treatments

4.1 Exoskeleton

Exoskeletons represent a significant technological advancement that aims to enhance human physical capabilities and overall quality of life. These wearable devices are intricately designed to collaborate with users, offering the potential to enhance physical performance and perform a wide range of tasks. Exoskeletons can be classified on the basis of their structural characteristics (rigid or soft), mode of action (active or passive), the technology driving them (including hybrid systems), and their intended purpose (assistance or rehabilitation).

The development of exoskeletons has a rich historical timeline, dating back to the 19th century with early devices like Nicholas Yagn's creations, which aimed to facilitate walking, running, and jumping using mechanical systems. This established the foundation for modern exoskeletons, emphasizing the principle of task facilitation. In the twentieth century, Lesley C. Kelley designed a device for walking and running assistance, and the 1960s marked a significant turning point with creations like the "Hardiman I" and Neil J. Mizen's exoskeleton, showcasing the use of technology to augment human capabilities. The subsequent decades saw a wide variety of exoskeletons developed for specific purposes, from arm support orthoses to leg propulsion devices. The 21st century brought about advances in computing and software, enabling the development of more sophisticated exoskeletons, such as the Berkeley Lower Extremity Exoskeleton (BLEEX) designed to carry external loads. The era also witnessed a shift toward personalized exoskeletons tailored for specific pathologies or user-intended movements, exemplified by designs like the motion assist device. The evolution of exoskeleton technology has been closely tied to advances in science and technology, with a growing trend in research and development in recent years. This review aims to classify exoskeletons based on their design characteristics to provide a comprehensive model for understanding and categorizing this evolving field.

Exoskeletons are versatile devices that can be used to address a wide range of physical conditions, from pathologies and traumas to degenerative conditions and malformations. This versatility has led to the development of numerous exoskeleton models, each tailored to specific needs. To make

sense of this diversity and provide a structured overview of the field, a general classification system is essential. A comprehensive general classification is required to categorize exoskeletons according to their design characteristics.

Body Part-Focused Category: This classification categorizes exoskeletons according to the specific body part to which they are designed to support. It distinguishes between "full-body" exoskeletons, "lower-body" exoskeletons, and "upper-body" exoskeletons, as well as those tailored for specific limbs or joints. This categorization clarifies what part of the body an exoskeleton is meant to assist.

Structure Category: Exoskeletons fall into two main structural categories: "rigid" and "soft." Rigid exoskeletons are built for durability and are often intended for challenging environments that are capable of carrying the user's weight. In contrast, soft exoskeletons, often called exosuits, are more commonly used in everyday settings. They are designed to be lightweight and form-fitting.

Action Category: Exoskeletons can be categorized on the basis of the type of action they provide. This results in two primary groups: "passive" and "active." Active exoskeletons actively assist or even perform movements for the user, while passive exoskeletons are designed for users with reduced strength but who can still carry out activities with assistance.

Powered Technology Category: Exoskeletons are powered by various technologies and can be categorized on the basis of these technologies. Hybrid exoskeletons are the most common and combine multiple technologies, such as electrical and mechanical systems. Electric actuators are also prevalent, offering precise control. Hydraulic and pneumatic actuators are less common due to the need for a fixed source of fluid or compressed air. Mechanical exoskeletons, which lack a power source, fall into the passive category.

Purpose Category: Exoskeletons are designed with specific purposes in mind and fall into two main categories: "performance" and "recovery." Performance exoskeletons are designed to improve physical capabilities, while recovery exoskeletons focus on addressing specific pathologies and medical conditions. Some exoskeletons serve two purposes, offering versatility in their applications.

Application Area Category: Exoskeletons can also be classified according to the application areas they target. This classification includes categories such as research, civilian use, clinical use, industrial use, military use, or multiple areas. It helps to understand where exoskeletons are intended to be used and for what specific purposes.

Exoskeleton technology is gaining traction in the healthcare arena, with a particular focus on its potential to help people with Parkinson's disease. Wearable exoskeleton devices, designed to provide mechanical support and assistance, are promising in addressing several key aspects of

Parkinson's disease management. The first among the advantages of exoskeletons in the context of Parkinson's disease is their ability to aid in walking. Many people with Parkinson's face difficulties related to their gait, such as shaking or experiencing episodes of freezing. Exoskeletons can provide mechanical support to the lower extremities, resulting in more fluid and efficient walking. In addition, these devices can offer clues and guidance, helping individuals overcome debilitating episodes of freezing. Another critical aspect that exoskeletons can address is balance and posture. Specially designed exoskeletons can provide the necessary support, allowing users to stand up and reducing the risk of falls. Fatigue is a common challenge for those living with Parkinson's disease, and exoskeletons have the potential to alleviate this problem by providing assistance with leg movements. Through mechanical support, exoskeletons reduce the physical effort required to walk, allowing individuals to cover greater distances with reduced fatigue. Exoskeletons are also finding a role in rehabilitation and physical therapy. They offer a structured and repetitive approach to help individuals improve motor function.

4.1.1 EKSO exoskeleton

During this thesis, the patients use the EksoGT exoskeleton of the EksoBionics Holdings Inc. company. The EksoGT is a high-tech wearable robot created to help people who have difficulty walking and standing due to mobility challenges. It uses sensors, motors, and mechanical elements to provide vital support and improve the user's ability to move. This wearable robot employs sensors that can sense user actions and intentions, including devices such as accelerometers, gyroscopes, and load sensors. These sensors continuously monitor the user's body position, balance, and walking patterns. The information collected by these sensors is processed by a control system that combines hardware and software. This control system interprets the user's actions and decides how the EksoGT should respond. The mechanical framework of the EksoGT is powered by electric motors and actuators. These components create the necessary forces to assist the user, especially when the control system determines that support is required, such as helping the user stand up or take a step.

Figure 4.1 EksoGT exoskeleton [33]

The design of the mechanical structure of EksoGT mimics the natural human skeleton, incorporating sturdy frames and joints strategically placed to provide support for the user. To ensure extended mobility and support, the EksoGT is based on a rechargeable battery or power source that powers the motors and control system. This arrangement enables the user to move around for an extended period of time before requiring a recharge. Using sensors, motors, and mechanical elements, it offers real-time feedback and customized gait training, helping people regain their walking abilities and refine their gait over time, often as part of a rehabilitation program.

4.2 Physio kinesiotherapy

Physio kinesitherapy, also called physiotherapy or physical therapy, is a field of health care that deals with physical problems and injuries. It uses exercises, manual treatments, and physical techniques to help people move better, reduce pain, and improve their overall physical health. Physio kinesiologists create personalized treatment plans that often include exercises to strengthen muscles, increase flexibility, and restore normal movement. It is commonly used for recovery after injuries or surgeries and to manage ongoing health problems. The main objective of physio kinesitherapy is to ensure that people can move well and feel less pain. Physio kinesiologists provide specialized care for people with Parkinson's disease, using various approaches to improve mobility and quality of life. They begin by assessing the specific needs of each patient, focusing on improving posture, balance, and muscle strength through customized exercises and training. These therapists also use techniques to address problems such as gait freezing, offer guidance on symptom

management, and suggest home exercises. The overarching objective is to enhance daily functioning and reduce the risk of falls, allowing individuals with Parkinson's to maintain independence and enjoy an improved quality of life.

Physiotherapists employ a wide range of exercises and techniques when working with people with Parkinson's disease, such as conventional physiotherapy, treadmill training, strategy training (including cueing), martial arts, Nordic walking, resistance training, aerobic exercises, balance and gait training, and other physiotherapy techniques.

Chapter 5

Materials and Methods

This thesis is part of a project carried out in collaboration with the Villa Margherita Rehabilitation Centre (Vicenza, Italy). The aim of the project is to evaluate the comparative effectiveness of various rehabilitative treatments on gait patterns in patients with PD with a focus on rehabilitation through the exoskeleton.

In this thesis, a subset of the original dataset was analyzed. In particular, two cohorts of subjects with PD were evaluated. Both cohorts underwent a training rehabilitation period of 4 weeks; the first was with an exoskeleton (Ekso Bionics Holdings Inc., EKSO group), while the other was with classic physiotherapy sessions (FKT group). Acquisitions in the gait laboratory of Villa Margherita were performed right before (T0) and after the training period (4weeks, T1). A comparative analysis was performed to assess and examine the disparities in various parameters between T0 and T1 within both cohorts. The parameters assessed encompassed spatio-temporal aspects, including stride and step length, cadence, and velocity, as well as kinematic factors such as joint angles. Furthermore, the analysis took into account kinetic elements, such as forces and joint moments, and EMG. The analysis was carried out individually for T0 and T1 within each group, specifically for Ekso (T0 and T1) and Fkt (T0 and T1). Furthermore, an evaluation was performed between the measurements T0 and T1 for each independent group, evaluating comparisons between T0 for Fkt and T0 for Ekso, as well as between T1 for Fkt and T1 for Ekso.

Figure 5.1 This figure illustrates the progression from "T0", representing data collected before any interventions, to "T1," which denotes data acquired after the implementation of rehabilitation treatment.

5.1 Participants

In this thesis, six subjects with PD were evaluated. Demographic data for participants can be found in Table 5.1.
As anticipated, the subjects were divided into two groups: the Ekso group, which received treatment with the Ekso exoskeleton, and the physiotherapy group (FKT group).

	Height (cm)	Weight (kg)	BMI (kg/m^2)	Age (years)
Ekso				
Subject 1	183	90	26.87	82
Subject 2	160	53	20.70	73
Subject 3	177	90	28.72	72
Fkt				
Subject 4	177	70	22.34	67
Subject 5	160	52	20.31	58
Subject 6	170	70	24.22	75

Table 5.1 Demographic data of participants in two groups

5.2 Data Acquisition

To collect biomedical and biomechanical data, a Vicon 8 camera stereophotogrammetry system was used. This system operates at a frequency of 120 Hz. The stereophotogrammetry system employs eight cameras strategically positioned to track reflective markers placed on the subject's body according to the Iorgait protocol, allowing for precise motion capture. Additionally, two force platforms were used. These force platforms (Bertec and AMTI Corporation in the USA) operate at a frame rate of 960 Hz. In addition, an EMG system (Cometa Wave Plus System), was incorporated into the setup. This EMG system operates at a frequency of 1000 Hz. The three systems work together in synchronization.

5.3 Pre-processing of the data

Data was preprocessed using Nexus Vicon software. The initial step of this preprocessing involves the selection of six dynamics (three for the left foot and three for the right foot) from each subject. Subsequently, these selected datasets are imported into the Nexus Vicon software interface. Following this, the next step involves checking all markers on the subject. If any markers are lost, the process includes reconstructing their trajectories.

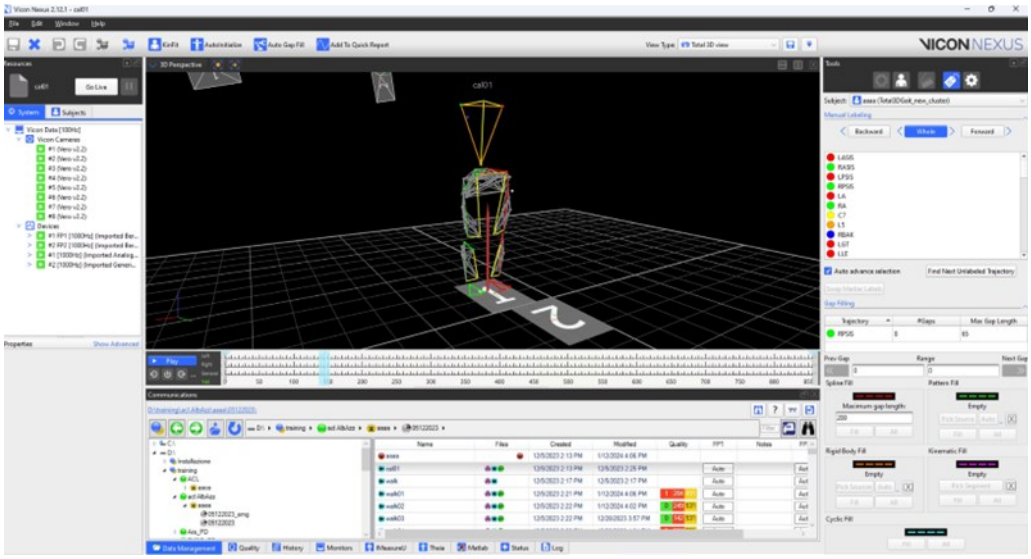

Figure 5.2 Software Vicon Nexus

Manually label 3D marker reconstructions:

The process begins with subject calibration, where the system is configured to accurately capture the individual's movements. Subsequently, the "reconstruct and label" processing task is executed to reconstruct the three-dimensional motion and assign labels to markers or body parts. To address potential data gaps, gap filling methods are employed, utilizing algorithms to estimate missing values.

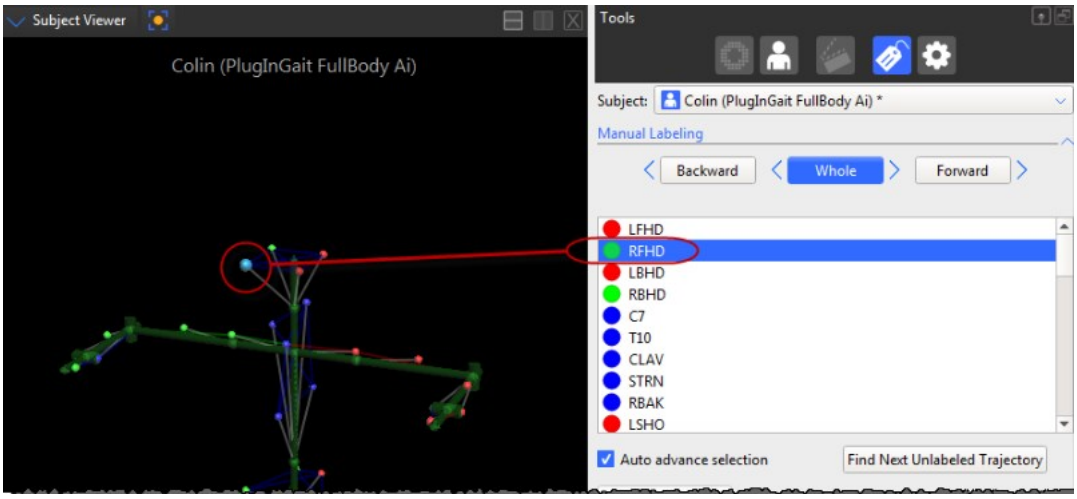

Figure 5.3 Manually label 3D marker reconstructions.

After 3D reconstruction and assigning labels to markers for each subject, instances of foot contact, lift-off, and recontact were identified for the right and left feet before and after treatment. A critical step involved reviewing these instances, specifically checking for any gaps in the markers. If such gaps were identified, the procedure required resolution and filling to ensure the completeness of marker data.

The fill options are as follows:

- **Spline Fill:** Execute a cubic-spline interpolation operation to fill the currently selected gaps. This option is suitable when there are frames without gaps on both sides of the gap; if there are gaps in these frames, the fill is rejected, necessitating an alternative gap-filling method.
- **Pattern Fill:** Using the shape of another trajectory without a gap to fill the selected gap. This tool is appropriate when there is a suitable marker with a trajectory akin to that intended for gap filling, typically when trajectories originate from markers attached to the same segment (e.g., ankle or heel markers).
- **Rigid body Fill:** Nexus's equivalent of the Bodybuilder's Replace 4 option. This option is suitable when a rigid or semi-rigid relationship exists between markers.
- **Kinematic Fill:** Using information on the connection of markers to segments in the labelling skeleton template (VST). To access this option, the Kinematic Fit pipeline operation may need to be run by activating the Kin Fit button on the Nexus toolbar.

In the course of this thesis, rigid body, pattern, and spline options were applied to fill gaps.

5.4 Elaboration of the data

To analyze and extract essential variables, codes developed at BioMovLab were used. Using these codes, angles, EMG, and spatio-temporal data were extracted for each subject before and after

treatment. Furthermore, forces and moments were analyzed for subjects who stepped on force plates. All analyses were performed using MATLAB R2022a.

5.5 Comparisons

A group of healthy subjects (BiomovLab database) was used as reference data to compare pathological groups. In the current study, a comparative analysis was performed on all extracted kinematics, kinetics (forces and torques), EMG, and spatio-temporal parameters between T0 and T1 of the Ekso groups, T0 and T1 of the Fkt groups, T0 of Fkt and T0 of the Ekso groups, T1 of Fkt and T1 of Ekso. Data was collected and represented graphically. In each diagram, three different colors were used to distinguish between the Fkt, Ekso, and healthy groups. Statistical parameter mapping (SPM) [26] was used and a t-test was used for statistical analysis, with a significance level set at $p < 0.05$ with Bonferroni correction. The statistical method of the t test has been used to determine if there is a significant statistical difference between the groups involved.

Furthermore, two statistical tests, the Wilcoxon signed rank test and the Wilcoxon-Mann-Whitney test, were used using MATLAB to compare spatio-temporal parameters collected from each group at both T0 and T1. The Wilcoxon signed rank test was used to detect differences between T0 and T1 within each group. This analysis encompassed spatiotemporal parameters (space and step width, time, velocity, stance, swing, and cadence) parameters. The comparison was made within the Ekso and Fkt groups separately. The Wilcoxon-Mann-Whitney test was used to discern differences in spatio-temporal parameters between T0 and T1 within independent groups. This comparison specifically involved T0 of Fkt and T0 of Ekso, as well as T1 of Fkt and T1 of Ekso.

Chapter 6

Results and Discussion

In this section, results related to the comparison of Joint angles, forces, torques, and EMG data are presented, as well as statistical results of spatio-temporal parameters. These comparisons include T0 for the Ekso and Fkt groups, T1 for the Ekso and Fkt groups, and the comparison of T0 and T1 for both the Ekso and Fkt groups with the control group.

The joints angles of Trunk (adduction-abduction, internal-external rotation, flexion-extension), pelvis (internal-external rotation, obliquity, tilt), hip (adduction-abduction, internal-external rotation, flexion-extension), knee (flexion-extension) and ankle (eversion-inversion, internal-external rotation, plantar-dorsiflexion) were collected: Each graph displays Joint angle values on the y-axis and percent of gait cycle on the x-axis.

The torques are collected from the hip (add-abd, intra-extra, flex-ext), knee (var-val, intra-extra, flex-ext), and ankle (inv-env, intra-extra, dorsi-plantar). Each graph displays Torque values on the y axis and the percent of gait cycle on the x axis.

In addition, ground reaction forces are analyzed and divided into three graphs: medial-lateral, vertical, and anterior-posterior forces.

As regards EMG, results from the anterior tibialis, gastrocnemius, rectus femoris, and biceps femoris are presented.

In each graph, the results of the statistical tests are represented using three different colours: one colour for the T0 vs Control group, another for the T1 vs Control group, and black for the comparison of the two groups. The color of groups are blue for Ekso T0 , Red for Ekso T1,yellow for Fkt T0 and Green for Fkt T1.

These bars indicate the results of the statistical T test [25] with a significance level of $p < 0.05$ with Bonferroni correction, highlighting a statistically significant difference during gait.

6.1 Angles

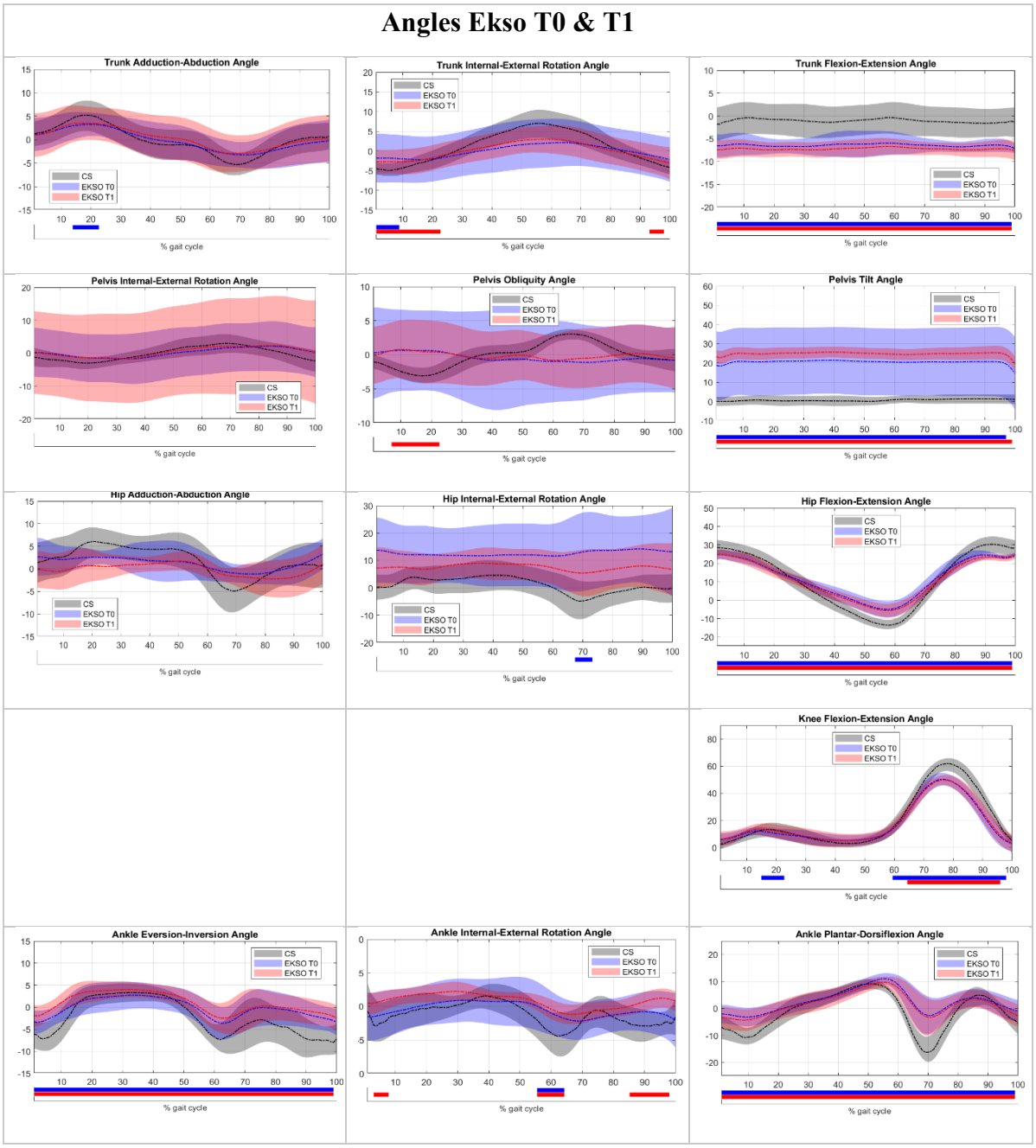

Figure 6.1 Graphs related to kinematics data. The figures illustrate three groups: T0 and T1 from the Ekso groups, and Cs representing the Control group.

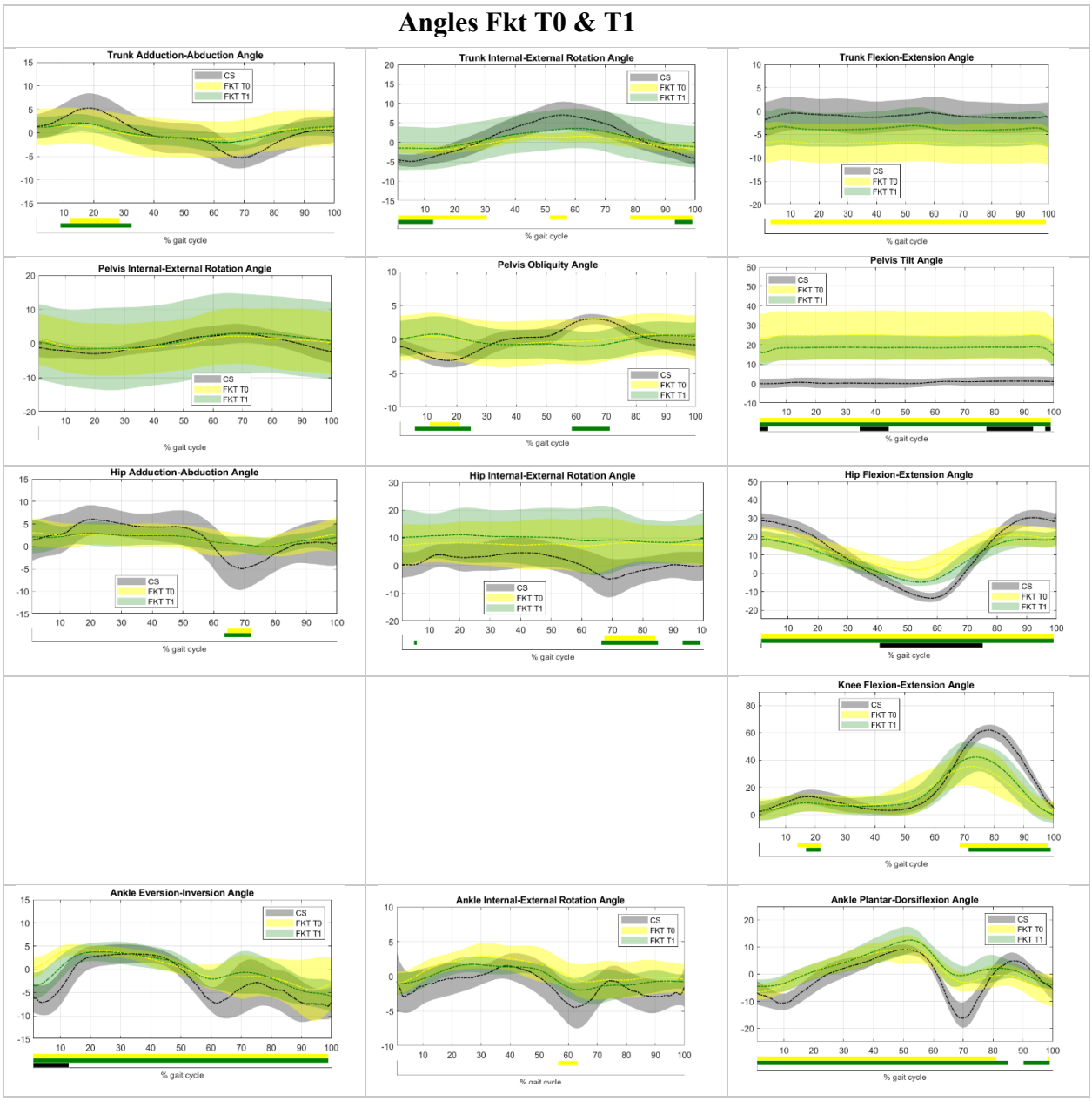

Figure 6.2 Graphs related to kinematics data. The figures illustrate three groups: T0 and T1 from the Fkt groups, and Cs representing the Control group.

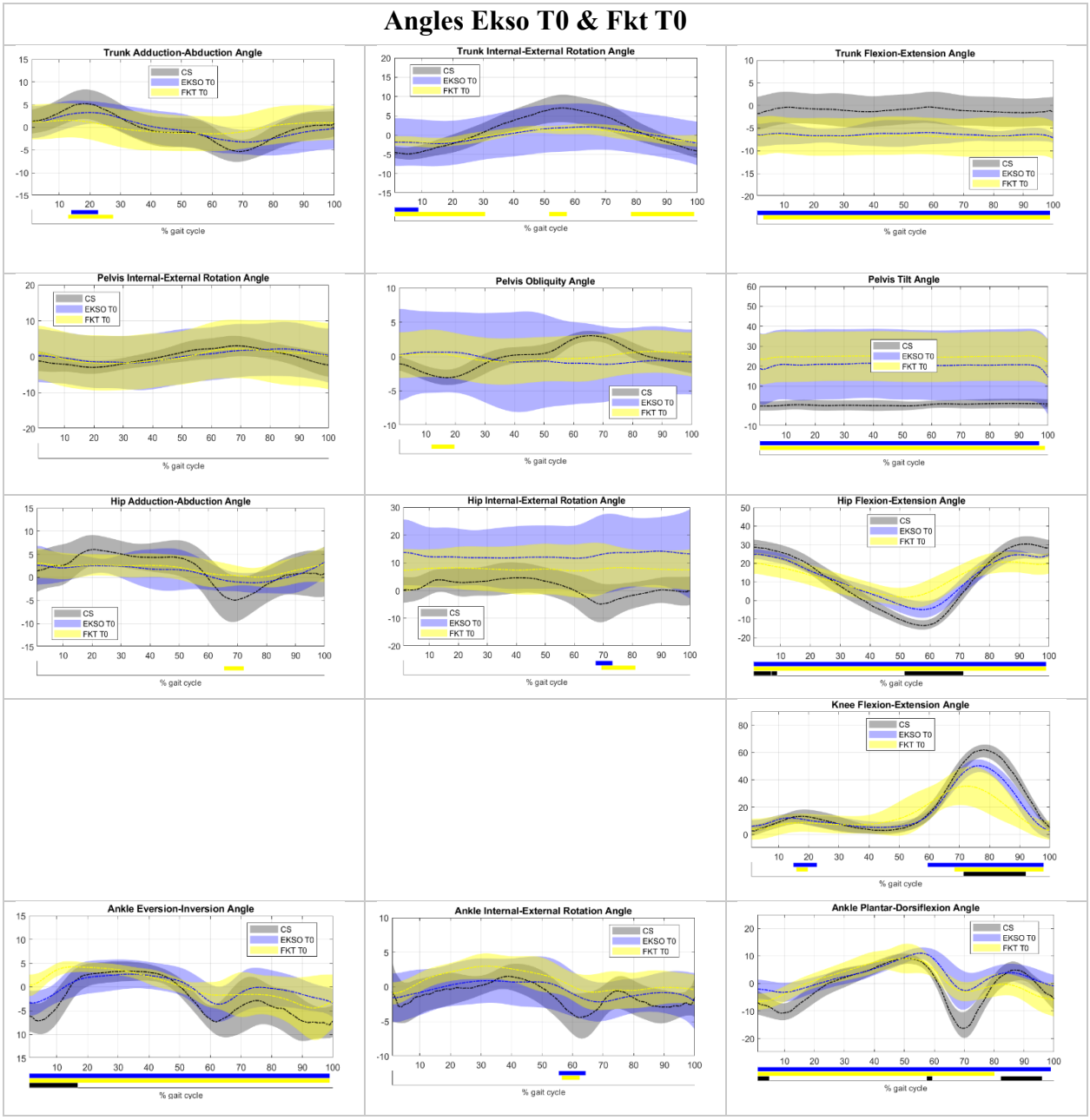

Figure 6.3 Graphs related to kinematics data. The figures illustrate three groups: T0 from Ekso and T0 from the Fkt groups, and Cs representing the Control group.

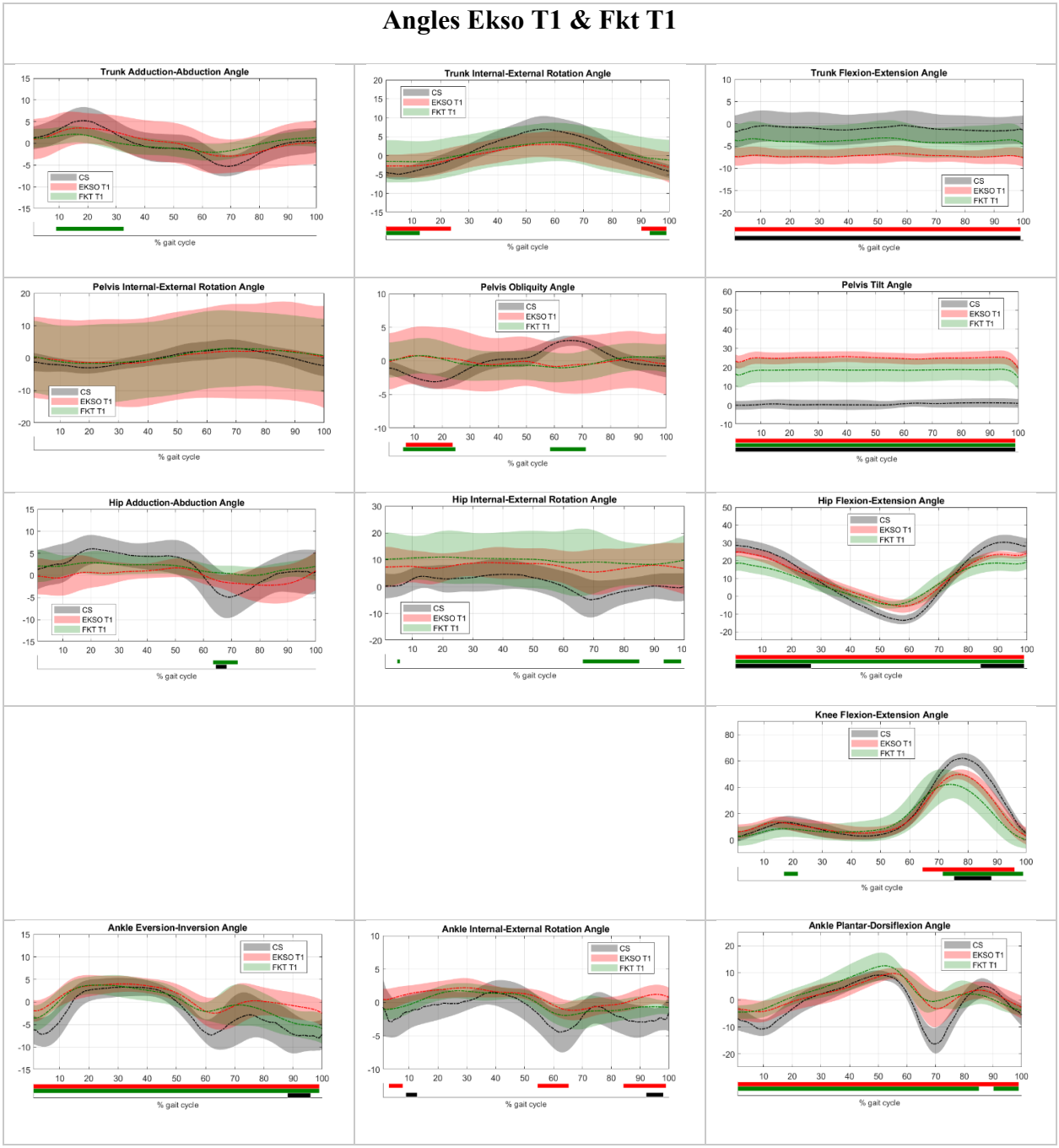

Figure 6.4 Graphs related to kinematics data. The figures illustrate three groups: T1 from Ekso and T1 from the Fkt groups, and Cs representing the Control group.

The results presented in Figures 6.1 and 6.2 provide a view of the changes in Join angle between different groups and time points.

In Figure 6.1, comparing the Ekso group (T0 and T1) and the control group, it is observed that there are significant differences between T0 and T1 with the control group and also throughout the gait cycle for various Joint angles, including trunk flexion-extension, pelvic tilt, hip flexion-extension, ankle eversion-inversion and ankle plantar flexion.

On the other hand, in Figure 6.2, comparing the Fkt group (T0 and T1) and the control group, there is a significant difference in flexion-extension of the trunk in T0. However, in T1, this measure appears to be closer to the control group than in T0. Again, significant differences were found between T0 and T1 throughout the gait cycle for pelvic tilt, hip extension, and ankle eversion-inversion in the Fkt group compared to the control group.

The differences observed between T0 and T1 in both Fkt and Ekso groups indicate that both treatments have resulted in changes in the Joint angles being studied. This can confirm that both Fkt and Ekso interventions have had an impact on the movement patterns of the subjects over the course of the treatment period.

Comparing T0 in the Ekso and Fkt groups in Figure 6.3 provides valuable visions into the baseline Joint angles before any treatment is applied. The presence of statistically significant differences between T0 Ekso and T0 Fkt throughout the gait cycle for various Joint angles, including trunk flexion-extension, pelvic tilt, hip flexion-extension, ankle eversion-inversion, and ankle plantar extension, suggests that initially, before the implementation of any interventions, the kinematic profiles of both groups were different from those of the control group: these may depend on the inclusion criteria for the Ekso rehabilitation program. These differences in baseline Joint angles between the Ekso and Fkt groups indicate that at the beginning, there were inherent dissimilarities in the movement patterns of the participants assigned to these two groups.

The comparison between T1 Ekso and T1 Fkt, presented in Figure 6.4, highlights several important findings on the effects of these interventions on the Joint angles.

First of all, the observation of a significant difference between T1 Ekso and the control group in trunk flexion-extension suggests that, after treatment with the Ekso device, the trunk movements of the participants were not similar to those of individuals without any specific intervention and also the results of the statistical test indicate that there are significant differences between Ekso T1 and Fkt T1 throughout the Gait cycle.

The significant difference observed between Ekso T1 and Fkt T1 with the control group in pelvic tilt suggests that the two treatment methods (Ekso and Fkt) influence pelvic tilt differently compared to the control group. This difference indicates that both the Ekso and Fkt treatments alter pelvic tilt kinematics in a manner distinct from the control condition.

Furthermore, the fact that the results of both Ekso and Fkt groups are different from each other further highlights the divergent effects of these treatments on pelvic tilt. This disparity suggests that Ekso and Fkt treatments may affect pelvic tilt through different mechanisms or with varying degrees of effectiveness.

Significant differences observed between T1 Ekso and T1 Fkt in hip flexion-extension, ankle eversion-inversion, and ankle plantar extension compared to the control group suggest that these two treatment methods exert distinct effects on these Joint angles.

6.2 Torques

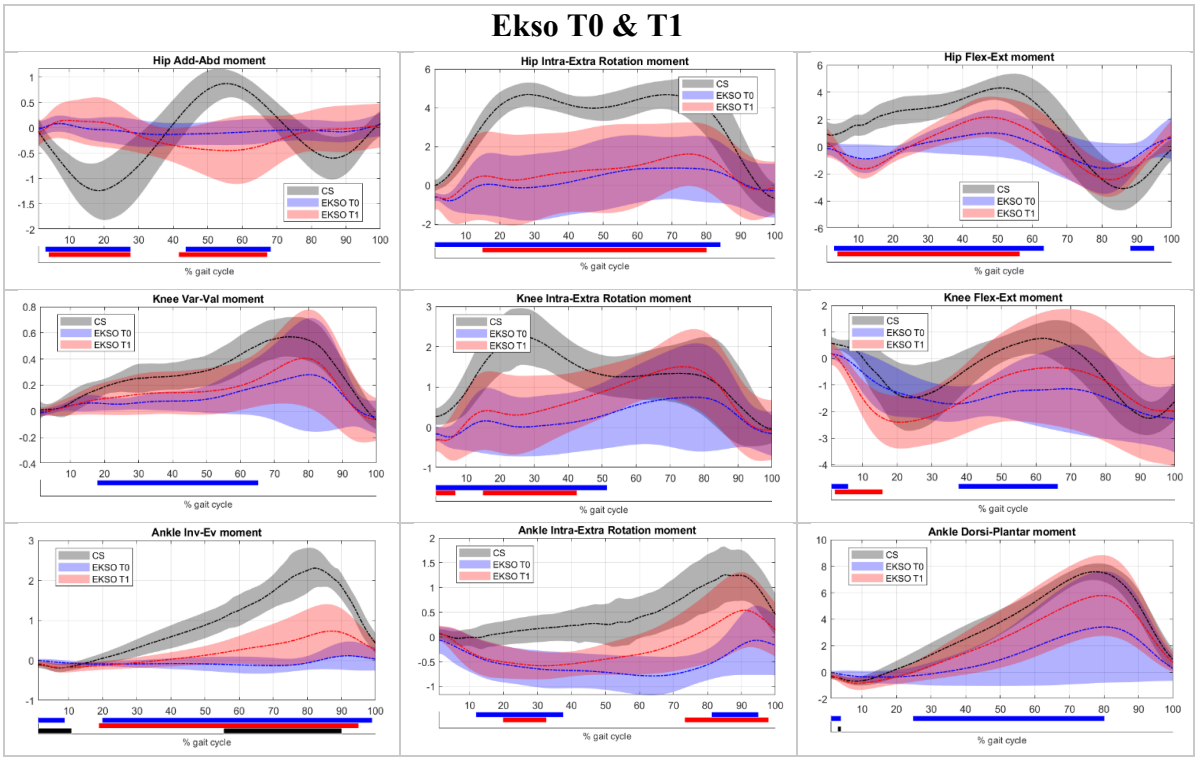

Figure 6.5 Graphs related to dynamic data. The diagrams illustrate three groups: T0 and T1 from the Ekso groups, and Cs representing the Control group.

6.3 Forces

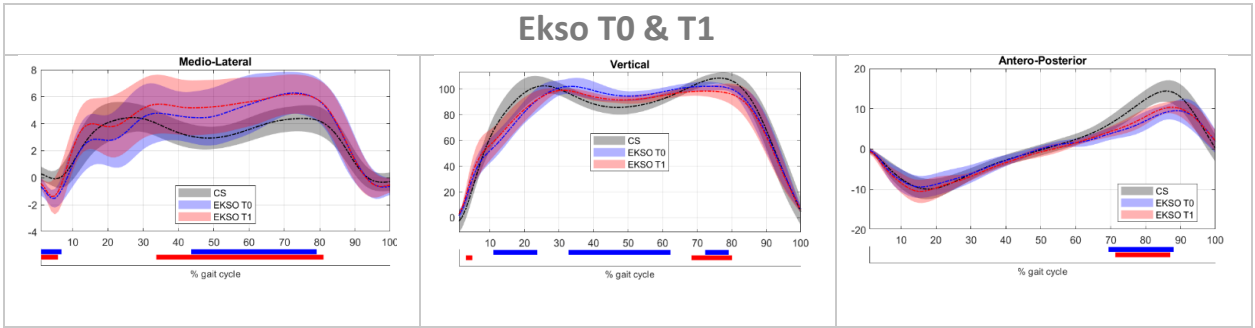

Figure 6.6 Graphs related to dynamic data. The diagrams illustrate three groups: T0 and T1 from the Ekso groups, and Cs representing the Control group.

The results presented in Figure 6.5, comparing moment measurements in the Ekso group and the control group, reveal significant differences in various parts of the gait cycle. Significant differences between T0 and T1 and control group are observed in the hip (add-abd, intra-extra, flex-ext), knee (var-val, intra-extra, flex-ext), and ankle (inv-env, intra-extra, dorsi-plantar).

Furthermore, the observation that T1 exhibits a behaviour similar to that of the control group compared to T0 in terms of ankle inversion-eversion, ankle intra-extra rotation, and ankle dorsi-plantar flexion moments suggest that, following the Ekso intervention, the ankle joint mechanics of the participants have shifted toward a pattern more closely similar to that of the control group. This could indicate a normalization or improvement in ankle joint function as a result of the Ekso intervention over time.

The results presented in Figure 6.6, focusing on the forces in the mediolateral, vertical, and anterior-posterior directions show significant differences in mediolateral forces between T0 and T1 and control group during the 40-80% (from the terminal stance to the midswing phase according to Perry et al. [20]) of gait cycle. The comparison between the vertical forces of the Ekso group at T0 and the control group reveals significant differences across most phases of the gait cycle. However, at T1, the vertical forces of the Ekso group demonstrate a closer similarity to those of the control group. This suggests that the treatment intervention administered to the Ekso group may have led to adjustments in vertical force distribution during walking, aligning more closely with typical gait patterns observed in the control group.

6.4 EMG

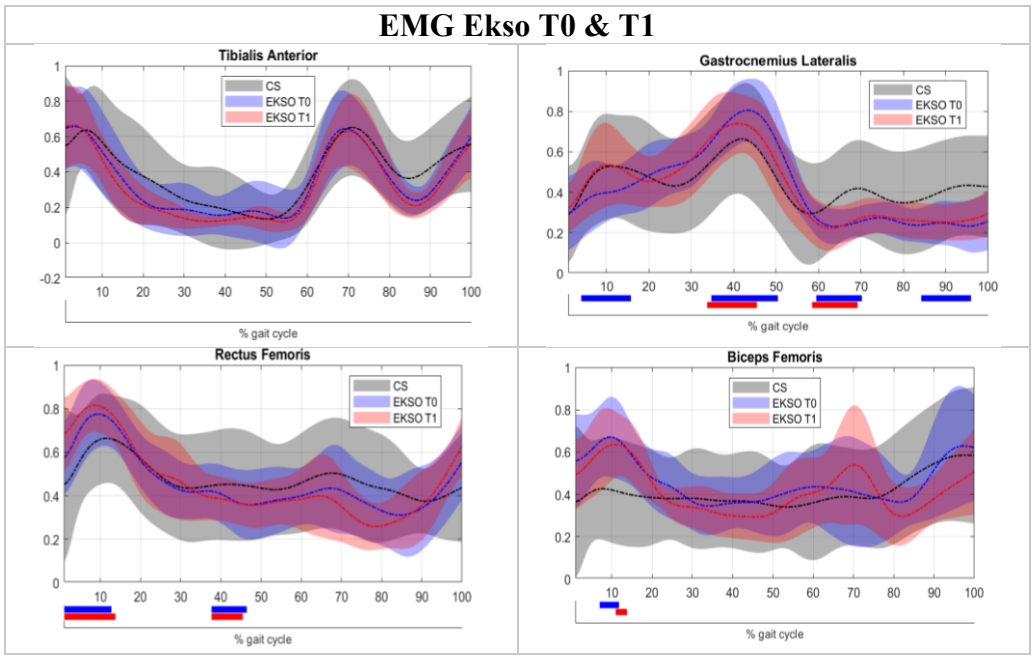

Figure 6.7 Graphs related to EMG data. The diagrams illustrate three groups: T0 and T1 from the Ekso groups, and Cs representing the Control group.

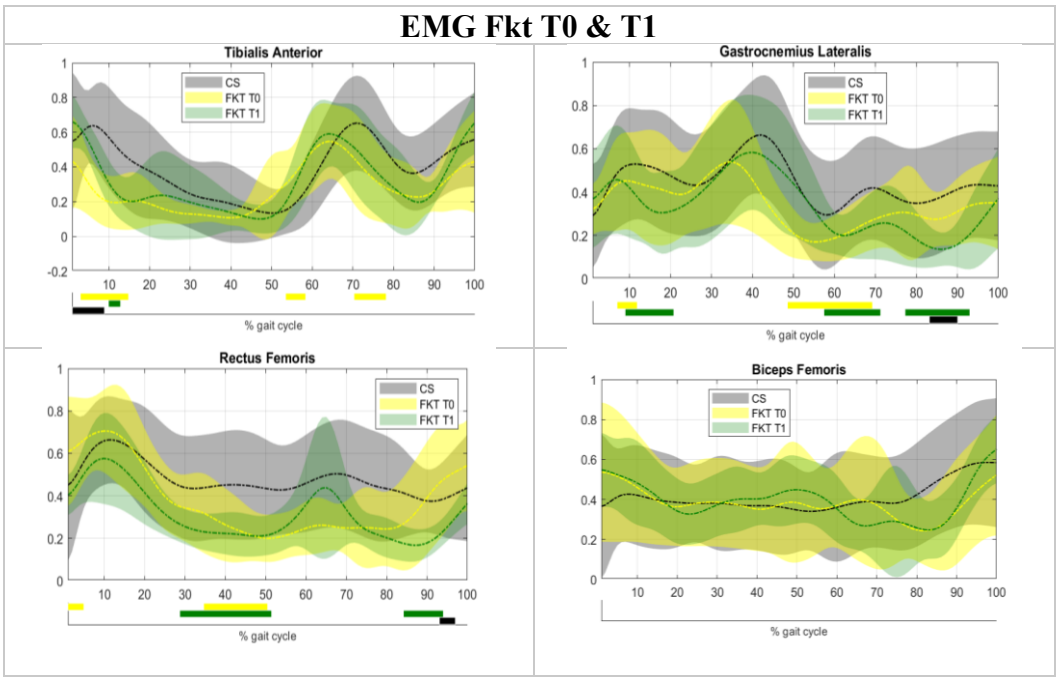

Figure 6.8 Graphs related to EMG data. The diagrams illustrate three groups: T0 and T1 from the Fkt groups, and Cs representing the Control group.

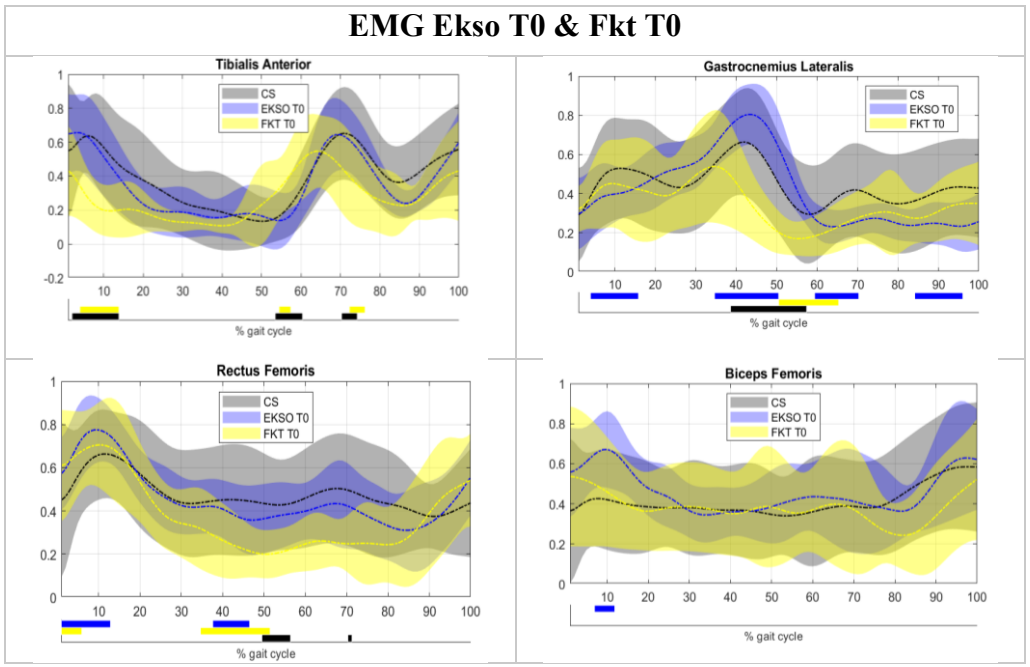

Figure 6.9 Graphs related to EMG data. The diagrams illustrate three groups: T0 from Ekso and T0 from the Fkt groups, and Cs representing the Control group.

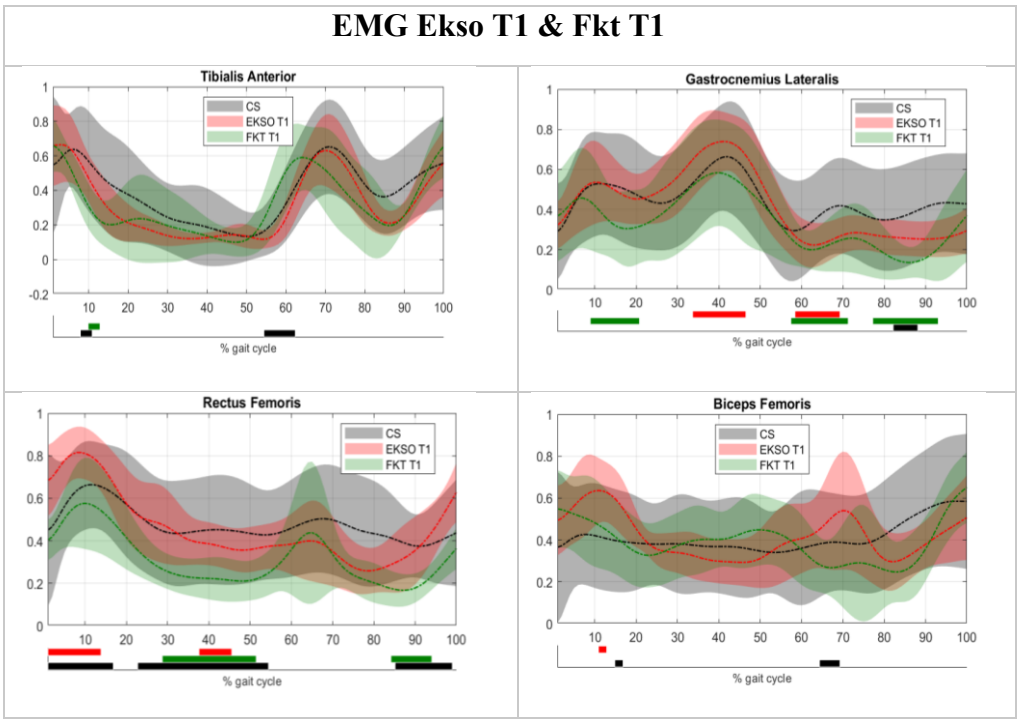

Figure 6.10 Graphs related to EMG data. The diagrams illustrate three groups: T1 from Ekso and T1 from the Fkt groups, and Cs representing the Control group.

The results of Figures 6.7 and 6.8, which analyze electromyography (EMG) measurements of the muscles at T0 and T1 for the Ekso and Fkt groups, evaluate the effects of these treatments on muscle activation patterns throughout the gait cycle.

The significant differences observed in the activity of the gastrocnemius lateralis and rectus femoris muscles between T0 and T1, compared to the control group, during certain phases of the gait cycle indicate that at T1, individuals using Ekso demonstrate a greater similarity to the control group.
In Figure 6.8, it seems that T1 exhibits behavior that closely resembles the control group in both the gastrocnemius lateralis and rectus femoris muscles.
The observations in Figure 6.9 show that at T0, both the Fkt and Ekso groups exhibit differences from the control group and the individuals before treatments.

The data in Figure 6.10 indicates that in T1, the Ekso treatment group exhibits patterns more closely resembling those of the control group compared to the T1 Fkt group. This suggests that the effects of the Ekso intervention on the measured parameters align more closely with the normal or expected patterns observed in individuals without any specific intervention, as indicated by the control group.

6.5 Spatio-temporal parameters

In this part are presented the statistical result of spatio-temporal parameters. The asterisks present in the tables, obtained through the Wilcoxon signed rank and Wilcoxon rank sum statistical tests with a significance level of $p < 0.05$, indicate a significant difference at all instances of walking.

	T0 Ekso		**T1 Ekso**		**CS**	
	Mean	**Standard Deviation**	**Mean**	**Standard Deviation**	**Mean**	**Standard Deviation**
Space (m)*	0.90	0.22	0.88	0.23	1.23	0.19
Time (s)	1.25	0.14	1.25	0.07	1.23	0.72
Velocity(m/s) *	0.72	0.15	0.71	0.19	1.06	0.15
Stance (%)	63.80	5.69	63.85	1.93	60.61	5.23
Swing (%)	36.19	5.69	36.14	1.93	39.39	5.23
Cadence(step/min)	48.79	8.67	48.02	2.61	52.47	8.98

Table 6.1 The statistical analysis results for the spatio-temporal parameters of T0 &T1 Ekso

	T0 Fkt		**T1 Fkt**		**CS**	
	Mean	**Standard Deviation**	**Mean**	**Standard Deviation**	**Mean**	**Standard Deviation**
Space (m)*	0.73	0.22	0.82	0.08	1.23	0.19
Time (s)	1.11	0.23	1.12	0.14	1.23	0.72
Velocity(m/s) *	0.65	0.11	0.74	0.11	1.06	0.15
Stance (%)	58.53	5.52	61.13	3.52	60.61	5.23
Swing (%)	41.46	5.52	36.14	1.93	39.39	5.23
Cadence(step/min)	56.38	12.68	54.20	7.04	52.47	8.98

Table 6.2 The statistical analysis results for the spatio-temporal parameters of T0 &T1 Fkt

	T0 Ekso		T0 Fkt		CS	
	Mean	**Standard Deviation**	**Mean**	**Standard Deviation**	**Mean**	**Standard Deviation**
Space (m)*	0.90	0.22	0.73	0.22	1.23	0.19
Time (s)	1.25	0.15	1.11	0.24	1.23	0.72
Velocity(m/s)	0.72	0.16	0.65	0.11	1.06	0.15
Stance (%)	63.80	5.70	58.53	5.52	60.61	5.23
Swing (%)	36.19	5.70	41.46	5.52	39.39	5.23
Cadence(step/min) *	48.80	8.67	56.38	12.68	52.47	8.98

Table 6.3 The statistical analysis results for the spatio-temporal parameters of T0 Ekso &T0 Fkt

	T1 Ekso		T1 Fkt		CS	
	Mean	**Standard Deviation**	**Mean**	**Standard Deviation**	**Mean**	**Standard Deviation**
Space (m)	0.89	0.23	0.82	0.08	1.23	0.19
Time (s)	1.25	0.07	1.12	0.14	1.23	0.72
Velocity(m/s)	0.71	0.18	0.74	0.11	1.06	0.15
Stance (%) *	63.85	1.93	61.13	3.52	60.61	5.23
Swing (%) *	36.14	1.93	36.14	1.93	39.39	5.23
Cadence(step/min) *	48.03	2.61	54.20	7.04	52.47	8.98

Table 6.4 The statistical analysis results for the spatio-temporal parameters of T1 Ekso &T1 Fkt

The significant differences observed between the T0 and T1 in both Ekso and Fkt treatments regarding space and velocity indicate notable improvements in gait characteristics following the interventions. These differences suggest alterations in distance covered and walking speed, reflecting enhancements in stride length, step width, and overall gait dynamics. The changes in velocity underscore improvements in functional mobility, while modifications in spatial parameters highlight refinements in gait quality and efficiency.

The significant differences observed in space, cadence, and step width between T0 for Fkt and Ekso treatments indicate disparities in these gait parameters at baseline. These differences suggest that individuals receiving Fkt and Ekso interventions may exhibit distinct gait characteristics before any treatment is administered.

The significant differences observed in swing, stance, cadence, and step width parameters at T1 for both the Fkt and Ekso groups indicate notable changes in gait characteristics following the

interventions. These differences suggest alterations in the duration of swing and stance phases, walking speed (cadence), and step width, reflecting improvements in gait dynamics and overall mobility.

Conclusion

This study investigated the effectiveness of two gait rehabilitation approaches for individuals with Parkinson's disease (PD).

Parkinson's disease is a progressive brain disorder causing movement issues due to the loss of dopamine-producing nerve cells. While the exact cause remains unsolved, it likely involves a mix of genetics, environmental factors, and aging. Tremor, stiffness, slowness, and balance problems are symptoms, but others like sleep disturbances, cognitive decline, and depression can emerge later. While there's no cure, deep brain stimulation, possible therapies, and rehabilitation treatments help manage symptoms and improve quality of life. In this sense, Ekso, a robotic exoskeleton, could prove to be useful in helping overcome rigidity and weakness that can be experienced during movement execution. In this study it is evaluated the effect of these alternative rehabilitation on Gait in PD individuals comparing its outcome against those of classical therapies.

The groups were divided into individuals receiving ‘classical’ treatments (Fkt group), those using Ekso therapy (Ekso group), and a control group made of healthy subjects.

Gait analysis was performed on both the Fkt and Ekso groups before and after treatments, and the results were compared with those of the control group.

According to the results, significant differences were noted between the T0 and T1 measurements for both the Fkt and Ekso groups, as well as between T0 and T1 of both groups compared to the control group, across a variety of parameters, including lower limb angles’ time series, EMG activity, joint’s forces and torques, and spatiotemporal parameters. Both Ekso and Fkt therapies led to substantial improvements in gait parameters compared to the T0 measurements. While both therapies proved to be beneficial, the optimal choice might depend on individual factors: i.e., Ekso, with its ability to overcome rigidity and weakness, could be ideal for individuals with severe gait impairments meanwhile the traditional approaches might resonate better with those preferring a more familiar rehabilitation method. Additionally, accessibility and cost might play a role, as Ekso therapy currently presents limitations compared to Fkt.[34]

This study highlights the potential of both Ekso and Fkt for improving gait function in PD. Future research should compare their long-term effectiveness, thus exploring combined approaches. Ultimately, optimizing rehabilitation strategies through continued research can lead to personalized

treatment options, empowering individuals with PD to maintain mobility and improve their quality of life.

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