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Gait Analysis of Patients Affected by Parkinson's Disease using Inertial Sensors

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ABSTRACT

Parkinson's disease is a chronic irreversible disease that worsens over time, whose clinical picture is extremely complex and varied. In fact, the diagnosis of the disease is not based on diagnostic tests but consists of a clinical investigation that analyses the patient's symptoms and medical history. The motor symptoms are considered the most characteristic element of Parkinson’s disease; these include gait disorder, bradykinesia, tremor, rigidity and in additional freezing of gait postural deformation and instability. Several rating scales are used to diagnose and monitor the disorder. Currently there are pharmacological and surgical treatments that are used to mitigate the effects of this disease. Gait is a relevant clinical evaluation tool because changes in gait affect the global health of the patient. Measurement has always been a difficult process done only in a clinical setting by a specialist largely through subjective testing. The spread of MEMS technologies has made it possible to carry out objective evaluations at a low cost. The work carried out in this thesis addresses the use of wearable inertial sensors, used for monitoring and diagnosing Parkinson's disease through gait analysis. The purpose of this thesis is to obtain temporal parameters, characteristics of the gait, through an algorithm that analyses the signals extracted from the sensors worn by each patient, and then to carry out a check that allows one to understand the reliability of this analysis compared to the subjective analysis carried out by the specialist. The dataset includes 15 patients affected by Parkinson's disease. The acquisition of the signals was carried out through inertial sensors positioned on the ankles during the execution of various motor tasks. The subjects involved had been diagnosed with Parkinson’s disease for at least a couple of years. For these measurements two wearable sensors attached to the ankles of the patients were used; the signals from tri-axis accelerometer and gyroscope were

taken into account. The recording of the signals of interest was conducted during the patient's motor inspection. The recorded signal has 6 components, relating to acceleration and angular velocity along the axes x, y and z. In this study the changes of direction, the stand and the postural transitions were analysed. To study the path of patients and obtain parameters comparable to clinical evaluations, a signal analysis on the output signals of both sensors applied on the ankles was performed. In particular the signals of angular velocity along the y axis were analysed. In the temporal domain, the two most relevant events in gait cycle are the initial heel contact, usually called heel strike (HS) and terminal contact, usually called toe off (TO). Both these events are used in gait analysis because the other temporal parameters such as swing, stance and stride time can be directly computed from them. The extracted parameters are: step time, swing time, stance time, stride time, strike time, double support and mid swing; these parameters were calculated for each task of each patient. After this computation comparisons have been done, in particular, the Wilcoxon Signed-Rank test was performed on the tasks of the same patient, the characteristic parameters of the gait recorded in each task were compared. Second step of this work was to evaluate the mean trend of the tasks performed by each patient. Finally, the Pearson correlation was evaluated between the parameters obtained from the task in which the patients walked at regime along a corridor and the value of clinical scales. The results obtained from this are satisfactory despite the limited dataset. In addition other studies in the literature support the use of wearable sensors for monitoring and diagnostics of Parkinson's disease.

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1 PARKINSON’S DISEASE

1.1 Definition And History

Parkinson's disease (PD) is a progressive degenerative neurological disorder that manifests with four main features: rest tremor, bradykinesia, rigidity and loss of postural reflexes.

The first definition of the disease is attributed to the British doctor James Parkinson, who described it as a pathology characterized by “involuntary tremor with reduced muscle strength in parts of the body at rest" and by "propensity to lean the body forward passing from a normal gait to a running movement ", in his "An Essay on a Shaking Palsy", published in 1817 (1).

Parkinson’s disease, along with Alzheimer’s is one of the most common neurodegenerative disorders. The incidence increases with age. The annual incidence rate, varying according to the studies, is between 2 to 21 cases out of 100’000 people, with higher values found in studies focused on age groups over 55 years (1).

Although Parkinson's disease is traditionally considered a movement disorder, in recent years, the clinical phenotype has been better described, showing that PD is a multisystem neurodegenerative disorder with motor and non-motor symptoms represented by sleep disturbances, olfactory dysfunction, complex of neuropsychiatric reactions, such as anxiety and depression, and dysautonomic manifestations, such as constipation, orthostatic hypotension and seborrheic dermatitis (2).

Even though the PD is not to be considered a terminal illness, it is clear, that this disorder leads to a decreased life expectancy. People diagnosed with Parkinson's disease can live for about 15-20 after diagnosis (3).

1.2 Pathophysiology

The main feature of PD is the cell death, up to 70%, of dopaminergic neurons in the substantia nigra, a grey nerve formation of the midbrain located in the cerebral peduncles, involved in the performance of many motor functions.

The consequence of the deterioration of dopaminergic neurons is the decrease of motor functions, secondly, the presence of non-motor symptoms suggests the degeneration of other sections of the brain (4) (5).

The causes of the disease are still not entirely clear, however through the literature it is possible to identify two most accredited theories regarding the pathogenesis of PD.

The first hypothesis argues that the cell death of dopaminergic neurons is caused by mitochondrial dysfunction and oxidative stress. The second hypothesis associates the deterioration of neurons with the phenomenon of "misfolding" of proteins in the substantia nigra pars compacta; these proteins can cause cell damage if they are not broken down by the immune system.

In 1912, the neurologist Friedrich H. Lewy took the first step towards understanding the neuropathology of PD by describing intra-neuronal protein aggregates in certain regions of the brain stem (6) (7). Subsequently, these lesions were confirmed at the

level of neurons of the mesencephalic substantia nigra and were called Lewy bodies (LB) (8).

Lewy bodies are cytoplasmic aggregates of proteins composed of a circular body surrounded by fibrils.

They are mainly into dopaminergic neurons of the substantia nigra and are mostly composed by insoluble α-synuclein. The α -synuclein is a soluble protein of 140 amino-acids encoded by the SNCA gene, normally by neurons. This protein takes part of the formation of presynaptic terminals, interacting with membrane phospholipids and other proteins.

In PD and other neurodegenerative diseases, α-synuclein aggregates to form insoluble fibrils, reducing the activity of neuronal cells.

Specialists believe that the disease may be the result of a combination of factors, in additional to age, ethnicity and gender, genetic predispositions and environmental pollution, in particular exposure to professional pesticides, herbicides and heavy metals, also play a fundamental role.

As for Genetic Factors, several studies show how the presence of a first degree relative with PD, increases the risk of disease, mostly at an early stage; specifically, it was found that 5% of patients are affected by a form of PD, at an early age due to hereditary factors. (7)

1.3 Clinical Features

Parkinson's disease is a chronic irreversible disease that worsens over time, the clinical picture is extremely complex and varied. In fact, the diagnosis of the disease is not based on diagnostic tests but consists in a clinical investigation that analyses the patient's symptoms and medical history.The cardinal characteristics of Parkinson's disease can be grouped under the acronym TRAP: Rest tremor, Stiffness, Akinesia better defined as bradykinesia and postural instability. Other signs are a flexed posture and motor blocks of the subject (9).

1.3.1 Motor Symptoms

The motor symptoms are considered the element most characteristic of Parkinson's disease, these include, gait disorder, bradykinesia, tremor, rigidity and in additional freezing, postural deformation and instability.

Gait disorder is the main form of postural balance impairment. Usually, at the early stages of PD, the swing of upper limbs on the affected side decreases and the lower limbs drags. As Parkinson's disease progresses thrust gait and panic gait develop, all of which make gait disorder the most disabling motor symptom. Altered dopaminergic signalling increase the risk of gait disorder. Thus, gait disorder is an emerging marker of Parkinson progression (10).

Bradykinesia refers to slowness of movement and is the most characteristic clinical feature of PD. This symptom is a hallmark of basal ganglia disorders, and it encompasses difficulties with planning, initiating and executing movement and with performing sequential and simultaneous tasks (11).

The first manifestation is often slowness in performing activities of daily living and slow movement and reaction times. This may include difficulties with tasks requiring fine motor control like using utensils. Other manifestations of bradykinesia include loss of spontaneous movements and gesturing, drooling, loss of facial expression (hypomimia) and decreased blinking.

In the most advanced stages of the disease, bradykinesia can manifest itself in the phenomenon of **freezing**, referred to by the patient as a sensation of "feet stuck on the ground".

Given that bradykinesia is one of the most easily recognisable symptoms of PD, it may become apparent before any formal neurological examination.

Rest tremor is another common symptom of disease, which occurs in at least 70% of patients. Tremors are initially unilateral, occur at a frequency between 4 and 6 Hz (3), and it usually begins from one side of the upper limb, into the ipsilateral lower limb, and then spreads to the contralateral upper and lower limb (12).

Rest tremor in patients with Parkinson’s disease can also involve the lips, chin and jaw. Typically, this symptom disappears with action and during sleep.

Rigidity is caused by an increased muscle tone. Although this affects all muscle groups, is prominent in those which maintain a flexing attitude of the trunk and limbs. In addition, rigidity of the neck and trunk may occur, resulting in abnormal axial postures like scoliosis. **Postural deformities** resulting in flexed neck and trunk posture and flexed elbows and knees are often associated with rigidity. However, flexed posture generally occurs late in the disease (13).

Postural instability tends to manifest late, it is manifested by the patient's inability to make normal postural adjustments required in the transition from one position to another and during walking. It is, therefore, one of the main causes the high incidence of falls and fractures in patients with advanced PD.

The symptoms described can join variously among themselves in each individual patient, configuring different possible clinical pictures: this led to the search for one clinical classification of the various disease subtypes.

1.3.2 Non-motor Symptoms

The spectrum of non-motor symptoms is very wide and includes autonomic dysfunction like dysphagia, difficulty swallowing, constipation and hypotension; cognitive/neurobehavioral disorders; and sensory and sleep abnormalities, such as excessive daytime sleepiness. Some of these are frequently present before the onset of motor symptoms (14).

Autonomic dysfunction may be the presenting feature of Parkinson's disease. They include orthostatic hypotension, sweating dysfunction, sphincter dysfunction and erectile dysfunction (3). The constipation is one of the earliest symptoms of the PD, it is estimated that 90% of patients suffer from this pathology. The disturbance tends to increase as disease progresses and is caused by the degeneration of dopaminergic neurons within the autonomic nervous system.

Cognitive and neurobehavioral disturbance can be as disabling as motor symptoms. Most of the patients with these types of disorders present apathy, depression, anxiety and hallucinations (15).

1.4 Diagnosis and Measurement Scales

Due to the different profiles and lifestyles of individuals with Parkinson's disease, motor and non-motor disabilities must be assessed in the context of each patient's goals and needs (16). Several rating scales are used to diagnose the disorder.

The Unified Parkinson's Disease Rating Scale (UPDRS) of Parkinson's disease it is the most consolidated scale for assessing this type of disability. Several studies make, and have made, use of the UPDRS to monitor the progress of the disease, which is not linear, particularly faster in the early stages of the disorder and in subjects with postural instability and walking difficulties (17).

In 2001 the UPDRS was updated by the Movement Disorder Society, which helpede to consolidate some unclear and ambiguous weak points. The new version bears the name of MDS-UPDS scale "MDS sponsored UPDRS revision".

The MDS-UPDRS is composed as a questionnaire consisting of 65 questions, to which the patient and the doctor partly answer, for each question it is possible to choose between five different answers, each of which is related to medical terms:

0 Normal: No compromise.

1 Minimum: Cognitive and / or motor impairment felt by the patient without any pratical interference with the patient's ability to perform normal activities and social interactions.

2 Mild: Clinically measurable cognitive and / or motor impairment but with minimal interference with the patient's ability to perform normal activities and social interaction.

3 Moderate: The cognitive and / or motor deficit interferes but does not preclude the patient from carrying out normal activities and social interactions.

4 Severe: Disease impairment precludes the patient from performing normal activities and social interactions.

The assessment consists of four parts:

Section I: treats non-motor symptoms, provides a clinical assessment of the patient's mental state, behaviour and mood;

Section II: provides information on the patient's daily activities through a self-assessment;

Section III: Provides a clinical assessment of motor capacity;

Section IV: deals with the analysis of motor complications (18).

The numerical score obtained from the UPDRS scale offers the opportunity for repeated comparisons of the same patient, obtaining information on the course of the disease over time; it also allows comparison between different patients in clinical trials.

The disease is difficult to detect and treat promptly, as it shows a wide variability in the medical clinics (Fahn, 2008) as well as in the somatic symptom progression.

During the test for PD diagnosis, the neurologist watches the patient performing specific tasks and assigns scores for each of them as required and established in MDS-UPDRS. This type of assessment is subjective, this fact leads to high variability of diagnosis among different neurologists or different medical centres.

Proper diagnosis of Parkinson's disease is very important for adequate prognosis and treatment, early and accurate diagnosis of PD may improve the long-term quality of life, while misdiagnosing a patient causes delay in receiving the appropriate treatment plan.

In this context, the use of smart technologies for Parkinson's disease applications has increased in recent years. In particular, wearable sensors are fundamental in helping clinicians perform early diagnosis, differential diagnosis, and objective quantification of symptoms over time (19) (20).

The scale Hoehn and Yahr (H&Y), published in 1967, is mostly used to provide a measure of Parkinson's disease progression. This scale makes assessments about functional deficits and characteristics patient's clinics (21).

The H&Y scale is based on the idea that the severity of disease is related to bilateralism of motor symptoms.

In particular, the scale has five levels, from level 1 that is the easiest situation, where the symptoms are mild to level 5 that represent the most severe condition, where the patient is forced to bed. It has been subsequently amended and two additional

intermediate levels 1,5 and 2,5 were added. The scale shows a good relationship between life quality and reduced mobility.

Update Hoehn and Yahr Scale

Level 1	Unilateral involvement only
Level 1,5	Unilateral and axial involvement
Level 2	Bilateral involvement without impairment of balance
Level 2,5	Mild bilateral disease with recovery on pull test
Level 3	Mild to moderate bilateral disease; some postural instability; physically independent
Level 4	Severe disability; still able to walk or stand unassisted
Level 5	Wheelchair bound or bedridden unless aided

A fast screening of mild cognitive degradation is provided by **Montreal Cognitive Assessment (MoCA).** The MoCA evaluate different cognitive domains: attention and focus, execution functions, memory, language, constructive attitude, abstraction, calculation and guidance. The time duration of this test is 10 minutes.

The test is quite easy, the patient is subject to tests divided into six cognitive area, the maximum score is 30 points, a score greater or equal to 26 is considered “normal” (7).

1.5 Pharmacological and Surgeon Treatments

Currently, for Parkinson's disease there is no cure, that is one that can lead to complete and definitive recovery. However, several treatments are available that allow one to control the symptoms, resulting in an improvement in the general condition and, therefore, in the life quality.

The therapeutic approach does not act by removing the cause, but only by decreasing the intensity of the various disorders. It must be established by the doctor, who consider the severity of the symptoms and the stage of the disease.

Treatments for Parkinson’s disease include **pharmacological therapies** and **surgical treatments** (22).

1.5.1 Pharmacological Treatments

Treatment of Parkinson’s disease puts drug therapies at first. This kind of treatments for care are aimed primarily at relieving and improving the motor symptoms of the patient, with the aim of improving the patient’s quality of life and making him more autonomous.

Some treatments also allow to partially attenuate non-motor symptoms; however, such drugs have a wide spectrum of side effects to be taken into account in the choice of treatment.

The treatment is therefore not established and defined a priori but depends on various factors including the age of the patient, the stage of the disease, the presence of cognitive disturbances and the presence of complications caused by drugs (22).

Most of the drugs currently used in Parkinson's disease treatments simulate the physiological stimulation of dopamine.

Dopamine is a neurotransmitter that has important functions for the control of voluntary movement, sleep and learning, it also affects behaviour and mood. Furthermore, it is mainly produced inside the brain, in particular, in the substantia nigra, while a small amount is synthesized by the adrenal glands.

Levodopa is considered the most effective drug for the treatment of Parkinson's disease, which is estimated to have a response and a reduction in symptoms in 80% of patients. Levodopa has led to a substantial improvement in the symptoms of the disease, allowing patients to maintain greater autonomy and independence for long periods of time. Since the main cause of the disease consists in the gradual reduction of dopamine inside the neurons, the administration of exogenous L-dopa makes it possible to fill this gap.

This treatment is very effective in controlling tremor and reducing bradykinesia and rigidity. Despite its effectiveness, Levodopa however has a whole series of adverse effects that can occur in association with long-term treatment; the most frequent complications are induced dyskinesia, mainly linked to the duration of treatment and the acquired dose, which appears as an uncontrolled movement, usually associated with the peak of the dose. The *"wearing off",* is the increasingly marked decrease of the dose effect, which leads to fluctuations between the *"on"* stage during which the patient is able to control symptoms and the *"off"* stage during

which dopamine has no effect and the patient has no control of motor fluctuations (23) (24).

Dopaminergic agonist drugs allow direct stimulation of dopaminergic receptors, and the drug that mimics their functionality. Dopaminergic antagonists do not guarantee effective motor control; for this reason they are used above all as mono therapy in the early stages of the disease, to delay the use of Levodopa or in addition to it in the advanced stages as they prevent the onset of induced motor complications. Also, these drugs have several side effects that limit their use such as drowsiness and sleepiness, nausea, hallucinations, confusion and compulsive disorders.

The **selective MAO-B inhibitors** (monoamine oxidase -B) are very useful for Parkinson's patients as they allow to increase the availability of endogenous dopamine, as well as prevent the synthetic from being degraded. These drugs allow to delay the motor complications induced by Levodopa, while when used in conjunction with it they tend to improve the "on-off" effect.

Unlike the others, **COMT inhibitors** (catechol-O-methyltransferase) are used exclusively in combination with Levodopa in advanced stages of the disease. It allows one to increase Levodopa levels within the brain by reducing peripheral metabolism. These inhibitors therefore allow to increase the effects of a dose but have side effects such as nausea, sleep disturbances and greater increase in dyskinesias (22)

Amantadine and **trihexyphenidyl** are two drugs to reduce tremors and dyskinesias. Amantadine increases the extracellular concentration of dopamine. It is mainly used in patients with marked dyskinesias, it is used in combination with Levodopa to treat drug-induced dyskinesia phenomena without attenuating its enhancing effects.

To treat symptoms such as tremor and stiffness, the most commonly used drugs are **anticholinergic** ones, although they are less effective than Levodopa and lead to the onset of various side effects such as glaucoma, blurred vision, dry mouth and states of confusion.

1.5.2 Surgical Treatments

People with Parkinson's disease respond well to treatment. In a minority of patients, however, the treatments are not effective and, over time, the degree of disability increases, compromising the performance of normal daily activities. However, advances in therapy offer patients with Parkinson's disease a life expectancy similar to, or nearly similar to, that of healthy people (25)

The surgical treatments currently in use for Parkinson's disease are the first approach to treatment, even before Levodopa. Nowadays, surgical treatments are addressed to patients with disease at an advanced stage and whose response to drug treatment is no longer considered effective. The interventions that can be performed are **thalamotomy**, **pallidotomy** and **deep brain stimulation (DBS)**.

Deep brain stimulation is the most popular surgical technique for the treatment of advanced stage Parkinson's, as it turns out to be the most effective with a reduced number of side effects. Moreover, DBS allows the reduction of motor symptoms

related to prolonged treatment with Levodopa or where treatment with the latter is no longer effective. It consists in the electrical stimulation of specific areas of the brain through the implantation of electrodes, connected to an internal pulse generator. The areas of the brain affected by this intervention are the internal area of the globus pallidus or the nuclei subthalamic, whose stimulation allows a marked improvement of the tremor, rigidity and bradykinesia, as well as an improvement in dyskinesias end “on-off” fluctuations (26) (27).

2 TECHNOLOGIES FOR PARKINSON’S DISEASE MONITORING AND DETECTION

2.1 mHealt and Wearable Sensors

Despite not being known a cure for Parkinson’s disease, early diagnosis and treatment is an advantage. Nowadays, new technologies offer innovative detection methods and help existing approaches, such as disease monitoring performed by a neurologist, provide more accurate detection of the disease (28).

In addition, new technologies such as wearable systems and mHealth offer the opportunity for continuous monitoring.

mHealth is an abbreviation for mobile health, a term used for the practice of medicine and public health supported by mobile devices. The term is most commonly used to address the use of mobile communication devices, such

as smartphones, and wearable devices such as smart watches, for health services, information, and data collection. Moreover, this technology has the ability to adapt to the life patient and has the ability to calibrate the intervention intensity based on the of patient's needs (29) (30).

In the context of Parkison's disease and particularly in detecting or monitoring motor symptoms, mHealth devices work very well with wearable sensors. Using an mHealth device combined with a wearable sensor, it is possible to observe the patient's activity in real time. Specifically, for PD monitoring, the mHealth device provides the user with a screening of the patient's condition.

Wearable sensors are portable and movable accessories that can be worn on the body or embedded in clothes. These devices include smart watches or pressure shoes, among others. They contain hardware and software technology, that allow the collection of kinematic data, their processing and transmission. Currently, most of the wearable devices used in the field of PD are gyroscopes, accelerometers, or magnetometers.Through specific motion programs, these devices can execute real-time monitoring of PD motion symptoms for establishing multiple data models. This kind of system enables neurologist to accurately analyse the patients' motion state in real time (31).

Studies have proven that wearable devices are as effective as the standard scale MDS-UPDRS scores in evaluating PD symptoms (20). These devices overcome the limitations associated with clinical evaluation scale in terms of objectivity, accuracy and sensitivity. In addition, the wearable devices are characterized by being highly sensitive, and this allows to detect subtle motor abnormalities (29).

A medical assessment may not reveal the true severity of symptoms or fully reflect patients' status in daily life. On the other hand, wearable devices provide physicians with a comprehensive report of status of patients in a single assessment, thus optimizing treatment plans. In addition, wearable devices can be used at any time and place.

Figure 1: mHealt for Parkinson Monitoring

2.2 PD Detection

Severe PD is associated to more intense motor symptoms and nonmotor, which inevitably lead to motor complications, such as motor fluctuations and dyskinesia (12). Therefore, early diagnosis and treatment to the effective management of PD are of great significance. To study the clinical manifestations and prognosis of disease accurate and objective evaluation tools are necessary (32).

For example, the use of inertial sensors such as accelerometers and gyroscopes, combined with communication technologies like Bluetooth, is now feasible and meets the needs of people with chronic disorders (Bonato, 2010). Another aspect to

consider is that the burden of care of patients increases with disease progression. In this regard, a study proposes the use of wearable health monitoring system to measure heart rate, temperature, electrocardiogram, tilt and fall of the homebound patients (33). In addition, this system, allows a remote assistance able to send health professionals information about patients.

Smart technologies are mainly used for the detection of motor disturbances that cover the entire progression of pathology: early diagnosis tremor motor fluctuations and home and long-term monitoring.

2.2.1 Detection of Motor Symptoms

Gait disorder is an emerging marker of Parkinson's disease progression. Usually, doctors use a Timed Up and Go (TUG) method to evaluate gait or balance of patients. "Time Up and Go" is a comprehensive test for evaluating the motion state of the patients, such as standing up, walking, turning, or sitting down (18).

Clinical analyses are often carried out in large and bright space, which does not reflect the real condition of patients' life. In addition, the evaluation scales are limited and little suitable for analysing the patients during their daily life, especially when they are affected by anxiety or depression and are therefore less ready to answer test questions. It should also be highlighted that the subjects with Parkinson's disease treated pharmacologically have a gait that varies during the day. Therefore, for a gait monitoring the wearable sensors are more effective. These devices are placed on different parts of the body, most commonly on waist, leg and foot, and provide a concise kinematic and dynamic parameter of gait. In this way

the device worn by patient provides parameters such as rhythm, length and amplitude of stride and periodicity of gait.

This method avoids subjective or inaccurate evaluations, indeed helps to evaluate the effectiveness of treatments with dopaminergic drugs, timing of therapy, or adjustment of treatment regiments.

Several studies have conducted objective monitoring of Parkinson's disease gait in experimental conditions or in daily life. For example, Weiss used a triaxial accelerometer on lower back to evaluate gait variability in PD patients before and after taking medication emulating the activities of daily life (33). The aim was to evaluate walk quality in real life and discriminate PD patients and healthy subjects; at the end the feasibility of wearable devices was verify for long-time monitor the gait in laboratory environment and promote the continuous monitoring of gait of PD patients in daily life.

Many of such studies show that sensor devices have high sensitivity when detecting gait disorder, with an accuracy in excess of 90% (28) and that wearable portable devices can detect gait or balance in real time. These devices also provide intelligent reminders through vision, auditory, and touch for PD patients when they experience FOG and falling events. Patients affected by **bradykinesia**, show slowness of movement at onset, or slow and clumsy movements, likewise reduced speed, or amplitude of movement during rapid and recursive movements. Bradykinesia significantly impairs the quality of life of patients. usually, doctors use the UPDRS scoring system to assess the severity of bradykinesia (0: normal; 1: slight; 2: mild; 3: moderate; and 4: severe) or TUG method (34).

Unlike standard evaluation approaches these devices can detect early-stage PD symptoms. The study conducted by Memedi reported that a touchscreen telemetry device was able to quantify motor symptoms during episodes and dyskinesia of advanced PD patients (35). Memedi demonstrated that the device could objectively measure motor complications. Several researches have proven that smart technologies and in particular wearable devices could efficiently perform automated assessment of PD patients.

Tremor is not life threatening, but it can affect the patient's ability to live comfortable life. Clinically, tremors are classified as resting tremors, postural tremors, or action tremors, the choice of treatment depends on the cause of the tremor; for this reason, accurate diagnosis of this symptom is critical. The evaluation of tremors depends on emotions during the day; therefore, regular outpatient follow-ups do not allow to have a correct evaluation of tremor. Thus, continuous monitoring of this symptom is necessary.

To obtain an objective measure and a long-term monitoring of PD tremors sensor systems such as accelerometer, gyroscope, optical motion capture system or inertial measurement unit (IMU) are used. This kind of technology is used to measure the frequency of tremors.

A study conducted by researcher Wile, included 41 patients which wore smart watch devices and monitored tremors in 3-6 minutes; the parameters were collected while the hands were at rest and outstretched. Wile have proved that the smart watch was highly specific and sensitive in distinguishing postural reemergent tremors of PD from essential tremor. These devices are easily applicable in the clinical as well

as the community settings. However, the monitoring duration was too short to fully characterize tremors.

The **Postural instability** is a common symptom of the several state of Parkinson's disease. With the freezing of gait, it is the main cause of fall. The instability is due to loss of postural reflexes. This symptom cause a life activity difficult, the gait become slower and change direction become difficult (36). To evaluate postural instability a *pull test* is used, which consists in a push behind the patient' shoulders to evaluate the postural response.

2.3 Gait Analysis in Parkinson's Disease Using Wearable Sensors

Wearable sensor systems used for gait analysis provides parameters that describe the space and the time of the motion, useful to investigate the progression of gait problems in Parkinson's disease.

In this case these devices are useful because they are non-invasive, low-cost, and objective. In additional wearable sensors are able to diagnose and monitor the progression of Parkinson's disease and are very useful to evaluate clinical efficacy before and after therapeutic interventions (37).

Patients suffering from Parkinson's disease consider gait disorder the first and most worrying symptomatology. This is one of the reasons why having robust and reliable tools for gait analysis is crucial. Wearable sensor systems can aid in gait analysis by providing spatio-temporal parameters useful to investigate the

progression of gait problems in PD, without a specialized laboratory. However, various methods and tools, with very high variability, have been developed.

2.3.1 Analysis of Walk Using Sensors Positioned at the Ankles

The path of a healthy person is a periodic movement, in particular the legs repeat a sequence of movements that bring the body forward, maintaining a stable position. During the walk, one leg works as a support while the other advances to a new support site, then the legs switch roles and the leg that was stable becomes mobile, while the mobile leg becomes stable.

Each gait cycle is made up of a series of repetitive and ordered actions, which follow one another at set time intervals. The moment of contact with the ground is easily observable, therefore, this is considered the beginning of the gait cycle. In particular, the beginning of the walking cycle corresponds to the instant in which the heel of the foot touches the ground (Heel-strike phase) and is followed by the phase in which the foot is completely resting on the ground, after the toes have touched the ground (Foot-flat phase); finally the heel of the foot comes off the ground (Heel-off phase) and then the toes also come off the ground to leave the foot in the air (Toe-off phase) (37).

A complete walking cycle consists in the time interval between two Heel-strike events belonging to the same foot and lasts an average of 1.2 s (38). Each cycle can be divided into the Stance phase (the foot touches the ground and in following it detaches from it) and the Swing phase (the leg undergoes at first moment an acceleration and then a deceleration).

Each cycle begins and ends with both feet touching the ground, while in the middle of the cycle only one foot touches the ground. the step cycle is divided into three intervals.

Initial phase - Double support: both feet are on the ground, the weight load of the body is equally divided between the feet.

One-leg support: it begins when the opposite foot is raised to swing. During this phase, the entire weight of the body is held on one leg.

Terminal phase - Double stance: begins with the ground contact of the contralateral leg and continues until the initial leg is raised to swing. In this phase the load distribution is very asymmetrical.

The stance phase represents 60% of the gait cycle, while 40% consists of the swing phase (17).

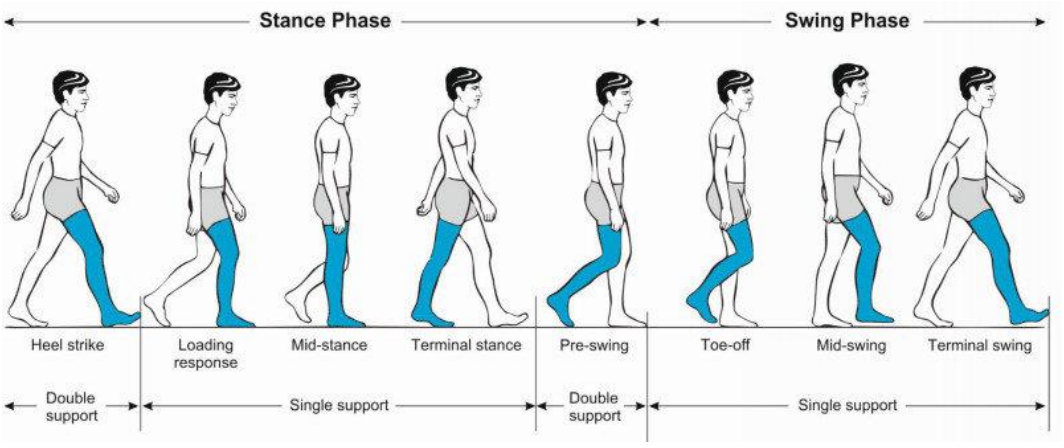

Figure 2: Event in a Cycle of Gait

2.3.2 Inertial Measurement Unit Device

IMUs are electronic devices that measure and report a body's specific force, angular rate and sometimes the orientation of the body. The device is composed of three uniaxial accelerometers orthogonal to each other to measure the three axes *x, y* and *z* simultaneously, one transducer (micro-electro-mechanical system MEMS) that detects movement and transforms the mechanical signal into an electric one. Frequently in IMUs the accelerometer is combined with a gyroscope. Also, gyroscope is a MEMS device, which measures angular velocities and orientation (39).

IMUs, thanks to the reduced size and costs of their components, are easy to wear and low-cost tools for movement analysis. In addition these can allow to estimate with great accuracy the kinematic parameters as well as the position, the acceleration, and the speed produced by the movement.

These measurement systems have transformed the functional analysis allowing an objective movement analysis of patients with neurological diseases. In particular, IMUs and the sensors that compose them (accelerometer, gyroscope, magnetometer), can allow to estimate with great accuracy the kinematic parameters just like the position, the acceleration, and the speed produced by the movement.

Accelerometer

An accelerometer is a sensor capable of measuring the acceleration along its axes, calculating the force detected with respect to the center of mass of the object. The

operating principle is based on the detection of the inertia of a mass when subject to acceleration.

The Accelerometer is mainly composed of a test mass connected to a mechanical suspension system. In the presence of an acceleration, the mass moves from its rest position in proportion to the detected acceleration. The change in position with respect to the reference, due to the force, generates an electric charge proportional to acceleration, thus allowing its measurement (40).

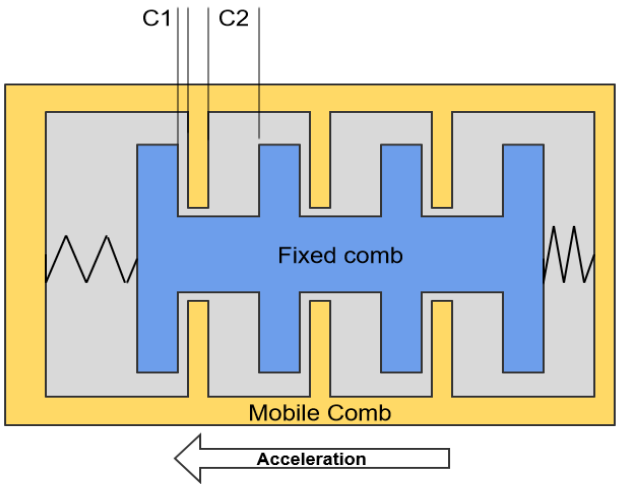

Figure 3: Accelerometer Scheme

Gyroscope

The gyroscope is a rotating device used for measuring angular velocity. Structure of this sensor is formed by a resonant test mass and is based on measurement of the Coriolis force applied to this mass to obtain the aforementioned velocity.

The gyroscope, in gait analysis, is mainly used for the measurement of posture and movement of segments of the human body (41).

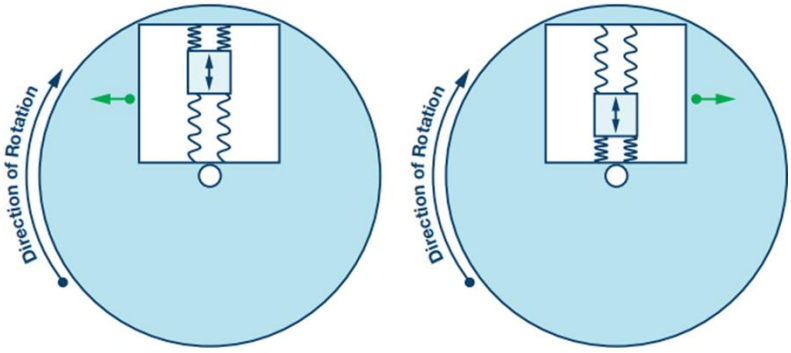

Figure 4: Gyroscope Scheme

Magnetometer

The magnetometer is a sensor that measures the changes in orientation of a body with respect to magnetic North pole exploiting the magneto-resistive effect. Magnetoresistance is the property of some materials to change the value of their electrical resistance in the presence of an external magnetic field.

Analysing the case of magnetic flux between two plates, the current undergoes the effect of the Lorentz force. This force changes the current flow among the two plates, and the current path turns out to be longer.

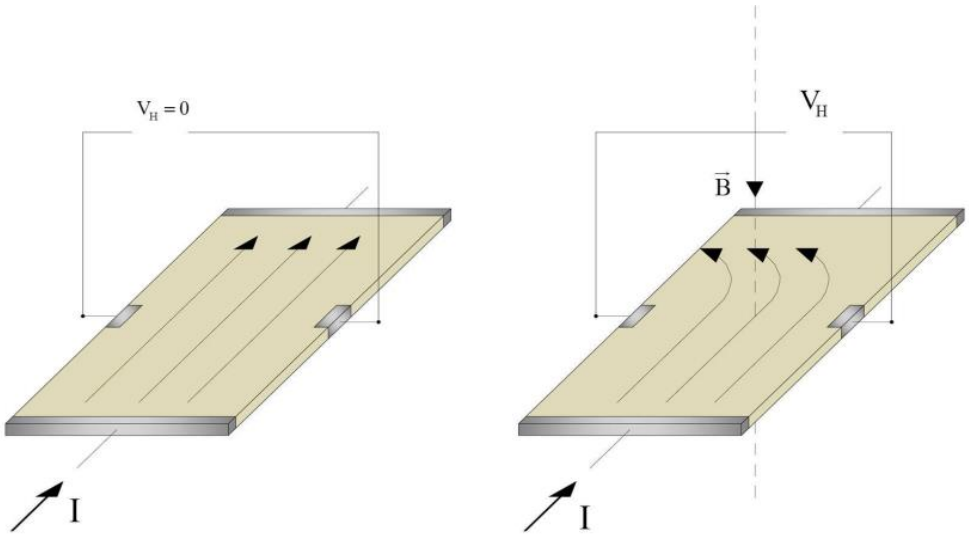

Figure 5: Analysis of the operation of Magnetometer

4. ACQUISITION AND DATA ANALYSIS

The aim of this work of thesis was identify the numerical parameters of gait of patients affected by Parkinson's disease. The parameters were obtained through the time-domain analysis of signals obtained from inertial sensors, tri-axis accelerometers, and gyroscopes. The signals were acquired during the walk of patients.

4.1 Dataset

The data acquisition was conducted at the Molinette Hospital, Turin, in the Parkinson and gait disorder ambulatory. 15 patients took e part to this study, 53,33% male and 46,67% female. The subjects involved had received a certain diagnosis of Parkinson's disease for at least a couple of years. The disease stage and postural state ware evaluated by a doctor through the UPDRS, Fall Efficacy

(FES), Hoehn and Yahr, MoCA scales, Parkinson's Disease and FOG questionnaires.

Table 1: Clinical Data

	N. of patients	Age (average + std)	Deasis duration (average + std)	H&Y (average + std)
Tot.	15	69,87 ± 7,66	10,93 ± 6,53	2,71 ± 0,67
Male	8	71 ± 9,62	12,25 ± 7,16	2,50 ± 0,76
Female	7	68,57 ±5,91	9,43 ± 6,60	2,93 ± 0,60

	UPDRS I (average + std)	UPDRS II (average + std)	UPDRS III (average + std)	MoCA (average + std)
Tot.	17,33 ± 4,84	20,67 ± 7,64	38,46 ± 14,13	2,5 ± 3,46
Male	16,75 ± 5,06	20 ± 8,43	38,75 ± 17,68	21,4 ± 1,85
Female	18 ± 5,26	21,42 ±7,87	38,14 ± 11,59	21,67 ± 5,35

After statistical analysis it was possible to evaluate that there are no significant differences between the data collected on male and female patients. The analysis was performed in *MATLAB*. The algorithm tests the null hypothesis that data of Male and Female are samples from continuous distributions with equal medians, against the alternative that they are not.

4.2 Sensor and Data Acquisition

For these measurements two *Nordic Thingy:52* were used attached to the ankles of the patients. In the case under study the sensors were connected through Bluetooth to a phone used to monitor the charge status of sensors and control the data collection.

Figure 6: Sensor device worn by the Patient

For measurements the signals from tri-axis accelerometer and gyroscope of each IMU were taken into account. Daily physical activities have a maximum frequency of 20 Hz, hence, the characteristics of the chosen sensors are suitable for measuring the chosen signals, in particular the 60Hz sampling frequency (42) (43).

Table 2: Accelerometer and Gyroscope specifications

	Range	Sample frequency
Accelerometer	± 1g	60 Hz
Gyroscope	± 1000 dps	60Hz

The detection system was positioned in such a way that the sensors had the x axis arranged to be parallel to the ankles like in the picture below. The sensors were anchored to the patient by means of a velcro-cuff in a stable position so that they did not change position during the walk.

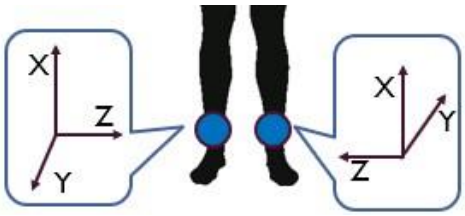

Figure 7: Orientation of the Axis on the legs

The recording of the signals of interest was conducted during the patient's motor inspection. In particular, the gait analysis was conducted by making the patient walk along a straight line inside the clinic for 2 or 3 times and making him/her take a turn once he/she reached the edge of the room to go back; then, in order to increase the difficulty, elements were introduced to create bottlenecks, such as the passage through two chairs positioned in such a way to narrow the roadway in which the patient was walking.

The data collected on the smartphone were then transferred to a PC to perform a first offline manual classification, carried out through a special *MATLAB* algorithm. Each signal was classified by observing the x, y and z components of the accelerometer and gyroscope and classifying the activity carried out in a specific task with a different number:

1. Timed-up-and-go test. The subjects stand-up from a chair, walks back and forth for 10 meters, and then sits down.

2. Stance. The subject keeps a still upright position for 1 minute.

3. Walk. The subject walks back and forth for 10 meters.

4. Walk + obstacle. The subject walks back and forth for 10 meters, with an interposition of two chairs (narrowing of the hallway).

5. Walk + motor dual task. The subject walks back and forth for 10 meters, carrying a glass full of water.

6. Walk + cognitive dual task. The subject walks back and forth for 10 meters, counting down from 100 to 0 with steps of

7. The second task was not taken into consideration for gait analysis.

4.3 Signal Characteristics

The recorded signal has 6 components, relating to acceleration and angular velocity along the vertical direction (x axis), the mid-lateral direction (y axis) and the antero-posterior direction (z axis). By observing the respective components of each signal, it is possible to appreciate characteristics and differences, which allow to distinguish the different activities that the subject is carrying out (in particular, as regards this study, the walk signals). In this study the changes of direction, the stand and the postural transitions were analysed.

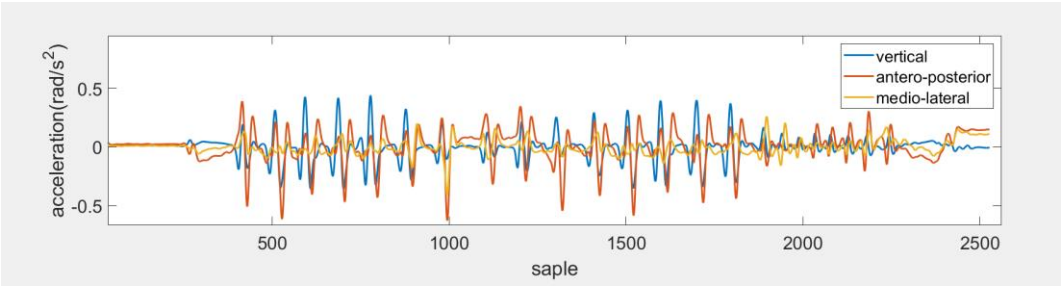

Figure 8: output signals of the sensor on left ankle – acceleration

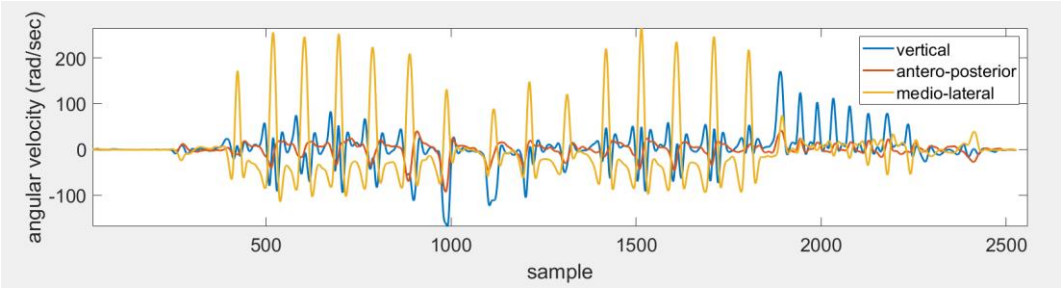

Figure 9: output signals of the sensor on left ankle – angular velocity

4.4 Signal Analysis

To study the path of patients and obtain parameters comparable to clinical results, a signal analysis was performed on the output signals of both sensors applied on the ankles. In particular the signals of angular velocity along the y axis was analysed.

For each signal it was identified a time period in which the patient was walk at regime.

First of all the signal was filtered with a fourth order Butterworth filter characterized by cut off frequency equal to 2.5 Hz. To obtain reliable results it was necessary identify the range of time where the signals exhibit a regular trend; for this reason it was necessary find a corrects peaks that represent a patients' path.

To do a feature extraction it was necessary to implemented an algorithm that finds significant peaks, the maximum and the minimum. To obtain good values of the desired parameters it was appropriate to keep in consideration only those peaks that are at least a certain number of samples apart from each other. Each peak has been identified in order to proceed with the computation of fundamental parameters in the walk analysis.

Both heel strike (HS) and toe off (TO) these events are used in gait analysis because of the other temporal parameters like swing, stance and stride time can be directly computed from them.

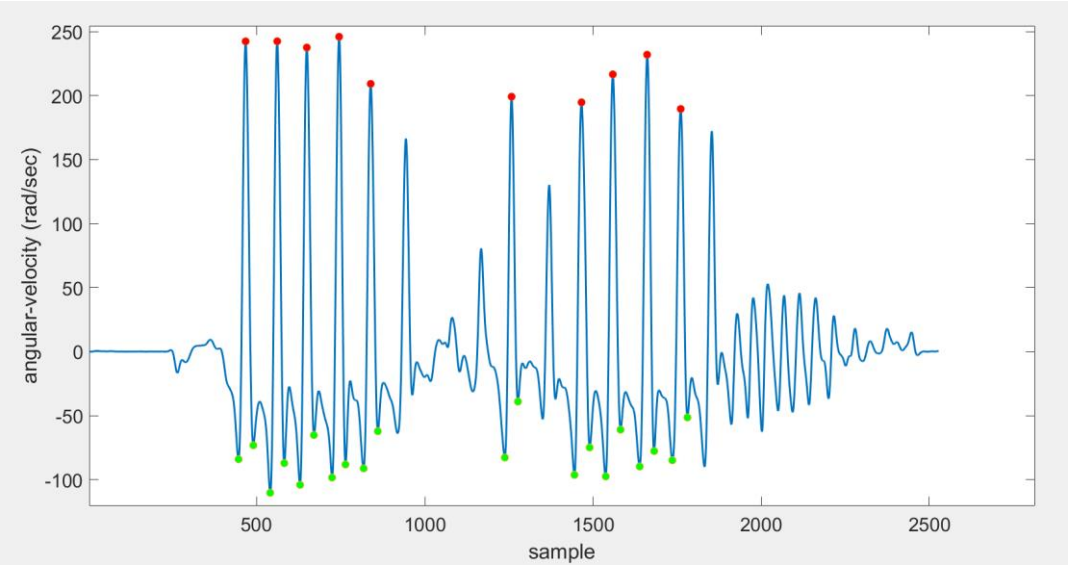

Figure 10: Analysis of fundamental Peaks for path monitoring

For the signal analysis it was considered important to take into account the following values:

- Step Time;
- Swing Time;
- Stance Time;
- Stride Time;
- Strike Time;
- Double Support;
- Mid Swing.

To find the parameters mentioned above, it was necessary to identify between the minimum peaks those to the right and left of each peak maximum. The minimum peaks represent the initial contacts and final contacts, the maximum peaks, instead, represent the time in which the foot is in the air.

The **Step Time** is the time between one step and another and is measured by calculating the time between the initial contact of one foot and the initial contact of the other foot.

The **Swing Time** is the amount of time the foot spends off the ground in the gait cycle, defined by the time from toe off to heel strike of the same foot. It was evaluated as the time elapsing between the initial and the final contact of the same foot.

The **Stance Time** is the contact time between the foot and the ground, and it was evaluated like the difference between the time of initial contact and final contact of the same foot.

The **Stride Time** is the time interval between two successive instants of contact between the same foot and the ground. It is calculated by evaluating the difference between two consecutive Heel-Strikes of the same foot.

The **Strike Time** is the time interval between two successive instants of swing peaks.

Double Support is the short time interval in which both feet are on the ground.

The **Mid Swing** goes from 75-87% of the gait cycle (43). During mid-swing, limb advancement continues, and the thigh reaches its peak advancement. Is the time interval that can be measured halfway between an initial and final contact.

In order to have reliable values that can be compared with the clinical data obtained from medical analysis, it was necessary to eliminate values that deviate 1.5 times the average of the vectors obtained (44).

4.5 Data Processing

For each task of each patient the parameters mentioned above were calculated, and then the mean and the standard deviation of all parameters were computed.

4.5.1 Tasks Analysis

The graph in the Figure 11 represents the number of patients that performed the tasks and the number of tasks that was possible to analysed.

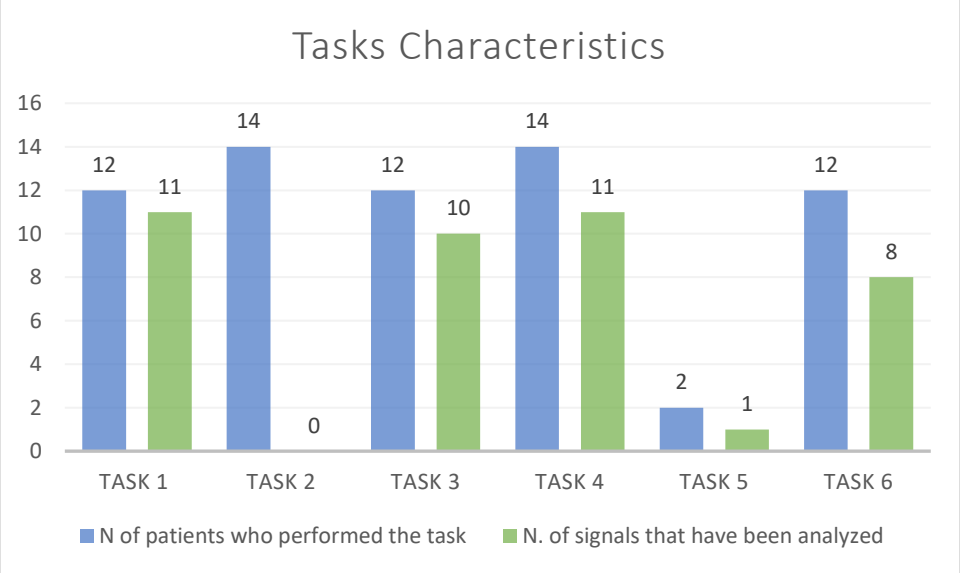

Figure 11: Tasks Characteristics

The most performed tasks are 2nd and 4th but the tasks that produced the most analysable signals are the 1st and the 4th.

The values of each parameter were saved in a structure in order to be able to perform comparisons between tasks of the same patient. For each patient the tasks were compared to a reference task i.e. a task is a task in which the patient walked straight. Cases where it was possible to analyse the task 1, this was taken as the reference task otherwise the task 3was used.

The comparison was computed through Wilcoxon signed-rank test, that allows to compute the probability that two matched samples X and Y come from continuous distribution with same mean. In Table 3 the results of the comparison are shown.

Table 3: tasks comparison for each patient

		Stride Time	Swing Time	Stance Time	Strike Time	Mid Swing
Patient1						
	task1-task4	**0.0156**	0.2500	0.0625	**0.0313**	0.2500
Patient2						
	task3-task4	0.0625	0.5	**0.0156**	0.0625	0.1875
	task3-task6	0.1563	0.6875	0.1563	0.1406	1.000
Patient3						
	task1-task4	**0.015625**	0.125	**0.015625**	**0.015625**	0.625
	task1-task6	0.15625	0.125	0.250	**0.046875**	0.250
Patient4						
	task1-task6	**0.015625**	**0.03125**	**0.015625**	**0.015625**	0.875
Patient5						
	task3-task5	**0.015625**	**0.0625**	**0.03125**	**0.015625**	0.421875
Patient6						
	task1-task4	**0.015625**	0.546875	**0.015625**	**0.015625**	0.4375

	task1-task6	0.21875	0.09375	0.09375	0.203125	0.25
Patient7						
	it was not possible to make a comparison					
Patient8						
	task1-task4	0.296875	**0.03125**	0.125	0.21875	0.750
Patient9						
	task1-task4	0.8750	0.8750	0.8750	1	0.625
	task1-task6	**0.015625**	**0.015625**	**0.015625**	**0.015625**	**0.03125**
Patient10						
	task1-task4	**0.03125**	0.125	**0.03125**	**0.015625**	0.1250
Patient11						
	it was not possible to make a comparison					
Patient12						
	task1-task4	0.7500	0.09375	1	0.343750	0.1250
Patient13						
	task1-task4	0.250	0.500	0.1250	0.234375	0.18750
	task1-task6	0.8750	0.6250	0.9062500	0.515625	0.125
Patient14						
	it was not possible to make a comparison					
Patient15						
	it was not possible to make a comparison					

This analysis was conducted only for the parameters Stride Time, Swing Time, Stance Time, Strike Time and Mid Swing as the parameters Double Support and Step Time reported few values and could not be used to obtain a reliable result.

For patients 3, 4, 5, 6, 9 and 10 a significant correlation was observed. The Strike Time is the parameter that has resulted most significant different from the other parameters with the score 54%. Stride Time and Stance Time resulted significantly

different in 46,66% of the performed tasks. In the following graph the percentages of variation of all the tasks is represented.

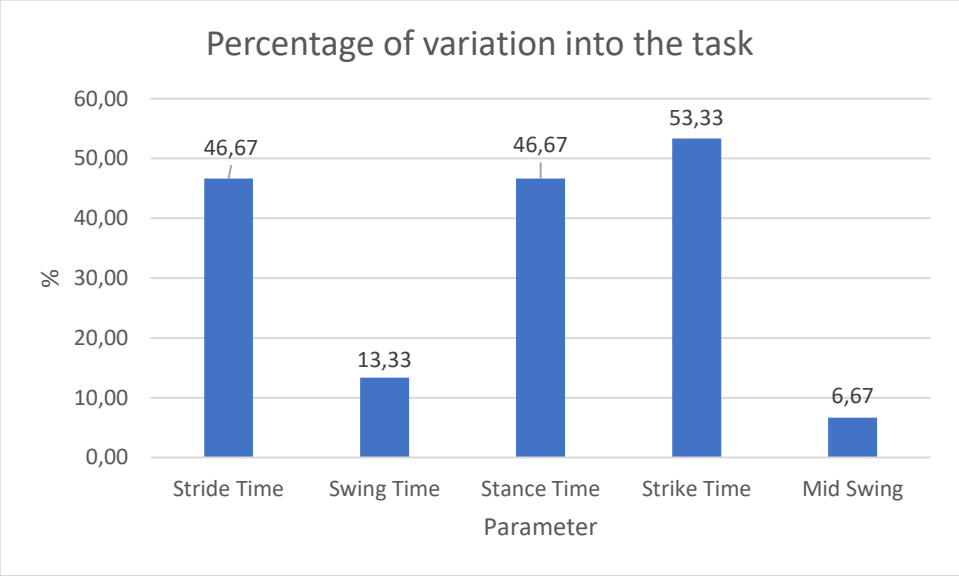

Figure 12: Percentage of variation in the tasks

Another step of this thesis work was to evaluate the average trend of the tasks performed by each patient. As it is shown in the Table 4, in most cases the mean increases from one task to another and, in particular, increases as the difficulty of the task increases.

Table 4: mean of tasks performed by the patient.

PATIENT	TASK	MEAN
Patient 1		
	T1	0.3333
	T4	0.3405
Patient 2		
	T3	0.3286

	T4	0.3429
	T6	0.3286
Patient 3		
	T1	0.3262
	T4	0.3190
	T6	0.3119
Patient 4		
	T1	0.3238
	T6	0.3167
Patient 5		
	T3	0.3167
	T6	0.3262
Patient 6		
	T1	0.3262
	T4	0.3333
	T6	0.3167
Patient 7		
	T4	0.3714
	T5	0.3667
Patient 8		
	T1	0.3190
	T4	0.3238
	T6	0.3238
Patient 9		
	T1	0.3119
	T4	0.3238
	T6	0.3476
Patient 10		
	T1	0.3310
	T4	0.3476
Patient 11		
	A/N	
Patient 12		
	T1	0.2833
	T4	0.2929
Patient 13		
	T1	0.3667
	T4	0.3571
	T6	0.3476
Patient 14		
	A/N	

Patient 15
A/N

For six patients the value of mean increases as the difficult increases, for fourth patients the value of mean decreases as the difficult increases, for two patients the mean value presents an irregular trend. For patient 11, patient 14 and patient a comparison15 was not possible to do. The signals extracted from the sensors during patients' walking was too disturbed to give reliable results that allow comparative tests to be carried out.

4.5.2 Correlation between Parameters and Clinical Analysis

After the analysis of the tasks performed by each patient, this study focused on the comparison of the parameters obtained from the task in which the patients performed a TUG (Time Up and Go) (task 1 or task 3) and the clinical analyses obtained through clinical scales. In more detail, for each patient the mean and the standard deviation of each parameter of task 1 or task 3 was evaluated. For patients 7 and 14 task number 4 was use because the signals extracted from the sensors during the execution of tasks 1 and 3 were too disturbed to obtain analyzable results. The means and Standard deviation of parameters were correlated with the clinical analysis.

To find the relevant parameters among all those the coefficient of Pearson correlation was calculated. This parameter represents the linear correlation between the value of mean or standard deviation of each parameter and the score of clinical analysis. The Pearson correlation coefficient always has a value between -1 and 1,

where -1 represent the complete negative correlation, 0 is no correlation and 1 is the complete positive correlation (46).

Given a pair of variables X and Y the formula of the Pearson correlation coefficient ρ is the following:

$$\rho_{X,Y} = \frac{cov(X,Y)}{\sigma_X \cdot \sigma_Y}$$

Where:

- cov is the covariance;
- σ_X is the standard deviation of X;
- σ_Y is the standard deviation of Y;

The statistical meaning of $\rho_{X,Y}$ is given by the *p-value;* this parameter is used to determine if the Pearson correlation coefficient is significantly different from zero.

In the case studied a very small *p-value* leads to the rejection of the hypothesis of correlation between the parameters considered. In particular, a threshold of *p-value* minor of 0.05 is selected.

The following tables show the results obtained from the correlation between the average of each patient's parameters and the results obtained from the clinical scales.

Table 5:correlation between UPDRS-III, FOG-Q and means of parameters

	UPDRS- III		FOG-Q	
	rho	**p-val**	**rho**	**p-val**
Stride Time	0.441253	0.09966325	0.4955189	0.0603406
Swing Time	0.28614	0.30118349	0.365842	0.1799098791
Stance Time	0.492493	0.062173493	0.5062529	0.054154770672
Strike Time	0.4347954	0.10531014	0.499711353	0.057866424
Mid Swing	0.286636	0.300309361	0.3792459	0.1632791580
Double Support	-0.270289	0.329902639	0.06999849	0.8042220
Step Time	0.43529	0.104863577	0.419201912	0.11985661

Table 6: correlation between MoCA, FES-1 and means of parameters

	MoCA		FES-1	
	rho	**p-val**	**rho**	**p-val**
Stride Time	-0.086948372	0.7579918	-0.035511324	0.90001578
Swing Time	0.03667536	0.896754244	-0.04271028	0.8798706
Stance Time	-0.161754	0.564657	-0.03328992	0.90624403
Strike Time	-0.08070474	0.774941228	-0.030914	0.912908
Mid Swing	-0.019211	0.945821451	0.0113649	0.96793474
Double Support	-0.034209564	0.90366495	-0.26786744	0.33442429
Step Time	-0.170785	0.542814099	-0.044878	0.873816

Table 7:correlation between PDQ-8 and means of parameters

	PDQ-8	
	rho	**p-val**
Stride Time	-0.254131238	0.360720882
Swing Time	-0.2072827	0.45853266
Stance Time	-0.29648015	0.283267665
Strike Time	-0.2566442	0.355826916
Mid Swing	-0.205857	0.461696838
Double Support	-0.3738687	0.1698237
Step Time	-0.035632847	0.8996752

Table 8: correlation between UPDRS-III, FOG-Q and standard deviations of parameters

	UPDRS-III		FOG-Q	
	rho	**p-val**	**rho**	**p-val**
Stride Time	0.25887	0.351520	0.5212	**0.0462952**

Swing Time	0.25041	0.368030	0.3626	0.1840580
Stance Time	0.41461	0.124384	0.57140	**0.0260704**
Strike Time	0.2529	0.36299	0.52111	**0.046375**
Mid Swing	0.2828	0.30703576	0.41373	0.125263
Double Support	0.20819	0.4565226	0.1657409	0.554969
Step Time	0.30781	0.2643722	0.42186	0.1172804

Table 9: correlation between MoCA, FES-1 and standard deviations of parameters

	MoCA		**FES-1**	
	rho	**p-val**	**rho**	**p-val**
Stride Time	-0.05846	0.29885	0.5212	0.2792
Swing Time	-0.009	0.25469	0.3626	0.35961
Stance Time	-0.13734	0.469694	0.57140	0.077305
Strike Time	-0.0618179	0.30028	0.52111	0.2768454
Mid Swing	-0.136784	0.266116	0.41373	0.33771473
Double Support	0.1047	0.1032067	0.1657409	0.71434966
Step Time	-0.04635	0.278309	0.42186	0.315184

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Table 10: correlation between PDQ-8 and standard deviations of parameters

	PDQ-8	
	rho	**p-val**
Stride Time	0.11940	0.67167
Swing Time	-0.13392	0.6341
Stance Time	0.17072	0.54295
Strike Time	0.1184	0.6742643
Mid Swing	-0.028243	0.920411
Double Support	0.05106	0.85658
Step Time	-0.0422	0.88127

Only in the table 8, for the FOG questionnaire there are some parameters with a significant value of *p-value*: stride time, stance time and strike time.

5. RESULTS

In this chapter we will explain the results obtained from:

- Wilcoxon Signed-Rank Test
- Mean Check of Patients' Tasks
- Pearson Correlation between Data and Clinical Scale.

5.1 Wilcoxon Signed-Rank Test

The Wilcoxon Signed-Rank test was performed on the tasks of the same patient. In particular, the characteristic parameters of the gait recorded in each task were compared.

From the values obtained it is possible to observe that overall, there is a correlation between the patients' tasks. In more detail, for 25% of the comparisons made there is a weak correlation, while only for 18.75% it is found that there is no correlation between the tasks. Specifically, it was hypothesized that if the result of the Wilcoxon Signed-Rank test reported a correlation value less than 0.05 for at least four parameters, then the correlation should be considered null.

5.2 Mean check of Patients' Tasks

Second step of this work was to evaluate the mean trend of the tasks performed by each patient. The results of this analysis seem quite good; for 50% of patients, the average of the parameters calculated for each task increases as the difficulty of the task increases. The other half of the patients have either an average value that

decreases as difficulty increases or an irregular trend that does not allow any conclusions to be drawn.

5.3 Pearson Correlation between Data and Clinical Scale

Finally, the correlation was evaluate between the parameters obtained from the task in which the patients walked at regime along a corridor (task 1 or task 3) and the value of clinical scales. The Pearson correlation reports, undoubtedly, the best results of this thesis work. This test showed that for each patient there is a correlation between mean value of parameters and the value of Clinical scales. The same is true for the correlation between standard deviation value of parameters and the value of clinical scales.

6. DISCUSSION

This thesis work proposes a robust algorithm able to recognize and save time-domain parameters useful for the analysis of the path. This can be applied in disease monitoring, particularly in this study was used for monitoring the path of Parkinson's disease patients.

Through the analysis of the signals recorded by the sensors applied to the ankles of each patient it was possible to identify a certain number of temporal parameters correlated with the trend of the patient himself.

The results obtained from different tests conducted are promising, the algorithm proved to be reliable for the recognition of the different phases of the gait cycle:

Pre-Swing, Initial Swing, Terminal Swing, Initial Contact, Loading Response, Mid Stance, Terminal Stance. In addition, the presence of different patterns among the patients does not seem to have complicated the activities to do, for most of the patients it was possible to obtain good results and make comparisons.

The results obtained from the Wilcoxon signed-rank test are satisfactory. The aim of this test was to verify how the time parameters collected vary according to the difficulty of the task. Results report that for 50% of patients, the average time to execute a step increases as the difficult of tasks increases. To achieve optimal results it would be necessary to increase the number of patients on which to perform this type of test.

The correlation between the parameters obtained by the algorithm and the clinical evaluations was positive in more than 90% of the cases. To confirm the feasibility and effectiveness of wearable sensors in the field of diagnostics and monitoring, it would be appropriate to extend the dataset and in particular also evaluate spatial or spatio-temporal parameters, such as: cadence, speed variability, velocity, stride length and step length (47) (48).

In addition, for remote monitoring in the home environment it would be appropriate to use wearable and practical sensors for the patients. Therefore, for future research it would be appropriate to study the gait in subjects suffering from Parkinson's disease through wearable sensors that can be applied to the wrist.

7. CONCLUSION

In this thesis work a method has been proposed to evaluate and monitor the path of individuals affected by Parkinson's disease through the analysis of temporal parameters. Irregular path is one of the most common symptoms in patients with Parkinson's disease, this is evaluated through kinematic tests presided over by a specialist. To have an objective evaluation it is possible to use an algorithm which, on the basis of pre-selected values, obtains parameters indicative of the patient's disease progression. The parameter values obtained can be defined as reliable thanks to the results of correlation with clinical evaluations, therefore, this demonstrates the validity of the use of inertial sensors in the field of diagnosis and monitoring of Parkinson's disease. Today, integrated sensors are within everyone's reach. This would allow the use of monitoring devices even outside the clinical environment, offering the possibility of continuous monitoring.

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