ANA FILIPA NIZA AGUIAR

VALIDITY OF A MARKERLESS 3D MOTION ANALYSIS SYSTEM FOR ASSESSING GAIT IN ACTIVE ELDERLY PEOPLE: INFLUENCE OF CLOTHING ON THE KINEMATIC AND KINETIC DATA

Biomedical Engineering Master's Dissertation Report

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FACULDADE DE MOTRICIDADE HUMANA

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I dedicate this dissertation to my parents, my brother, my sister-in-law and my boyfriend for their patience, advice, and unwavering support.

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Abstract

Gait analysis (GA) is crucial for understanding age-related changes, falls and instability in active older adults. Traditional GA methods have significant limitations, particularly related to marker/sensor positioning, calibration and controlled environment, prompting the exploration of alternative approaches. Therefore, there is a growing interest in markerless (ML) analysis methods for tridimensional gait analysis (3DGA) in active older adults.

Although the ML system seems appealing due to its ability to overcome the limitations of other methods, the exact influence of clothing on the collected data is still unknown. Therefore, the aim of this study is to investigate the influence of clothing on the kinetic and kinematic data obtained from the gait of active healthy elderly individuals.

This cross-sectional observational study included thirty participants and compared two types of clothing conditions: Minimal Clothing (MC) (tight shirt and lycra shorts) and Self-selected Clothing (SSC) (unrestricted casual clothing) while the participants walked back and forth in a walkway of 12m long at their desired and comfortable speed. The main variables analyzed were lower limb joint angles and moments.

The results obtained showed almost no differences between clothing conditions. The overall kinematic and kinetic curve patterns, across all joints and axes, were similar. The Root Mean Squared Difference (RMSD) values ranged between 1.6º to 3.7º for joint angles and 0.02 Nm/Kg to 0.11 Nm/Kg for joint moments, reinforcing the overall low deviation between the clothing conditions.

In conclusion, the output of this work shows that what was thought to be a limiting factor for this type of analysis did not prove to be one, since the results were positive and within expectations, following previous studies, highlighting the potential of validity of this kind of system.

Keywords: : Gait analysis; Aging; Active older adults; Kinetics and Kinematics.

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List of Acronyms and Abbreviations

3D	Tridimensional
3DGA	Tridimensional Gait Analysis
BMI	Body Mass Index
CoF	Cut-off frequency
CPF	Composite Physical Function
DOF	Degrees of Freedom
GA	Gait Analysis
MB	Marker-based
MC	Minimal Clothing
ML	Markerless
MLGA	Markerless Gait Analysis
MoCA	Montreal Cognitive Assessment
MRI	Magnetic Resonance Imaging
POSE	Position and Orientation of the Segment
RMSD	Root Mean Squared Difference
ROM	Range Of Motion
SD	Standard Deviation
SSC	Self-selected Clothing

List of Symbols

%	Percent
<	Lower than
>	Bigger than
±	Plus or minus
≤	Lower or equal than
≥	Bigger or equal than
Hz	Hertz
Kg	Kilogram
Kg/m^2	Kilogram per square meter
m	Meter
N	Newton
Nm/Kg	Newton meter per Kilogram
º	Degree

1. Introduction

Gait studies are crucial to understand changes in movement that occur with normal aging, which may be related to falls (Maki & McIlroy, 2006; Michalska et al., 2021) and/or postural control (Michalska et al., 2021). Although there are qualitative observation scales to analyze movement, these tools are more subjective and may not have the necessary sensitivity to accurately identify subtle changes that may occur in gait upon aging (Buckley et al., 2019).

There are several methods for performing a quantitative tridimensional gait analysis (3DGA), which can be divided into invasive and non-invasive methods. Invasive methods include X-ray stereophotogrammetry, bone pins and biplanar videoradiography (**Figure 1.1**). The disadvantages of these methods are mainly related to the high costs and the exposure to radiation, in the case of X-ray stereophotogrammetry and biplanar video radiography, and the fact that a confined space and invasive surgical intervention are required during the examination, in the case of bone pins.

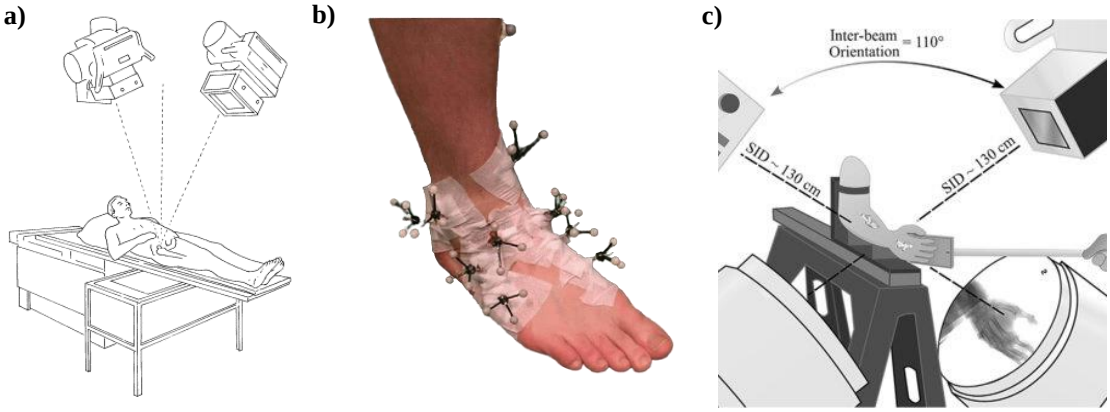

Figure 1.1 *Invasive methods: a) X-ray stereophotogrammetry, b) bone pins and c) biplanar videoradiography (Adapted from (Akhbari et al., 2019; Maiwald et al., 2017; Valstar et al., 2002))*

Non-invasive methods include non-invasive image analysis systems, electromagnetic systems, inertial systems and optical systems (**Figure 1.2**). Non-invasive image analysis systems, like Magnetic Resonance Imaging (MRI), have disadvantages related to the limited volume capture of anatomical details and the high costs involved (Sheehan & Smith, 2018).

Figure 1.2 *Non-invasive methods: a) electromagnetic systems, b) inertial systems and c) optical systems (Adapted from (Cresswell et al., 2017; Hafer et al., 2015; Skvortsov et al., 2024))*

In electromagnetic systems, there can be a distortion in the results if there is metal around the measurement area (Bull et al., 1998; Schuler et al., 2005) and there is an increase in noise and a decrease in signal quality if the distance between the sensor and the transmitter is greater than stipulated, which rounds about 1,5m (Urbanczyk et al., 2021). Furthermore, these types of systems are only able to collect at low sample frequencies of around 30Hz (Schuler et al., 2005).

Inertial systems have advantages over electromagnetic systems since they allow us to collect data far away from the computer and with a higher sampling frequency. On the other hand, this kind of system, particularly their constituents, are prone to interference from magnetic fields created by other devices, which makes their low accuracy unfeasible to consider in studies of linear data, in which the error is bigger (Della Croce et al., 2018; Mobbs et al., 2022).

Optical systems include active markers and passive markers systems. The limitations in the first case are related to the fact that the person needs to have power supplies, or a computer attached to them, which can alter movement due to the discomfort caused. In the second case, there is the limitation of the extreme control required over the surrounding environment, particularly in terms of lighting. In such cases, artificial lighting is typically chosen to ensure consistency and avoid fluctuations in brightness, which might occur if external lighting were used. Additionally, there is the need to cover all elements that could reflect light (such as certain types of footwear) and, finally, the requirement for tight-fitting clothing, which can alter the movements of the participants, making the results less reliable (Gorton et al., 2009; Mobbs et al., 2022; Robles-García et al., 2015; Stebbins et al., 2023).

Although electromagnetic systems, inertial systems and optical systems work differently, they all require the placement of markers or sensors, so the result of the examination is affected by this placement and by the artifact generated by the soft tissues (Zemp et al., 2014). The artifact that arises not only generates error, but also increases the collection time (Fiorentino et al., 2017).

Considering the limitations of the aforementioned methods, gait analysis (GA) using markerless (ML) methods represents a promising approach. The latest methods incorporate artificial intelligence to identify the subject's joint centers, mitigating the errors related to poor marker positioning (Heitzmann et al., 2022) and allowing the person to be assessed while using their usual clothing.

Recent studies show that 3DGA using ML systems in healthy adults show that ML systems are reliable and valid (S. Liang et al., 2022; Riazati et al., 2022). However, this system has limitations regarding the detection of certain joint centers, namely the ankle joint, and the detection of certain angles in the frontal plane, namely the anterior pelvic tilt (Augustine et al., 2023; Scataglini et al., 2024).

Regarding the first issue related to the detection of joint centers, some studies suggested that this happened due to the variations in shoe types, particularly in the shoe sole and in the shoe height, used in the protocols (Eltoukhy et al., 2017; Mentiplay et al., 2015). After removing the footwear factor from the protocol, some authors have hypothesized that there was low contrast between the participants' skin and the walking pad, which made it impossible to make a clear distinction between those, specifically in the moment of the foot contact with the ground (Ma et al., 2020; Scataglini et al., 2024).

Concerning the issue related to the detection of the anterior pelvic tilt, one of the hypotheses is that one of the factors generating this error is the clothes that the participants wear, such as long trousers and overlapping clothing (Augustine et al., 2023; Heitzmann et al., 2022). Besides that, there is another hypothesis stating that this may be related to the shift that occurs in the accumulation of fat from the lower limbs to the pelvic region upon normal aging, hence the importance of studying samples with elderly people (Sepe et al., 2011).

Besides the clothing used, other factors can also influence the results, namely the changes that naturally occur with normal and healthy aging. It is also known that gait parameters, such as joint angles, joint moments and joint power in the sagittal plane, will change with aging (excluding any age-related diseases).

Studies have shown that in most cases, regarding the kinematics, there can be seen an increase in hip flexion at heel-strike and peak flexion; decrease of hip and knee extension at heel-strike; decrease in the ankle dorsiflexion also at heel-strike. Besides that, there can also be seen an increase of the Range of Motion (ROM) at the hip and knee and a decrease of ROM in the ankle (Boyer et al., 2017).

Further, in some studies regarding the kinetics, it is observed an increase of the hip flexion moment and a decrease in the knee flexion moment and ankle dorsiflexion moment; an increase in hip extension moment and in ankle plantar flexion moment, and a decrease in knee extension moment; finally, there can be seen an increase in hip power generation and a reduced knee and ankle power generation (Boyer et al., 2017).

In addition to these parameters, it is also possible to see changes upon aging in the spatiotemporal variables, such as lower velocity, shorter stride and step length and also lower cadence (Chung et al., 2023; Kowalski et al., 2022).

1.1. Motivation and Objectives

The motivation for conducting this study has several key points, being the primary motivation the contribution to scientific knowledge, since the elderly age group is not typically chosen for this type of studies. Then, we have the contribution to the healthy behaviors, particularly the healthy aging, and well-being of the active older people, as a more accessible and painless evaluation will promote greater attention and ease the process, allowing to detect small nuances that might arise in gait, allowing for timely interventions; the development of specific protocols, which can only be drafted if there are several previous studies dedicated to validity of the systems; and finally, the social impact, considering that more accurate analyses can help shape health policies that encourage healthy movement, even in older age stages.

As previously described, markerless gait analysis (MLGA) still has some limitations regarding the clothing used by the people assessed, since there is still unknown the influence and impact that the attire may have on the collected data. Therefore, the aim of this study is to verify the influence of clothing worn on the kinematic and kinetic data obtained using ML systems in active healthy elderly.

1.2. Structure

This dissertation is organized into five main chapters and its corresponding subchapters, a references chapter and, finally, an appendix with 8 annexes attached. Further there is an overview of each chapter:

- Chapter 2: A review of the state of the art is conducted regarding GA methods, both invasive and non-invasive, followed by a comparison with other studies that considered different types of clothing in their conditions. Finally, an approach is made concerning the changes that naturally occur with healthy aging.
- Chapter 3: The description of the methodology followed is provided, starting from the beginning of the study, which involved recruiting the sample of participants, followed by the study design. Subsequently, the methods for data collection, which include the filling of questionnaires – MoCA, eligibility, characterization, EQ5D-3L and CPF – processing – through Python, Visual Studio Code, Theia and Visual3D – and analysis – mainly using Excel – are addressed. Additionally, at this stage, the variability in the clothing condition chosen by each participant – SSC – is also explored in a more visual manner.
- Chapter 4: At this stage, the results obtained are presented, both from the kinematic analysis – where the joint angles and their behavior in both clothing conditions studied were discussed – and from the kinetic analysis, which examined the behavior of the joint moments under these same conditions. To better visualize the aforementioned, graphs and tables were used to clearly summarize the results.

- Chapter 5: In this chapter, a discussion is carried out to compare all the parameters obtained and to connect them to the clothing condition. Additionally, an overall comparison is made between the results of both analyses, and the limitations identified are highlighted, which should be addressed in future studies to enhance the robustness of this methodology.
- Chapter 6: Finally, some conclusions are drawn that, in a way, summarize the work conducted. Additionally, future perspectives and potential studies are presented to overcome the limitations observed in this work.

2. State of the Art

2.1. Motion Analysis Methods

Quantitative analysis of tridimensional (3D) motion can be performed through invasive and non-invasive methods. Regarding the invasive methods, there are bone pins, X-ray stereophotogrammetry and biplanar videoradiography (Stebbins et al., 2023). The non-invasive methods include non-invasive image analysis systems, electromagnetic systems, inertial systems and optical systems (Maletsky et al., 2007).

In these systems, the concept of Position and Orientation of the Segment (POSE), which is a process of calculating the three translational parameters and three rotational parameters – usually referred to as six degrees of freedom (DOF) – is relevant, since this is the way of pinpointing the joint centers (Sethi et al., 2022).

Bone pins, which are a crucial part of studying artifacts generated by soft tissue, are generally used to measure the magnitude of relative errors – defined by the relative motion between two or more markers that define a bone segment – and the magnitude of absolute errors – described as the motion of a marker in relation to the bone landmark it represents – through comparison between data obtained by markers placed on the skin and markers fixed on bone pins.

After obtaining the magnitude of both errors, the data obtained by subcutaneous markers is compared with the data obtained by bone pins, from which results a direct measure of soft tissue movement in relation to the skeletal system (Stief, 2018; Wolf et al., 2022). Despite being a viable method, it ends up not being the most suitable due to being extremely uncomfortable and invasive for the person (Stief, 2018).

X-ray stereophotogrammetry is a technique generally used in order to obtain accurate 3D measurements from a radiograph. The way this works is basically related to the geometric characteristics of an object, since the calculations are only possible due to the fact that there is repetition of movements between repeated examinations (Kärrholm, 1989).

This gait analysis method provides 3D information, not only about POSE, but also about bone's relative motion. The disadvantages of this system are related to exposure to ionizing radiation, low resolution, difficulty in focusing during motion and the appearance of artifacts (Smith & Sheehan, 2018).

Biplanar videoradiography uses multiple views of X-ray examinations to capture bone movement. This method uses X-ray images obtained from two different perspectives to deduce accurate 3D information of the bones, particularly the POSE. This system allows: a) 3D knowledge of the exact locations of the joint centers and b) the possibility of accurately extracting the angles made by them (Kessler et al., 2019; Miranda et al., 2011).

This type of system can track the movement of a target joint, allowing the kinematics of various joints, such as the shoulder, hip, and knee, to be studied for a wide range of activities, including walking and running. Despite the advantages, this method presents limitations related to high costs and radiation exposure, making it impractical for applications that require frequent GA (Gray et al., 2018). The disadvantages of the invasive motion analysis systems are further synthesized in **Figure 2.1.1**.

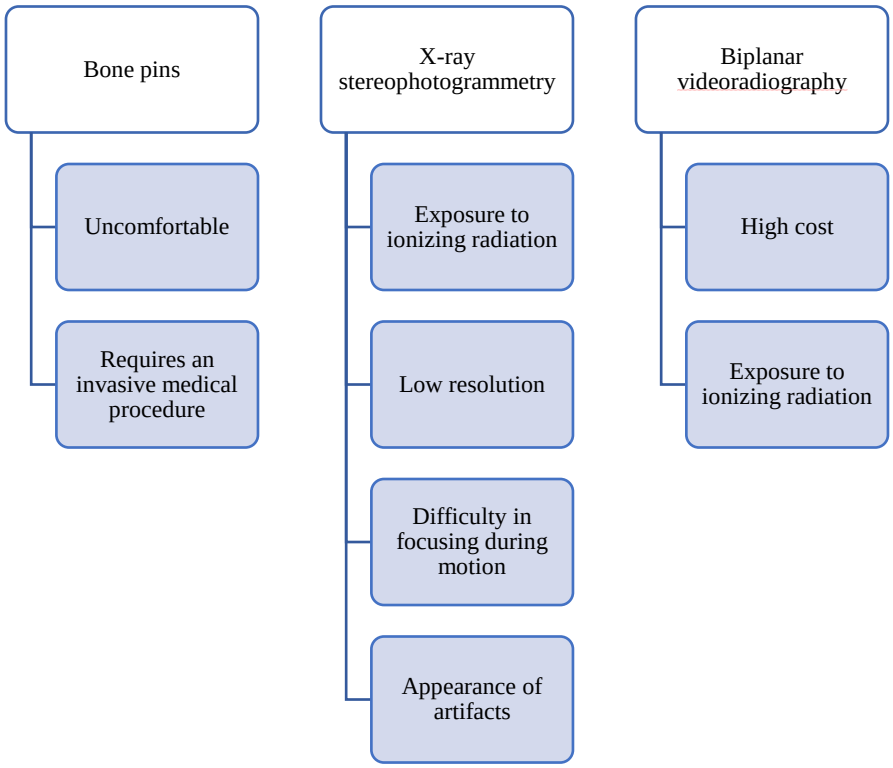

Figure 2.1.1 *Disadvantages of the invasive motion analysis systems mentioned.*

In the scope of non-invasive motion analysis systems, while attempting to eliminate the risks associated with prolonged contact with ionizing radiation, non-invasive image analysis systems that use MRI emerge. With these systems, it is possible to conduct qualitative studies of ankle joint movement and quantitative studies of active knee joint movement, per example (Sheehan & Smith, 2018).

This technique offers 3D quantitative data, having the advantage of high resolution and accuracy and the disadvantages of a limiting capture volume of anatomical details, especially in body parts where there is visual obstruction, per example the pelvic area, or when the surface is not well defined, considering that there's still an issue regarding the high costs (Smith & Sheehan, 2018).

Electromagnetic sensor systems record the POSE of a sensor relative to an emitted electromagnetic dipole field, and, through these, anatomical locations can be identified. These systems are limited in their accuracy due to the artifacts that are created by various metals in the measurement space (Selbie & Brown, 2018). In addition to this, they also have the disadvantage of requiring case-by-case calibration in order to obtain precise analyses, a smaller collection distance (1-3m) and a lower sampling frequency (100-120Hz) in comparison in other methods (Smith & Sheehan, 2018).

Inertial sensor systems measure linear acceleration – through accelerometers – angular velocity of the joints – through gyroscopes – and have a global reference frame – through the magnetometer. Through the combination of these three devices, this system can then perform calculations to determine the POSE, making it possible to perform the analysis of the gait (Della Croce et al., 2018).

Although this seems to be a very appealing method, due to the fact that it has a longer collection distance, being 10-30m in real-time monitoring, and a higher sampling frequency (50-200Hz) in comparison with other methods, the three devices are prone to interference from magnetic fields generated by other devices, which makes considering them for more detailed studies unfeasible due to low precision. The difference from other systems is that in this case, the determination of POSE is indirect, hence the need to perform the aforementioned calculations (Della Croce et al., 2018; Mobbs et al., 2022).

Optical systems are divided into systems that use active markers and systems that use passive markers. In the first automatic motion measurement system, which involved the use of active markers, the researchers used a video camera, a computer and a set of active markers at specific anatomical locations (Gorton et al., 2009).

The most noticeable advantage of this type of system is that, due to the sequential activation of markers emitting light, the POSE was already known by the computer and the main disadvantage is that the person needs to have power sources or a computer attached to them in order to enable the necessary reception of energy for marker activation, which inhibits data collection outside the laboratory context and makes the data collection a difficult task (Gorton et al., 2009; Robles-García et al., 2015; Stebbins et al., 2023).

Passive marker systems – which capture movements via optoelectronics – can identify POSE due to the use of infrared cameras because, unlike the previous system, these markers can reflect light coming from the cameras that shine on them. This allows the identification of POSE for subsequent calculation of respective joint positions and angles (Buckley et al., 2019). In this kind of system, the marker locations can be detected with sub-millimeter precision (Buckley et al., 2019; Topley & Richards, 2020), which also increases the precision and accuracy of the result. On the other hand, the need of a controlled environment for reliable results, may alter participants' movements because they are aware they are being observed, potentially leading to attempts to disguise any atypical gait pattern (Gorton et al., 2009; Robles-García et al., 2015), and we also have marker occlusions and unwanted reflections, with these being the main limitations of this kind of system (Skurowski & Pawlyta, 2022).

The systems using sensors and/or markers present issues related to their placement. Since this hardware must have exact locations for reading to be done with the least possible margin of error, if its placement is not carried out properly, errors that compromise the accuracy of the examination may come into sight (Zemp et al., 2014). In addition to this, these systems also have the disadvantage that, considering that the bone landmark is the point to be analyzed, artifacts from soft tissues can surface, which not only generates errors, but also increases the collection time and discomfort of the participant (Benoit et al., 2006; Fiorentino et al., 2017). The disadvantages of the non-invasive motion analysis systems are further summarized in **Figure 2.1.2**.

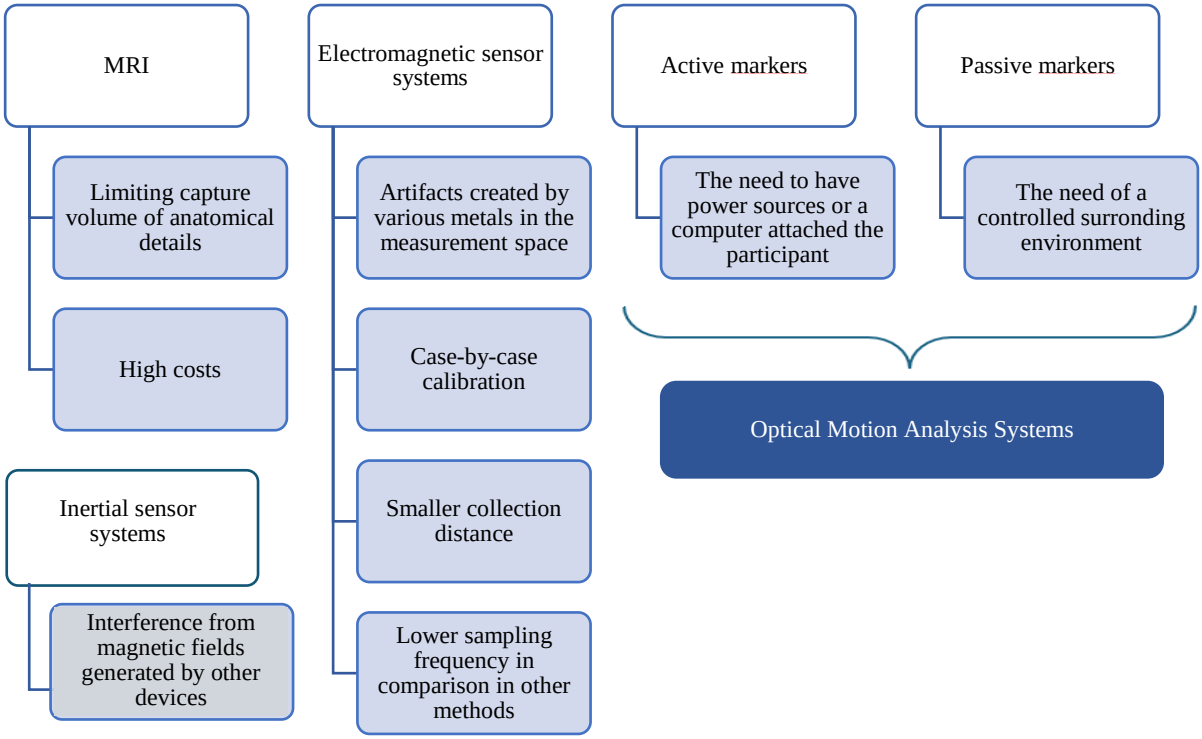

Figure 2.1.2 *Disadvantages of the non-invasive motion analysis systems mentioned*

Considering that a flaw-free method has not yet been found, attempts have been made to opt for less time-consuming methods that are independent of specialized technicians, thus giving rise to ML motion capture methods. This methodology uses video images to record motion without the need for sensors/markers (Wade et al., 2022).

The analysis of gait through ML methods represents a promising approach when there is a need for rapid acquisition of motion data in various gait-related contexts. By contrast to methods requiring person contours, the latest innovations incorporate artificial intelligence to identify subject joint centers, removing the errors related to sensor/marker misplacement from the equation (Heitzmann et al., 2022).

As expected, this method still has its issues. This system has problems in detecting anterior pelvic tilts. This happens due to long trousers and layered clothing. In addition to this, in the case of child patients, they may be more prone to changing their gait patterns when being on an unusual environment or when being observed (Augustine et al., 2023; Heitzmann et al., 2022).

The estimation of POSE in marker-based (MB) and ML systems is obtained by using at least three non-collinear bone landmarks to define the POSE of body segments, which is represented by the relationship between a local coordinate system and a global coordinate system (Caldwell et al., 2014).

Regardless of the system type, either in MB or ML systems, the central positions of the joints are estimated through regression approaches based on anthropometric measures from medical images, if you want to estimate the central position of the hip joint (Harrington et al., 2007) or functional approaches that approximate the center of rotation between two elements, if you want to estimate the articular center of the knee or ankle joint (Leboucher et al., 2021; Salami et al., 2020).

The difference between the systems can be seen in the articular point detection, since in passive MB systems these points are detected due to the reflection of infrared light and in the ML systems, the location of the joint centers is estimated using a set of training images, which is why artificial intelligence mechanisms are used (Kanko et al., 2021).

2.1.1. Clothing Comparison

As mentioned above, the clothing worn by the participants during the collection can clearly alter the result obtained (Augustine et al., 2023; Heitzmann et al., 2022). The clothing used in these studies may vary between a standard version – in which all the participants wear the same type of clothing – and a non-standard version – in which the participants have greater freedom to choose the clothing they consider most suitable for the collections (Horsak et al., 2024; Kanko et al., 2024).

In a study where standardization of the clothing type was carried out, most kinematic and kinetic results were consistent between systems – MB and ML – being the joint center positions, sagittal, frontal and axial plane angles differed by residual angles (Kanko et al., 2024).

Alternatively, it is also possible to standardize clothing in terms of color, in this case black and white clothing with the same type. Although there are differences in every calculated parameter – flexion, adduction and abduction, for both hip and knee – the main effects of sessions and interactions were not statistically significant for the variables of interest, meaning that although there were differences between white and black clothing, they were not significant enough to be considered related to the color of clothing (Valencia et al., 2023).

Regarding the studies in which a) there is no standardization or b) standardization is done only to a certain extent, the results show that clothing has a minimal effect on the results of ML motion capture in general (Horsak et al., 2024; Keller et al., 2022).

In a study where, in one trial, the participants were wearing unrestricted clothing and in the other trial they were wearing shorts and gym shirts, despite having lack of control of some variables – sleeve length and clothing color – the differences obtained were smaller than what was previously stated as the relevant threshold (Keller et al., 2022).

In the case of a study in which the participants had an unrestricted clothing trial and a minimal clothing trial, it was found that the clothing had minimal effects on the kinematics, not constraining movement, where there was only an addition, on average, of less than one degree to the Root Mean Squared Difference (RMSD) values for most of the variables, but it was also found that the segment lengths showed weak to moderate agreement between the clothing conditions, so it can be said that despite not showing much difference in the kinematic data, precision is compromised in this type of trial (Horsak et al., 2024).

It was also possible to observe, in a study conducted with participants with knee osteoarthritis, where clothing was not standardized, and all participants were assessed in the attire and footwear they chose to wear for each visit – representing a self-selected clothing scenario – with the aggravating factor that participant's choice of clothing and footwear varied slightly between visits.

Despite these variations, the study showed that measurements were repeatable between sessions, even with varied clothing scenarios. These changes of clothing, although might seem a limitation, are what truly represent the real-life scenarios in which, sometimes, the clothing standardization can't be achieved and, therefore, the outcomes reported in this study reflect this context (Outerleys et al., 2024).

Previous studies have some limitations, mostly regarding the type of movement studied, since some of them do not study the gait in particular, meaning they opt for jumping or running motion. Besides that, there is not usually a large sample nor a representative sample. In spite of the limitations, the conclusion seems to be similar in all of studies – clothing does not seem to have a major effect on the collections carried out (Ito et al., 2022; Valencia et al., 2023).

It is worth mentioning that the difference in this study compared to the others is the age group since, in previous studies, the sample is generally composed of adolescents or even adults, meaning that elderly people are rarely included, for whom the gait analysis is so important due to the changes that naturally arise with age, as will be reported later.

2.2. Gait Changes due to Aging

The gait cycle is divided into two main phases – stance phase, that makes up about 60% of the movement, and swing phase, that makes up about 40% of the movement. Besides this division, gait can also be subdivided into 8 steps – initial contact, loading response, mid stance, terminal stance, pre-swing, initial swing, mid swing and terminal swing (Stöckel et al., 2015).

The gait cycle begins when one foot – per example, the right foot – makes its first contact with the ground (initial contact or heel-strike) and ends when the same foot ends up touching the ground again. The stance phase occurs when there's contact with the ground, by the heel, toes or the foot overall, while the swing phase occurs when there's no contact with the ground, while the foot is in motion (Luximon & Zhang, 2006).

The phase that includes most of the movement – the stance phase – starts when the foot touches the ground with at the heel (heel-strike), and ends when the foot leaves the ground, being the last contact made with toe (toe-off) (Luximon & Zhang, 2006).

Regarding the swing phase, this starts when the foot stops having contact with the ground and end right when the foot is almost in contact with the ground again, meaning that meanwhile, all this portion of the movement happens with the foot off the ground (Luximon & Zhang, 2006), as can be seen in **Figure 2.2.1**.

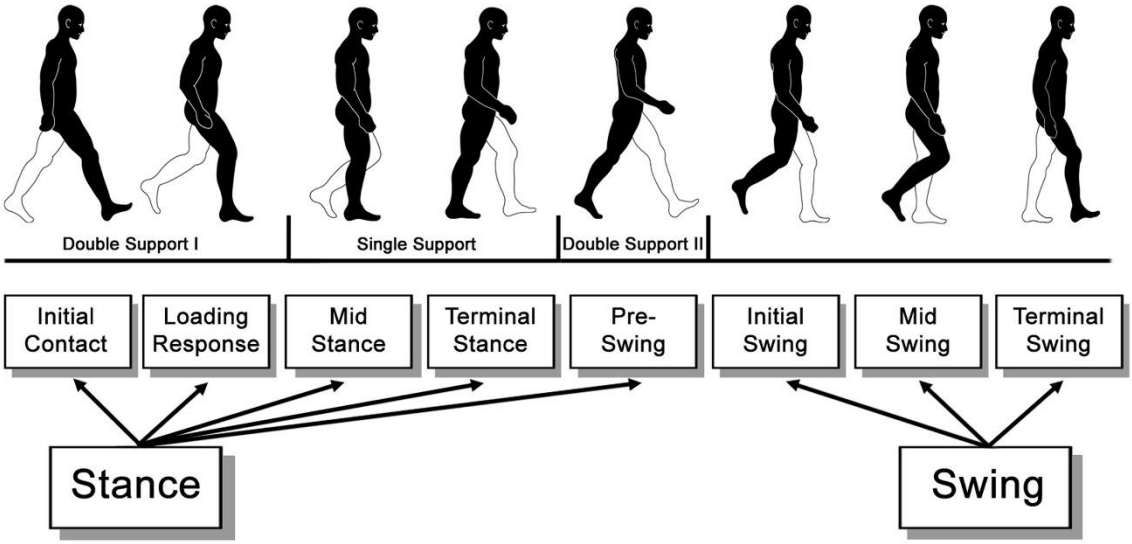

Figure 2.2.1 *Gait cycle phases ((Stöckel et al., 2015))*

With normal aging, certain conditions may arise in the neuromuscular system, including changes related to strength and balance (Michalska et al., 2021), which might affect gait. These changes can result in a decrease in mobility, which is a significant concern as this can affect overall health and, in some cases, even increase the risk of mortality (Leivseth et al., 1992). It is also crucial to highlight the possibility of muscle atrophy when mobility is practically non-existent (Boyer et al., 2017). As such, movement studies are important for understanding these changes, which is why comparative studies are usually carried out between young and older adults.

As the level of muscle strength declines with normal aging, there's an hypothesis that state that people unconsciously choose to recruit the hip extensor muscles more (Cofré et al., 2011; Franz & Kram, 2014) as a proposed compensation strategy, regarding the reduced role of the ankle plantar flexor (Franz, 2016), which may be indicative of a distal to proximal shift in muscle function with age (Boyer et al., 2017). However some studies report almost no differences at the hip power for the elderly (JudgeRoy et al., 1996; Kerrigan et al., 1998).

Some kinematic parameters – which refer to the angles – of the movement tend to change upon aging. Studies show a decrease of hip extension at heel-strike, peak flexion and peak extension, having a more pronounced ROM in comparison with younger adults; decrease of knee extension at heel-strike and midstance, decrease of knee flexion at peak flexion in the swing phase, having a more pronounced ROM in comparison with younger adults, as seen in the hip (Boyer et al., 2017). Regarding the ankle, we can see a decrease in ankle plantar flexion at toe-off and peak plantar flexion, a decreased dorsiflexion at heel-strike and a reduced ROM, in comparison with younger adults (Boyer et al., 2017).

Regarding gait kinetics – which refer to joint moments and joint power – it can usually be seen some reduction in the knee flexion and extension moments, as well as in ankle dorsiflexion moment. Besides that, there can be usually seen an increase in the flexion and extension moments of the hip, as well as an increase in the ankle plantar flexion moment (Boyer et al., 2017). In the power matter, we can usually observe an increase of hip power generation and a decrease in knee and ankle power generation (Boyer et al., 2017).

Concerning the spatiotemporal parameters, later studies have shown that with normal aging comes a decline in the velocity, cadence, step length and stride length (Chung et al., 2023; Kowalski et al., 2022).

In short, in terms of gait kinematics, the most significant changes are in the joint angles of lower limbs – a decrease in hip extension and a greater ROM in comparison with younger adults; a decrease of knee extension at heel-strike and a greater ROM in comparison with younger people; a reduced ankle dorsiflexion at heel-strike and a reduced ROM in comparison with younger adults.

Regarding gait kinetics, the most significant changes are in the joint moments of force – an increase in hip extension and flexion moments and in hip power generation; a decrease of knee extension and flexion moments and in knee power generation; a decrease of ankle dorsiflexion moments and in ankle power generation, and an increase of ankle plantar flexion moment, with this being the most important peak of elderly people gait, since this is directly related to the force used for propulsion, which is the mechanism that allows the body to move forward during walking. These changes are summarized in **Figure 2.2.1**.

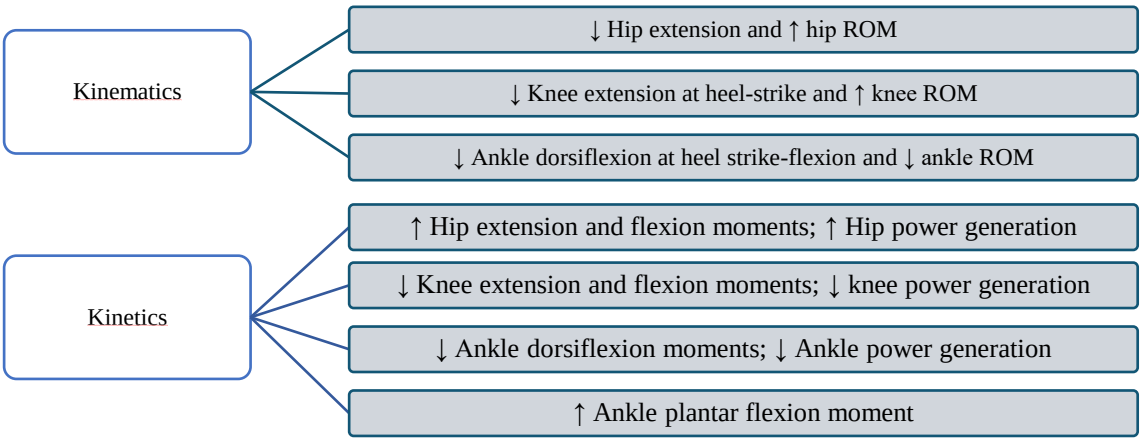

Figure 2.2.2 *Most common gait changes that occur upon healthy aging.*

The changes previously mentioned and summarized in **Figure 2.2.2** above appear throughout the stance phase, since this is the one most related to the preparation of the limb for the next contact with the ground (Pranke et al., 2006).

3. Methodology

3.1. Study Design and Sample

For this observational study with a cross-sectional design, a convenience sample of 30 active and healthy elderly people who met the following inclusion criteria, which was based on previous similar studies, were recruited:

- 65 years or older;
- Living independently;
- Being able to speak and read European Portuguese;
- Being able to answer the questionnaires;
- Being able to walk 100 meters independently, without the need of walking aids.

Active elderly people who met the following exclusion criteria were excluded:

- Report a diagnosis of any cardiac, pulmonary, musculoskeletal or neurological condition and/or mental illness that may affect the ability to walk;
- Taking any medication that affects the ability to walk.
- Having any pain or other symptoms in the lower limb that affects the ability to walk;
- Having any cognitive impairment (Montreal Cognitive Assessment (MoCA) score < 23);
- Being obese (Body Mass Index (BMI) >30 Kg/m^2).

After agreeing to take part in the study, the volunteer participants from the community associated with the Lisbon Living+ program, whose objective is to establish, promote, coordinate, and implement a program of activities in the Health field, focusing on the promotion of healthy living and active aging, filled in a free, informed, and explicit consent form (**Appendix I**), which contained general information about the study, as well as who would have access to the data, how it would be processed, the duration of participation, the benefits and risks of participation, how confidentiality would be handled, among other equally important information. The Faculty Ethics Committee (CEIFMH nº1/2022) approved this study.

3.2. Data Collection Procedures

Data collection involved participants to fill an eligibility questionnaire (**Appendix II**) and then they were applied the Portuguese version of the MoCA (Freitas et al., 2013) (**Appendix III**), by a certified assessor. The participants who met all the criteria were then invited to the data collection.

The eligibility questionnaire (**Appendix II**) included the collection of sociodemographic information, such as age, nationality, place of birth, educational qualifications, weight and height, whether the participant used any walking aid (walker, cane) or had any prosthetics in the lower limb joints, the presence of recent pathologies in the lower limbs, the presence of pain, and, finally, the existence of clinical conditions that could affect gait or balance (Parkinson's disease, multiple sclerosis, epilepsy, rheumatoid arthritis, fractures in the lower limbs, etc.). Regarding the MoCA (**Appendix III**), data was collected on visuospatial/executive ability, naming, memory, attention, language, abstraction, delayed recall, and orientation. In **Figure 3.2.1**, we have an excerpt of the aforementioned questionnaire.

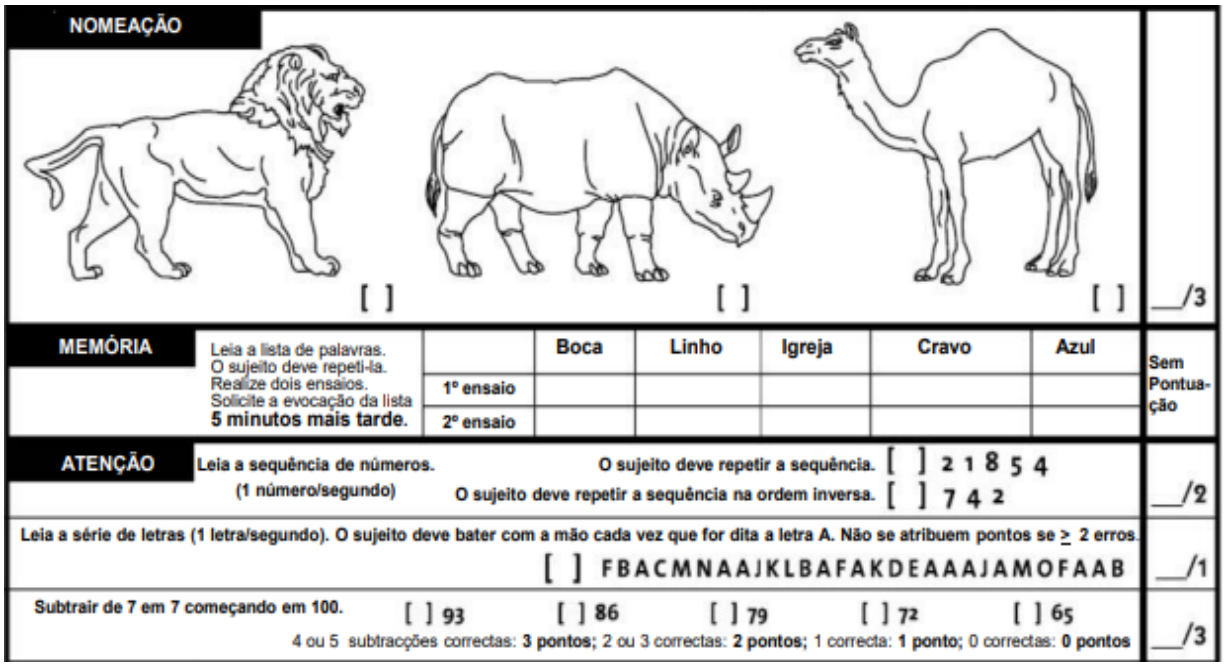

Figure 3.2.1 *Excerpt of the MoCA (Adapted from (Freitas et al., 2013))*

Once in the laboratory, the researcher checked if the participants had changed their demographic data or if any new events had occurred that influenced their health since completing the first questionnaire. Once everything was checked, the participants then filled in three more questionnaires:

- A characterization questionnaire (**Appendix IV**) which complemented the information obtained from the eligibility questionnaire (**Appendix II**);
- The Composite Physical Function Scale (CPF), adapted for European Portuguese (Moniz-Pereira et al., 2023)(**Appendix V**);
- The EQ5D-3L questionnaire, adapted for European Portuguese (Ferreira et al., 2013)(**Appendix VI**).

The characterization questionnaire (**Appendix IV**) was used to collect data regarding residence, professional status, health data related to gait pathologies (tripping, slipping, losing balance, etc.), the frequency of falls associated with these problems, the presence of pain, and, finally, the performance of physical exercise in the last 3 months, including its duration, frequency, and whether it was medically prescribed or not.

Regarding the CPF (**Appendix V**), it aimed to assess the participants' ability to perform daily tasks on a scale from 0 to 2, where zero corresponded to "cannot perform" and 2 corresponded to "can perform without assistance". Tasks such as basic personal needs, walking outdoors, light and heavy household chores, climbing and descending stairs, carrying light and heavy loads, among others, were assessed.

Finally, the EQ5D-3L questionnaire (**Appendix VI**) aimed to evaluate the participant's health condition on the day through a quantitative and qualitative description of mobility, self-care, usual activities, pain/discomfort, and anxiety/depression. Additionally, in the EQ5D-3L, there was a scale allowing the participants to rate their health from 0 to 100, where zero meant "the worst health imaginable" and one hundred meant "the best health imaginable" (**Figure 3.2.2**). It is important to emphasize that, indirectly, some of these questionnaires were also part of the exclusion criteria, because if a participant stated having pain or discomfort that could compromise their gait, the data gathered from this participant could not be considered for the study.

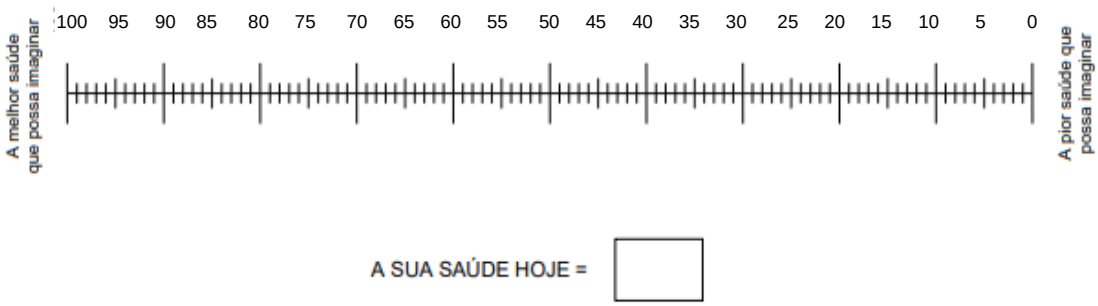

Figure 3.2.2 *Excerpt of the EQ5D-3L (Adapted from (Ferreira et al., 2013))*

After that, the participants performed the Timed Up & Go Test, which required the participant to get up from a chair, walk 3 meters, go around a cone and return to the chair at a pace that was comfortable for them (**Figure 3.2.3**). After completing the questionnaires and conducting the Timed Up & Go Test, the participants' mass and height were measured by the research team, to confirm what was stated previously in the questionnaires.

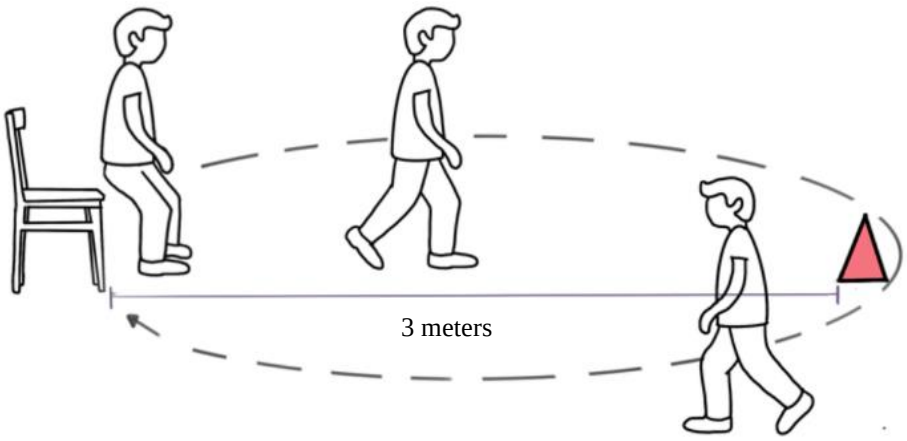

Figure 3.2.3 *Timed Up & Go scheme (Martín-Díaz et al., 2023).*

The participants walked along the laboratory twice in the same session: one with minimal clothing – MC – specifically lycra shorts and a sports t-shirt, and one with self-selected clothing – SSC – where the only clothing standardization was in the shoes, that had to be sports type. In the MC scenario, both MB and ML systems were used, whereas in the SSC scenario, only the ML system was used for data collection purposes. For the matter of the present study, only the data retrieved from the ML system was considered.

To better understand the lack of standardization, besides the shoe type imposed on the participants, it is important to see **Figure 3.2.4**. It is also important to emphasize that both trials were conducted randomly; that is, for some participants, the first trial was performed under the MC condition and the second trial was performed under the SSC condition, while for others, the first trial was conducted under the SSC condition and the second trial was performed under the MC condition, mainly in order to reduce the bias, to have homogeneity of the groups and also to achieve generalization of the results (Lim & In, 2019).

Figure 3.2.4 *SSC condition and the participants chosen attire (Carvalho et al., 2024).*

To collect markerless gait kinematics, the Qualisys Track Manager (v2021.03.1 Qualisys AB, Gothenburg, Sweden) was used with 8 Miqus cameras (Qualisys, SE) and synchronized with kinetic data, which was collected using 3 force plates (9283U014, Kistler Instruments Ltd, Winterthur, Switzerland; FP4060-07&FP4060-05-PT, BERTEC, Columbus OH, USA).

Kinematic data was collected at a sampling frequency of 85Hz, and kinetic data was collected at a sampling frequency of 850Hz. The participant was instructed to walk back and forth in a walkway of 12m long at their desired and comfortable speed. Only cycles in which both feet had stepped fully on the force platforms were considered.

Overall, around twenty cycles per participant were deemed valid, but only eight gait cycles were considered, as reliability seems to stabilize at eight cycles, and only the right-side joints – right hip, right knee and right ankle – were considered (Carvalho et al., 2024), since there is an assumption of symmetry between the right and left sides in healthy people and also because there is a convention of using the right side in many biomechanical previous studies (Wu & Wu, 2015).

Below, in **Figure 3.2.5**, it is possible to see the force platforms on which the participants had to walk, numbered from one to three, the reference used for the calibration of the MB and ML data collections and 2 of the 8 Miqus cameras (Qualisys, SE) set up for this data collection.

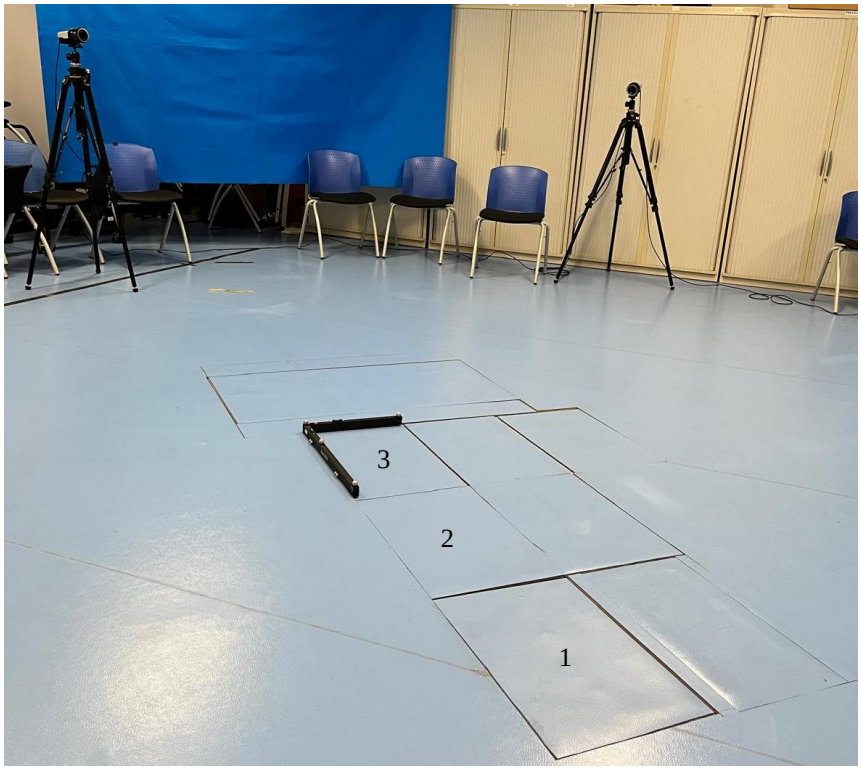

Figure 3.2.5 *Force Platforms and some Miqus cameras (Qualisys, SE) of the Biomechanics and Functional Morphology Laboratory, Faculdade de Motricidade Humana.*

The entire data collection procedure is outlined and summarized in **Figure 3.2.6**. It is important to emphasize that only the MoCA questionnaire was administered by an assessor, due to the need for scoring, particularly because this is one of the exclusion criteria (MoCA score < 23).

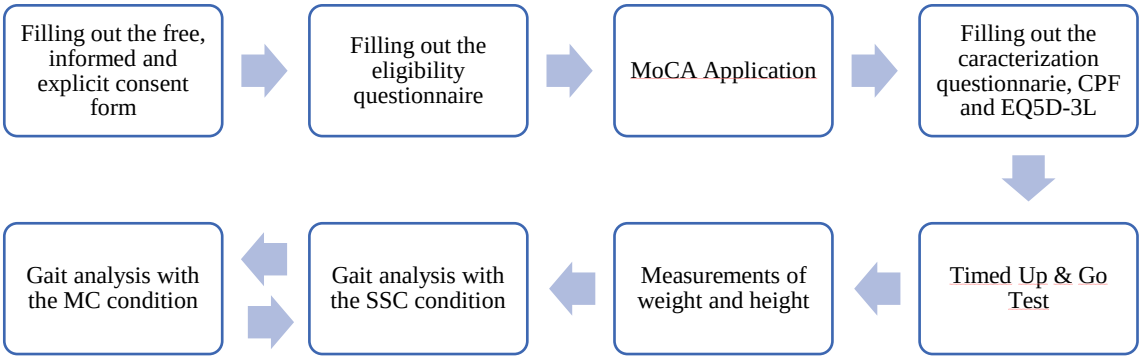

Figure 3.2.6 *Data collection procedures.*

3.3. Data Treatment Procedures

The most common filter used in movement analysis is Butterworth filter, particularly a 4th order low-pass filter (Erer, 2007; Yu et al., 1999). To determine the filter cut off frequency (CoF), residual analysis (Winter, 2009) was implemented through an algorithm developed using Python in Visual Studio Code (v1.95.1) (**Appendix VII**).

This algorithm allows the dynamic file selection, cleaning and processing the data, calculating the optimal CoF based on Winter's residual analysis (Winter, 2009), filtering the data according to this CoF, which allows the removal of noise without removing relevant data, and, finally, saving the filtered data in a new file, thus preserving the raw data for possible error purposes. It's important to emphasize that this algorithm was only used to find the optimal CoF, meaning that only the code presented in **Figure 3.3.1** was in fact used for this matter, even though the other previously mentioned functionalities were also available.

Using this algorithm, CoF in the range of 6-8Hz were obtained, since there were small variations between participants. After testing the 6-8Hz range, an optimal CoF of 8Hz was considered, as it was the one that removed the most noise without largely affecting the signal. This CoF was applied in Theia (Markerless Inc, CA, v2023,1,0,310) using a Woltring generalized cross-validity quintic-spline (GVCSPL) filter, while determining the POSE through Inverse Kinematics 3D pose-estimation with 6 DOF at the pelvis and 3 DOF at the hip, knee and ankle joints.

```
    # 8 - Use KneeLocator to find optimal cutoff frequency
    kneedle = KneeLocator(valid_cutoff_frequencies_range1,
sum_residuals_range1, curve='convex', direction='decreasing')    #
Initialize KneeLocator
    optimal_cutoff_frequency = kneedle.elbow   # Finding the
elbow/knee (OCF)
    if optimal_cutoff_frequency is not None:
        optimal_cutoff_frequencies[col] = optimal_cutoff_frequency  #
Store optimal frequency for each column

# Calculate overall optimal cutoff frequency
overall_optimal_cutoff_frequency =
np.nanmean(list(optimal_cutoff_frequencies.values()))  # Mean of
optimal frequencies across columns
```

Figure 3.3.1 *Code used to find the optimal CoF within the data obtained.*

Also, in Theia (Markerless Inc, CA, v2023,1,0,310), there was the need to use a model, specifically one of the existing. The model used was the Full Body Model that basically consisted of one whole-body kinematic chain, where abdomen and neck segments were included (some of the pre-defined models do not present these) and head that allowed 3 DOF.

After calculating the model POSE, this file was exported to a .c3d file, which contains the 4x4 POSE matrices for each model segment and the local coordinates of the anatomical landmarks of the distal segments of the model (feet, hands, head). All the general segments – pelvis, abdomen, torso, neck and head – had a parent, an origin and a specific joint and all the segments that appeared in the left and right – right and left upper arm, per example – had, besides the parent, origin and specific joint, proximal and distal parameters.

Per example, when considering the torso, we had abdomen as the parent, base of the neck as the origin and the joint as three rotational DOF and one translational DOF; when considering the right upper arm, we had torso as the parent, right shoulder as the origin, the joint as a free joint (6 DOF), the right shoulder as the proximal and the right elbow as the distal. In this case, it is important to notice that only the lower limb and the trunk were considered.

Later, the previously obtained CoF was applied through a Butterworth filter in kinetic data in Visual3D (HAS-Motion Inc., Kingston, ON). Already during the use of Visual3D, some changes were made to basic human metrics – Mass and Height – while already using the model.

After adjusting the variable parameters, it was necessary to use distinct pipelines that allowed merging the force data for each file, modifying the force platforms parameters, performing auto-zero and analog data filtering with the previously calculated cutoff frequency (Kristianslund et al., 2012), creating the automatic gait events, performing the calculations of the kinetic, kinematic and spatiotemporal variables, creating graphs that allowed the observation of the behavior of each joint – hip, knee, and ankle – throughout the gait cycle. Gait cycle events (Foot-on and foot-off) were determined using force plate signals with a threshold of 20N.

Lower limb joint angles were calculated using a XYZ Cardan sequence and ZYX for pelvis segment angle in Visual 3D. The lower limbs are generally analyzed using the XYZ Cardan sequence because this sequence tends to represent the typical order of joint rotations in gait: flexion/extension (X-axis), abduction/adduction (Y-axis), and internal/external rotation (Z-axis).

The ZYX Cardan sequence (Rotation, Obliquity, Tilt) is preferred for the pelvis because it more accurately reflects the anatomical movements of the pelvis that are important in GA: rotation (about the vertical axis), obliquity (tilting side-to-side), and tilt (forward/backward), especially in cases where both tilt and rotation are significant, since movements like obliquity and tilt can be isolated and better understood (Baker, 2001).

Internal joint moments were determined through Newton-Euler inverse dynamics, normalized to subjects' body mass, and computed relative to the proximal segment. (Carvalho et al., 2024; Inai & Takabayashi, 2023).

Traditionally, in forward dynamics, given a set of initial conditions and a set of forces as inputs, the goal is to predict motion over time. In biomechanics, the process often occurs in reverse. Instead of predicting motion from forces, the motion can be measured, using, for example, motion capture systems, and then the forces and moments that caused the observed motion are calculated.

This process is called inverse dynamics and generally uses the Newton-Euler method, which applies the laws of motion (Newton's second law for translation and Euler's equations for rotation) to rigid body segments (Robertson, E. Caldwell, et al., 2014).

The entire data treatment procedure is outlined and summarized in **Figure 3.3.2**. Everything not included in the brackets of Visual Studio Code and Theia was performed in Visual3D.

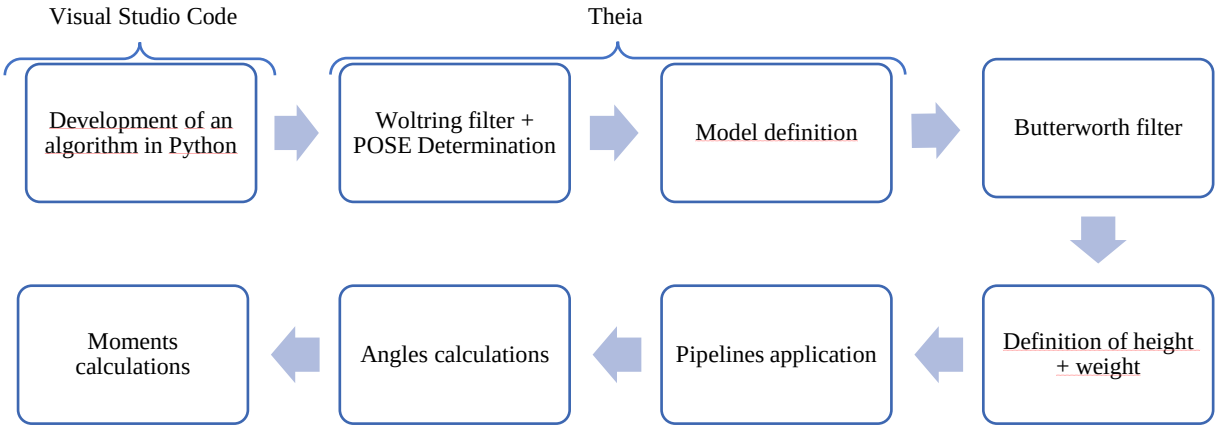

Figure 3.3.2 *Data treatment procedures.*

3.4. Data Analysis Procedures

The data analysis was conducted using Excel, both for graph creation and calculations. In terms of graphs, plots were created to assess the influence of clothing based on the overlapping or lack of it in the representative curves of the trajectories for the two clothing scenarios. Average values were considered for the making of the curves, and the standard deviations were considered to create a shaded area to identify where greater variability in the data occurred, particularly assessing whether the phase of the gait cycle had an influence, so graphs obtained by combination of the mean values of each clothing condition and associated standard deviation (SD) values were computed.

Additionally, point-by-point difference graphs were created by subtracting one condition from the other, with MC used as the reference. This choice was based on the assumption that MC shares the same clothing characteristics as the reference non-invasive method – MB analysis. Thus, the calculations for these graphs were performed using MC - SSC.

This method allows us to determine a difference value between all curves regarding the clothing condition. Based on previous studies (Carvalho et al., 2024; Kanko et al., 2024), values lower than <5° for kinematics and lower than ≤5% for kinetics were considered as acceptable. 5º was used as a direct form of measurement because of the study carried out by McGinley et al. (McGinley et al., 2009). 5% was used as an indirect form of measurement – relative comparison – and, although this value is not included in many studies, 5% is a minor error in 100%, but another value could have been used, but if so there would be no way of comparison.

Regarding calculations, in addition to the averages and standard deviations used to generate the aforementioned graphs, the RMSD were also computed. This parameter indicates how discrepant the data are, with values closer to zero being better. Moreover, the relative differences obtained in the angles and in the moments in sagittal, frontal and axial planes, were calculated to better understand the influence of the chosen attire on these parameters. These analyses allowed for the identification of whether one condition prevailed over the other. The evaluation of the results is summarized in **Figure 3.4.1**.

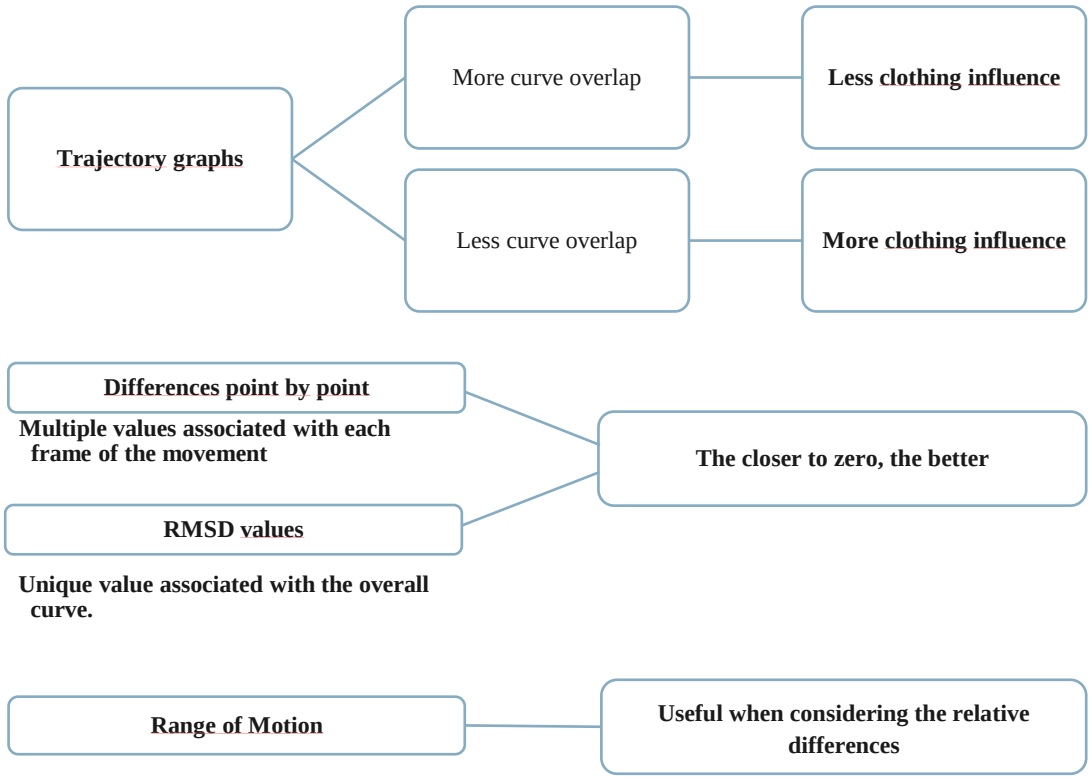

Figure 3.4.1 *Data analysis procedures.*

RMSD were computed for each participant using **Equation 3.4.1** and the mean was calculated and considered to do the comparison between joints, axis and clothing conditions.

Equation 3.4.1 *Root Mean Squared Difference*

$$RMSD = \sqrt{\frac{\sum_{i=1}^{N}(x_{MC_i} - x_{SSC_i})^2}{N}}$$

Where x_{MC_i} is the value of each parameter in the MC condition at time point *i* in the gait cycle for a specific individual, x_{SSC_i} is the value of each parameter in the SSC condition at time point *i* in the gait cycle for a specific individual and N is the total time points of a cycle.

To simplify, assuming the hip angle of participant X is under analysis, x_{MC_i} is the angle made by the hip in the time point *i* regarding the clothing condition MC for participant X, x_{SSC_i} is the angle made by the hip in the time point *i* for participant X regarding the clothing condition SSC and *N* is the number of frames, in this case 100, processed in a gait cycle.

It's important to mention that the moments amplitude was used only to calculate the relative error values and also that the moment peaks were considered for the kinetic analysis.

The anatomical planes considered as reference for the present study are represented in **Figure 3.4.2**, as seen below. In the sagittal plane we can see flexions, extensions, dorsiflexion and plantarflexion; in the frontal plane we can see abductions and adductions and, in the axial plane we can see internal and external rotation.

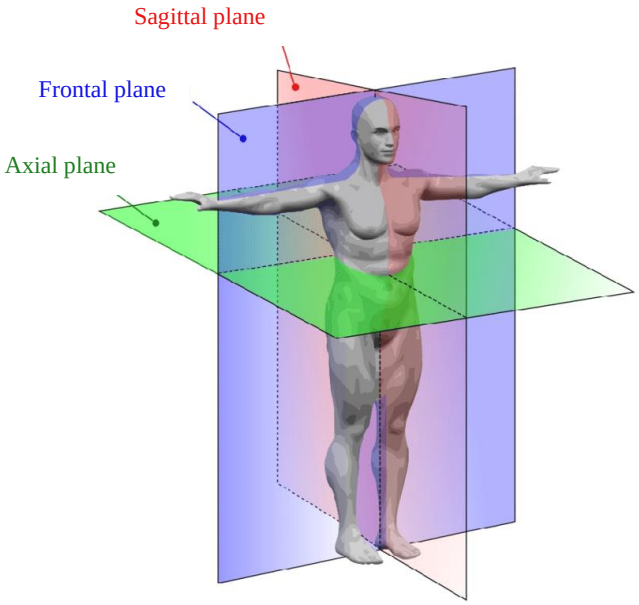

Figure 3.4.2 *Anatomical planes considered (Adapted from (Adistambha et al., 2012))*

Flexions, adductions, internal rotations and dorsiflexion were considered movements with a positive value. Extensions, abductions, external rotations and plantar flexions as movements with a negative value.

4. Results

4.1. Kinematic Analysis

Participants had a mean age of 75.2 ± 7.7 years, mean height of 164 ± 9.12cm and mean mass of 67.3 ± 8.9Kg. Sixteen of them were males and fourteen were females. Joint angle patterns were similar between clothing conditions, with the exception of the hip angle in the frontal plane, where a lower overlap between curves can be seen (**Figure 4.1.1**).

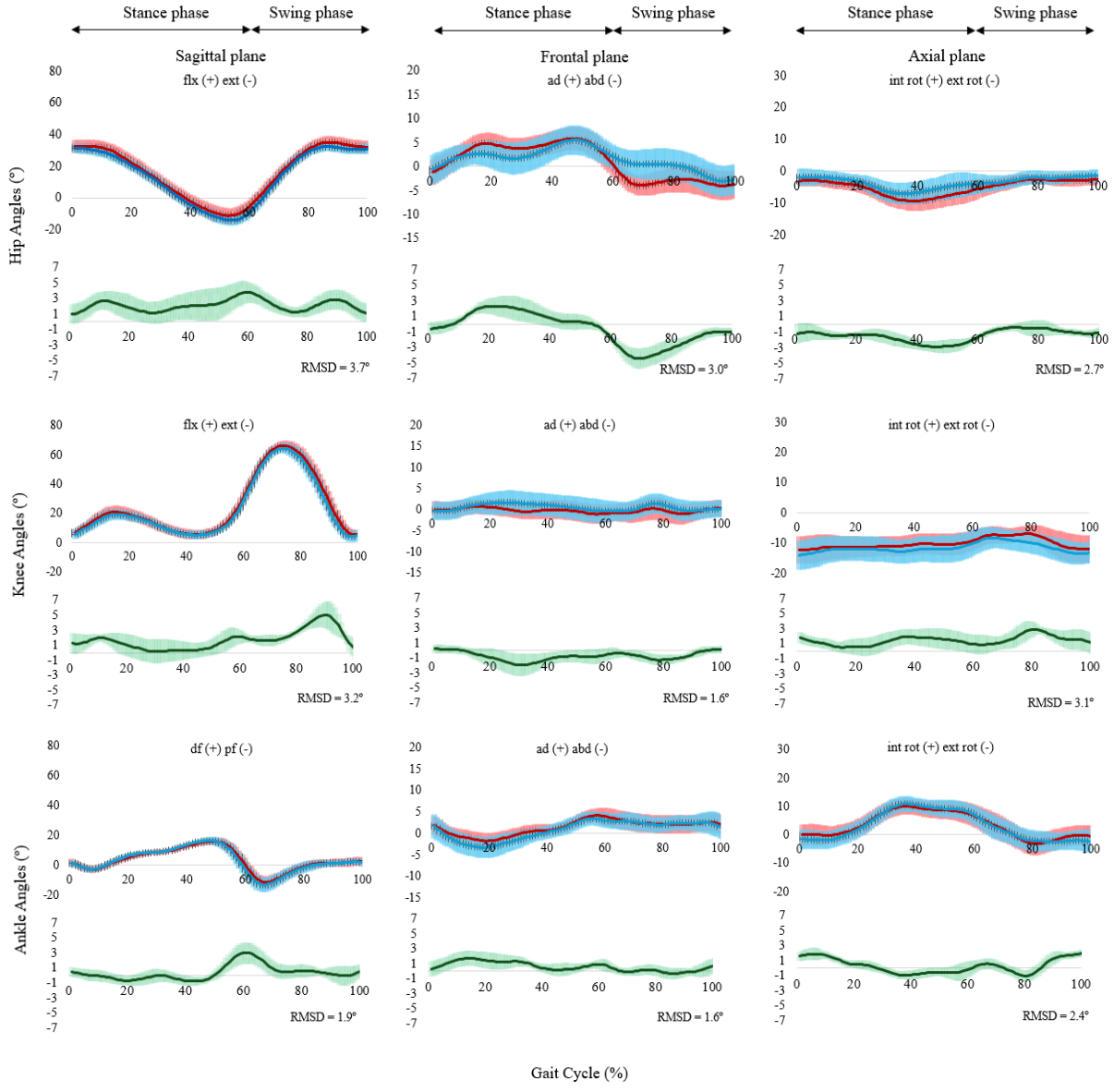

Figure 4.1.1 *Gait cycle waveforms for the right hip, knee, and ankle angles in the sagittal (X), frontal (Y), and axial (Z) planes for all subjects (n = 30) between clothing conditions. Solid lines represent the mean waveform. SSC is blue, MC is red, the difference between conditions is green. Shaded areas represent SD from the mean. Total RMSD values across all subjects for each joint component are represented within corresponding plots. Abbreviations: flx, flexion; ext, extension; ad, adduction; abd, abduction; int rot, internal rotation; ext rot, external rotation; df, dorsiflexion; pf, plantar flexion*

When it comes to the point-by-point differences, which are displayed in the green portion of **Figure 4.1.1**, while the green line represents the average difference between both conditions, the shadow area displays the associated error, calculated through the SD. The differences are mostly below 5° across all planes of motion, with the sagittal plane angles showing the largest absolute differences, particularly in the hip and knee joints.

In the sagittal plane, the hip joint angle had the highest RMSD value (3.7º), followed by the knee angle (3.2º), and finally the ankle angle (1.9º). In the frontal plane, the hip joint angle had the highest RMSD value (3.0º), followed by both the knee and ankle angles, which had the same RMSD value (1.6º). Finally, in the axial plane, the knee angle had the highest RMSD (3.1º), followed by the hip angle (2.7º) and the ankle angle (2.4º).

Regarding the ROM, small differences were also seen between both clothing conditions, with a maximum absolute difference of -2.5º. The absolute differences between both clothing scenarios were in the range of [-2.5; 1.8]º and the relative differences were in the range of [-22.0; 15.7]%. The results obtained are furthermore shown in **Table 4.1.1**.

Table 4.1.1 *ROM across all planes and all joints. Abbreviations: $\bar{X}$ – Mean; SD – Standard Deviation; MC – Minimal Clothing; SSC – Self-Selected Clothing.*

JOINT	PLANE	CLOTHING CONDITION				DIFFERENCES	RELATIVE DIFFERENCES
		MC		SSC		MC - SSC	
		$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	
HIP	SAGITTAL	47.0	4.0	47.5	4.6	-0.6	-1.2%
	FRONTAL	11.5	2.8	9.7	4.0	1.8	15.7%
	AXIAL	8.5	2.4	7.9	2.5	0.6	7.2%
KNEE	SAGITTAL	62.7	3.0	62.3	3.7	0.5	0.8%
	FRONTAL	4.6	1.7	5.6	1.7	-1.0	-22.0%
	AXIAL	7.3	3.7	8.3	2.2	-1.0	-13.1%
ANKLE	SAGITTAL	28.0	3.8	30.6	4.3	-2.5	-8.9%
	FRONTAL	6.7	1.9	8.0	2.0	-1.3	-19.2%
	AXIAL	14.7	3.2	16.7	2.8	-2.0	-13.8%

In the case of the relative comparison between the hip joint angle in the sagittal and frontal planes, although the RMSD values are similar, having only a difference of 0,6º in absolute value of the correspondent RMSD values, relative differences in ROM of -1.2% and 15.7%, respectively, are noted.

The same can be observed when comparing the hip joint angle in the frontal and axial planes, where, despite an absolute difference of only 0.3º, relative differences in ROM of 15.7% in the frontal plane and 7.2% in the axial plane, can be observed.

Regarding the knee joint angle, when observing sagittal and axial planes, despite an absolute difference of only 0.6º, relative differences in ROM of 0.8% and -13.1%, respectively, are noted.

Finally, regarding the ankle joint angle, particularly in the comparison between the sagittal and frontal planes, there is an absolute difference of 0.3º and relative differences in ROM of -8.9% for the sagittal plane and -19.2% for the frontal plane.

Still regarding the relative differences, the joint and plane that appear to be most problematic, presenting a greater value of relative difference, is the knee joint angle in the frontal plane.

Based on the results of ROM in this kinematic analysis, it appears that the clothing conditions do not seem to influence the results, meaning that has a minimal impact on gait kinematics in elderly participants, as absolute differences were below 5º for all variables. It is important to note, however, that these absolute differences have a higher impact, i.e., relative differences are superior, in frontal and axial planes of motion.

As can be confirmed through **Figure 4.1.1**, the overlap of the trajectories in the frontal and axial plane is less noticeable compared to the overlap observed in the sagittal plane. Furthermore, it is also possible to note that the graphs showing a higher RMSD value – hip in both frontal and axial planes and knee in the axial plane, with RMSD values of 3.0º, 2.7º and 3.1º, respectively – are also the ones with the weaker overlap, establishing a direct correspondence for these particular cases.

Besides this, it is also possible to see, in those cases previously stated as the ones more problematic, a more heterogeneous differences graph. The RMSD value of the ankle in the axial plane is 2.4º and the RMSD value of the ankle in the sagittal plane is 1.9º, meaning that it is not correct to assume in this case that all sagittal plane holds the higher RMSD values. Hence, after observing the graph of the trajectory of every subject, it was found that subject 017 had axial plane ankle angle waveform graphs that appeared different when comparing the two clothing scenarios (**Figure 4.1.2**).

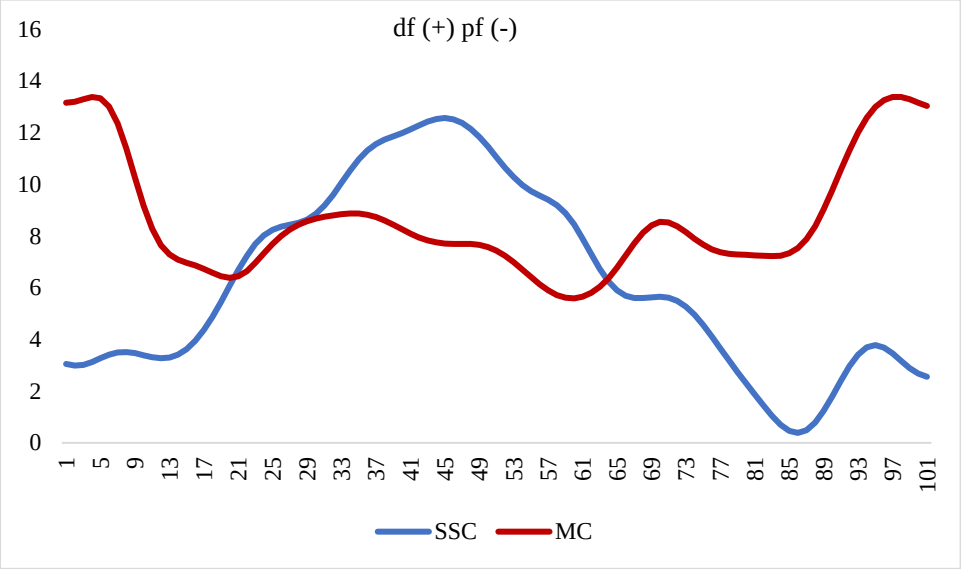

Figure 4.1.2 *Subject 017's axial plane ankle angle waveform graphs. Abbreviations: SSC, Self-selected Clothing; MC, Minimal Clothing; df, dorsiflexion; pf, plantar flexion.*

All these particularities are going to be further discussed in the next chapter, as well as the next analysis regarding the kinetic data.

4.2. Kinetic Analysis

Joint moment patterns for the hip, knee, and ankle were consistent between clothing conditions. In the sagittal plane, the moments recorded was 0.11Nm/Kg, 0.07Nm/Kg and 0.05Nm/Kg, for the hip, knee and ankle, respectively. Similarly, in the frontal plane, the moments were 0.08Nm/Kg, 0.06Nm/Kg and 0.03Nm/Kg, for the hip, knee and ankle. Lastly, in the axial plane, the moments were 0.03Nm/Kg for the hip and 0.02Nm/Kg for both knee and ankle.

When it comes to the point-by-point differences, which are displayed in the green portion of **Figure 4.2.1**, the differences are relatively small across all axes and the hip joint is the one presenting larger difference, in the range of [0.05; 0.15] Nm/Kg, across planes. Besides that, small differences between both clothing conditions were also seen, with a maximum absolute difference of -0.13Nm/Kg. The absolute differences between both clothing scenarios were in the range of [-0.13; -0.01]Nm/Kg and the relative differences were in the range of [-15.1; -0.7]% (**Appendix VIII**).

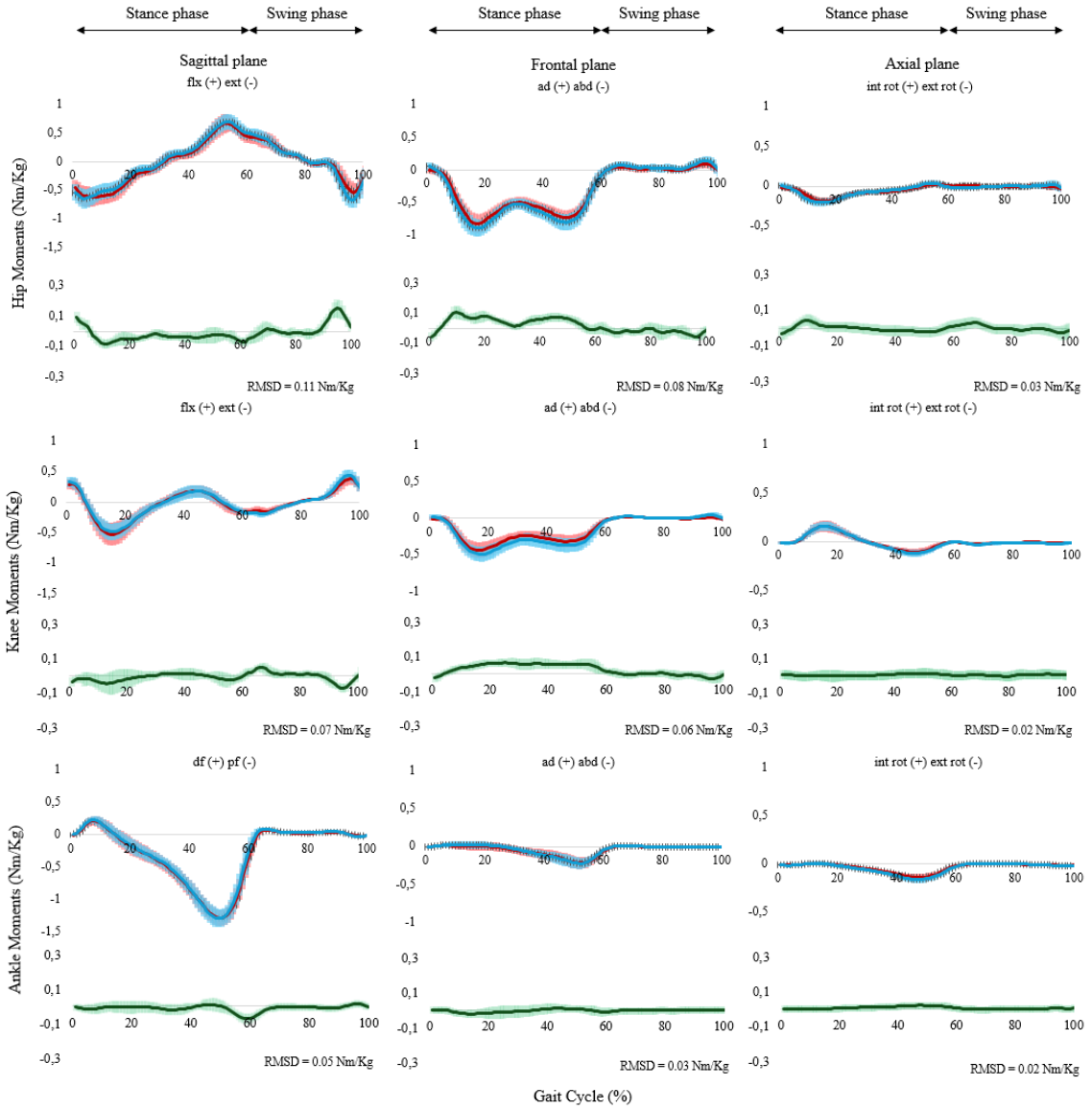

Figure 4.2.1 *Gait cycle waveforms for the right hip, knee, and ankle moments in the sagittal (X), frontal (Y), and axial (Z) planes for all subjects (n = 30) between clothing conditions. Solid lines represent the mean waveform. SSC is blue, MC is red, the difference between conditions is green. Shaded areas represent SD from the mean. Total RMSD values across all subjects for each joint component are represented within corresponding plots. Abbreviations: flx, flexion; ext, extension; ad, adduction; abd, abduction; int rot, internal rotation; ext rot, external rotation; df, dorsiflexion; pf, plantar flexion*

After the first results were obtained, there was the need to calculate the peaks associated with each joint and each plane, particularly the hip and ankle minimum and maximum peaks in the sagittal plane. The aforementioned peaks observed in the MC and SSC conditions are described in **Table 4.2.1**.

Table 4.2.1 *Hip, knee and ankle maximum and minimum peak moments in the sagittal plane. Abbreviations: $\bar{X}$ – Mean; SD – Standard Deviation; MC – Minimal Clothing; SSC – Self-Selected Clothing*

JOINT	LIMITS	CLOTHING CONDITION				MC - SSC	RELATIVE DIFFERENCES
		MC		SSC			
		$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	
HIP	MÁX	0,70	0,15	0,73	0,13	-0,03	-4,02%
	MIN	-0,73	0,14	-0,74	0,12	0,01	-1,79%
KNEE	MÁX	0,41	0,09	0,45	0,09	-0,05	-11,66%
	MIN	-0,54	0,18	-0,50	0,14	-0,04	7,64%
ANKLE	MÁX	0,22	0,07	0,24	0,05	-0,01	-5,25%
	MIN	-1,30	0,12	-1,30	0,14	0,00	-0,05%

The maximum amplitudes of the aforementioned peaks were 0.70 ± 0.15Nm/Kg and 0.73 ± 0.13Nm/Kg, for the peak hip flexion moment, for the conditions MC and SSC, respectively; 0.41 ± 0.09Nm/Kg and 0.45 ± 0.09Nm/Kg, for the peak knee flexion moment, for the conditions MC and SSC, respectively; 0.22 ± 0.07Nm/Kg and 0.24 ± 0.05Nm/Kg, for the peak ankle dorsiflexion moment, for the conditions MC and SSC, respectively.

Regarding the minimum amplitudes, the results obtained were -0.73 ± 0.14Nm/Kg and -0.74 ± 0.12Nm/Kg, for the peak hip extension moment, for the conditions MC and SSC, respectively; -0.54 ± 0.18Nm/Kg and -0.50 ± 0.14Nm/Kg, for the peak knee extension moment, for the conditions MC and SSC, respectively; lastly, -1.30 ± 0.12Nm/Kg and -1.30 ± 0.14Nm/Kg, for the peak ankle plantarflexion moment, for the conditions MC and SSC, respectively. As it can be seen, the relative differences between the peaks observed in the MC condition and the SSC condition were minimal, differing by [-11.66; 7.64]%. These results are going to be further discussed.

Regarding the relative differences, although this haven't had has much discussion as in the previous case, the joint and plane that appear to be most problematic, presenting a greater value of relative difference, is the knee joint moment in the frontal plane.

As the peak of the plantar flexion moment of the ankle is so important for the elderly, as previously mentioned and as will be discussed later, we tried to understand whether clothing had any interference in this parameter, which was not demonstrated, as it can be seen in **Figure 4.2.2**.

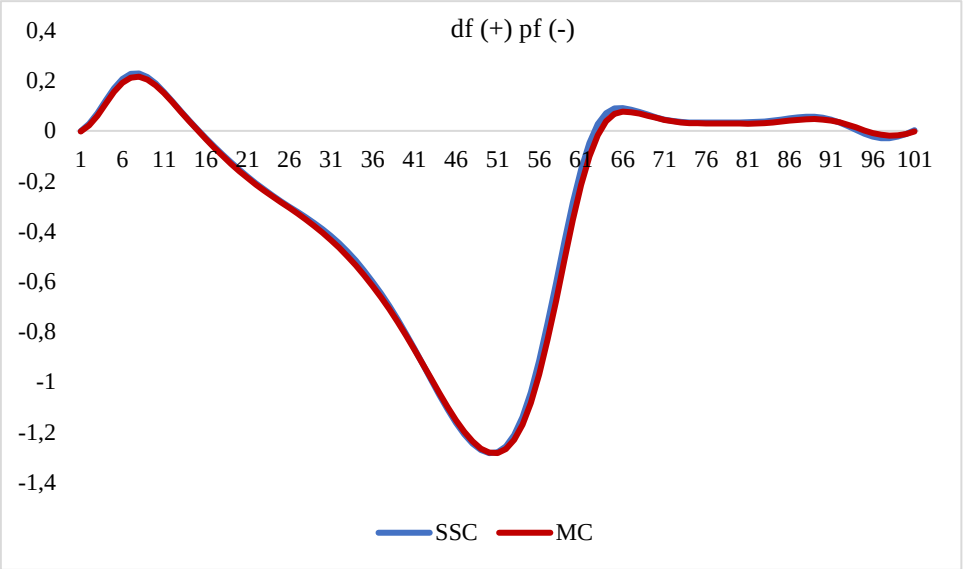

Figure 4.2.2 *Peak of the plantar flexion moment of the ankle waveform graph. Abbreviations: SSC, Self-selected Clothing; MC, Minimal Clothing; df, dorsiflexion; pf, plantar flexion.*

Based on the results of this kinetic analysis, the attire conditions do not seem to influence the results, meaning that it has a minimal impact on gait kinetics in elderly participants, although relative differences in frontal and axial planes may surpass 5%.

5. Discussion

In this study, the influence of clothing on the gait of healthy older individuals was analyzed by comparing lower limb kinematics and kinetics across two conditions: minimal clothing – MC – and self-selected clothing – SSC. It was observed that there was a minimal difference in the results obtained in the comparison between the clothing conditions when studying both kinematics and kinetics. The differences seen were not considered relevant, especially for the most important parameters, when analyzing gait in healthy older adults – lower limb angles and moments.

5.1. Kinematic Analysis

The results obtained agree with previous investigations which report low discrepancies when working with MLGA, even when there are changes in the clothing scenarios between trials (Keller et al., 2022). It was possible to observe almost no differences across the axes – x, y, and z – and in the three joints studied – hip, knee and ankle.

The graphs that display the trajectory obtained from the kinematic analysis appear to follow the same path both between individuals and point-by-point, suggesting that the average values are representative of the sample, as seen in previous studies (Winner et al., 2023) (**Figure 4.1.1**), meaning that there doesn't seem like there is any outlier regarding the lower limb joint angles. Concerning the point-by-point differences, the sagittal plane is the one presenting the largest absolute differences (± 5°) across the gait cycle, particularly in the hip and knee joints (Zhai et al., 2023).

The RMSD values are low, indicating the overall low deviation between the clothing conditions. This means that clothing does not seem to have a much noticeable effect on the gait parameters, particularly in the kinematics of the movement. It is important to notice that although the higher RMSD value is usually associated with the sagittal plane, as seen in previous studies (Y. Liang et al., 2022; Zhai et al., 2023), did not demonstrate to be the case for all the parameters in this study.

The RMSD value of the ankle in the axial plane showed a residual higher value than the RMSD of the ankle in the sagittal plane, thus not allowing the assumption that RMSD is higher for all joints in the sagittal plane, as previously seen in the literature (Keller et al., 2022). Although this is not entirely out of what was seen in the literature, when trying to understand what could have induced this variability, it was noticed that subject 17 presented different curve patterns for the two clothing conditions (**Figure 4.1.2**) with the curve closer to expected being the blue curve – related to the MC condition – which may have led to greater standard deviations and consequently greater relative difference values. This may have been caused by a calculation error or an event that occurred in one of the trials, where the participant could have accidentally changed their gait pattern slightly, which is why it would be important to particularly study this participant's gait cycles again (Ludwig et al., 2016).

Speaking of relative differences, the plane and joint that demonstrated the greatest parameters were the knee in the frontal plane, as seen in the literature (Byrnes et al., 2022). This can be explained by the fact that the knee, especially in the frontal plane, plays a crucial role in distribution of forces and stability during gait, which is why there will always be small nuances from individual to individual (Kumar et al., 2013). Furthermore, the knee has smaller amplitude movements in the frontal plane, so any change causes a high relative difference. This can be explained by the fact that the ligaments and hinge joint restrict movements in the frontal plane (Santos & Oliveira Neto, 2023).

As previously stated, the overlap of the trajectories is less noticeable in the frontal and axial planes when compared to the overlap observed in the sagittal plane, as seen in the literature (Stenum et al., 2024). This could possibly be explained due to the fact that, even though they might have similar differences, since the amplitude is larger, the same difference in degrees in the sagittal plane has much less impact than in the other planes.

Besides that, it is also possible to see around the same values of RMSD for the hip in both frontal and axial planes and knee in the axial plane (Keller et al., 2022), possibly meaning that these values of a greater deviation are aligned with the less significant overlap, as well as the point-by-point differences graph, meaning that these had a higher variability of values across subjects.

Regarding the ROM, the results show that clothing, which could be considered as a limiting factor (Gao et al., 2022; Rahmatalla et al., 2005), did not seem to be one in this case. In this study, the differences obtained were not considered significant since the absolute differences followed what was seen in the literature (McGinley et al., 2009), as well as the relative differences (Wade et al., 2022). It is important to highlight that that observing a zero value only indicates that the subject is closer to the reference anatomical position (Oberg et al., 1994).

Although all the differences are below the threshold observed in the literature, an overall analysis must be conducted. That is, it is important to note that, even though the highest RMSD absolute values were in the sagittal plane for the most parameters, it is also in this plane where the greatest overlapping is observed and where the relative ROM differences are lower.

The planes with the least overlapping are the frontal and axial planes, and in these, higher relative differences are observed. This may be related, on one hand, to the higher amplitude in the sagittal plane (Y. Liang et al., 2022; Zhai et al., 2023), but on the other hand, the differences in the trajectories are more pronounced in the planes with greater relative differences, meaning that the differences in the trajectories in the frontal and axial planes align with the relative difference values.

In summary, the joint angles observed are similar to those expected for the task and population under study, particularly in the elderly population, according to what is observed in the literature (Saga & Saga, 2024).

5.2. Kinetic Analysis

Regarding the graphs obtained from the kinetic analysis, minimal differences were observed both between individuals and point-by-point, suggesting that the average values are representative of the sample (Winner et al., 2023)(**Figure 4.2.1**), meaning that there doesn't seem like there is any outlier regarding the moment values of lower limb joint moments. The curves for the SSC and the MC conditions appear to follow the same trajectory, which seems to indicate similar movement patterns during the gait cycle, as seen in previous studies (S. Liang et al., 2022).

As for the differences seen in the moments, it was observed that the amplitude of joint moments is generally higher in the sagittal plane for all lower limb joints, which is expected, as this direction corresponds to the movements of flexion/extension, the main movements observed during the GA (Lugade et al., 2011), which might be the main reason why, proportionally, the relative differences are smaller for this plane compared to the others (Scataglini et al., 2024).

When analyzing moments in the frontal and axial planes, it is important to understand that observing a zero value indicates the absence of force moment (Camomilla et al., 2017). Thus, when identifying lower moments, we may be observing minor lateral or rotational variations (Schache & Baker, 2007), which might contribute less to the movement, particularly in the gait.

Point-by-point differences graph shows that the absolute differences are relatively small across all planes. The hip joint moment is the one presenting the largest difference, followed by the knee moment, and lastly, the ankle moment, and these results follow what was seen in the literature (Scataglini et al., 2024), which again might be related to the traditionally observed gait movement of flexion and extension.

The RMSD values are also quite small, meaning that clothing does not seem to have a much noticeable effect on the gait parameters, particularly in the kinetics of the movement. It is also important to notice that the higher RMSD value is associated with the sagittal plane, particularly to the hip joint moment and knee joint moment, being higher in the hip joint moment, what can also be seen in the literature (Flood et al., 2023).

Consistency in both clothing conditions was seen. Both absolute and relative differences between clothing scenarios followed what was seen in literature (S. Liang et al., 2022). Based on the results of this kinetic analysis, it also appears that clothing does not seem to influence the results, meaning that it has a minimal impact on gait kinetics in active elderly participants, although some relative differences in frontal and axial planes may surpass 5% (Carvalho et al., 2024).

Considering that the absolute differences are low, and the relative differences are high, being the highest in the knee joint moment in the frontal plane, it was necessary to observe at which point in the cycle the maximum and minimum values were taken. It was observed that, in some graphs, particularly in the ankle in the frontal and axial planes, there were participants who showed higher amplitudes of moment than the others at certain points of the movement, which may have led to the extraction of maximum and minimum values at different phases of the gait – for example, some during the swing phase and others during the stance phase. This could be the cause of the variability that generates the standard deviation and, consequently, the relative differences (Amrani El Yaakoubi et al., 2023).

Regarding the peak analysis made previously on this study, and since the peak hip flexion moment and the peak ankle plantarflexion moment are considered as the most important in elderly healthy gait (Boyer et al., 2017), it was necessary to investigate whether they were influenced by the clothing or not. As it was seen it this study, the peaks showed amplitudes that follow the range stated in the literature (Johnson et al., 2021) and had the same exact value in the waveform graph, meaning that the clothing did not seem to influence the outcome of this analysis. Below is **Table 5.2.1**, which provides a clearer view of the key points discussed.

Table 5.2.1 *Summary of the discussion regarding the analyses - kinematic and kinetic*

Kinematic Analysis	Kinetic Analysis
Results agree with previous investigations with difference clothing scenarios - minimal differences.	The graphs obtained showed minimal differences, suggesting that the average values are representative of the sample, agreeing with previous studies.
The RMSD values are low, indicating the overall low deviation between the clothing conditions.	The amplitude of joint moments is generally higher in the sagittal plane since this direction corresponds to the movements of flexion/extension, the main movements observed during the GA.
The overlap of the trajectories is less noticeable in the frontal and axial planes, and this could possibly be explained due to the fact that, similar differences in different amplitude planes look different.	The RMSD values are quite small, meaning that clothing does not seem to have a much noticeable effect on the gait parameters.
The ROM results show that clothing, which could be considered as a limiting factor did not seem to be one in this case.	The calculated peaks showed amplitudes that follow the range stated in the literature, meaning that the attire did not seem to influence the results.

In sum, the moments of joint strength observed are those expected for the task and population under study, particularly in the elderly population, according to what is observed in the literature (Kirkwood et al., 2007).

5.3. Comparative Analysis

Although the results of the kinematic and kinetic analyses in absolute values enabled the affirmation of the minimal influence exhibited by the different clothing scenarios, it was important to make a comparative analysis. In the present study, the joint angles had a wider range of differences in comparison with the moments, being the maximum amplitude of the differences 36.8% and 15.8%, for the angles and the moments, respectively. The maximum amplitude of the difference in angles is more than double the maximum amplitude of the difference in moments (Huang et al., 2024; S. Liang et al., 2022).

Data recorded in the frontal and axial planes showed greater relative differences in comparison it those presented in the sagittal plane, in both analyses. This is consistent with the literature, probably due to the greater ROM observed in the sagittal plane, as previously discussed, associated with the flexion and extension movements, which are typical of the lower limb joints, particularly during gait (Eitzen et al., 2015).

Although the differences are within the expected threshold reported in previous studies (S. Liang et al., 2022; Lugade et al., 2011; Zhai et al., 2023), particularly in the frontal and axial planes, the relative differences are much greater possibly due to the lower signal amplitude when compared to the data observed in the sagittal plane.

Regarding the trajectory graphs, it is possible to observe greater overlap in the moment graphs compared to the angle graphs. A likely reason for this is that the force measurements are more precise, which consequently results in more accurate moment graphs, as seen in other similar studies (Stenum et al., 2024).

In what concerns the different phases of gait, there does not seem to have been any interference from these phases in the results obtained, since no significant differences were found in either the stance phase or the swing phase, as observed in the literature (Keller et al., 2022).

5.4. Limitations

Even though the outputs of both kinematic and kinetic analyses are in accordance with what was theoretically expected, there were some limitations. One of the key limitations was that in this study there was no standardization of clothing in the SSC condition, which could translate into a less accurate POSE estimate, due to differences in the texture and color of the subjects' clothing (Yang & Park, 2024), although it does not seem to have had much influence, since the results obtained seem to follow those obtained in previous studies (Kanko et al., 2024; Keller et al., 2022). However, the fact that clothing was not restricted resulted in greater variability in the choice of clothing, which ended up better reflecting what would be seen in a real-life circumstance.

Second, the analysis was made in a controlled laboratory environment, with natural light restriction, which might have caused some influence in the recorded videos (Scataglini et al., 2024). Finally, although previous studies settled an acceptable threshold of 5º in differences of joint angles (McGinley et al., 2009), it is important to notice that even 5º degrees might be too much, considering that there might be some studies that would benefit of more precision (Yang & Park, 2024).

6. Conclusions

Gait analysis (GA), although it is not a field of biomechanics that has emerged recently, still requires further research to make this medical methodology as comfortable, safe and accurate as possible. The aim of this work was therefore to investigate the influence of clothing on kinematic and kinetic gait data of older adults obtained through ML methods, using two clothing conditions: self-selected clothing (SSC) and minimal clothing (MC), with the objective of being able to use this system in clinical settings and outside of them, considering all its potentials that give it an advantage over other existing and accurate methods.

The results of the kinematic analysis show that the overall patterns regarding angles and ROM are quite similar between clothing conditions. Besides that, there does not appear to be much dominance of MC or SSC. Still, the sagittal plane is the one showing the largest absolute differences and the largest ROM across lower limb joints – hip, knee, and ankle. Regarding the results of the kinetic analysis, although similar to the kinematic ones, the results regarding the RMSD values were even better, since this was lower, and the closest to zero, the better. The results obtained are supported by previous research where equivalent results were obtained.

RMSD confirmed what was already seen since it was quite low for both analyses – kinematics and kinetics – and it ranged from 1.6º to 3.7º in the angles and 0.02 Nm/Kg to 0.11 Nm/Kg in the moments, meaning that in both cases, the clothing does not seem to have a much noticeable effect on the gait parameters, although it's important to notice that the highest absolute RMSD value is associated with the sagittal plane, in both kinetics and kinematics for the majority of the parameters, excluding the ankle joint angle in the axial plane, that has a higher RMSD value than the ankle joint angle in the sagittal plane.

In ROM, the results were not considered significant since the differences were less than 5º in all cases, confirming what had been already seen, but in the kinetic analysis, some of the parameters had differences superior to the defined threshold.

Although the relative errors obtained are higher in kinetic analysis compared to kinematic analysis, since the amplitude of the parameter itself is smaller, it is not possible to conclude that the results are generally worse, because the relative differences were only made regarding the ROM and the amplitude of moments.

In a general context, it is possible to observe that joint angles had a wider amplitude of differences, while joint moment differences had a narrower amplitude, resulting in less than half of the differences presented in the kinematic analysis. This may be associated with the fact that force measurements are more precise, which consequently makes the moments more accurate.

This study contributed to the knowledge about MLGA systems, particularly because the study was made in older adults and the majority of the studies are made with middle-aged adults, where the effect of aging is less noticeable in most cases. This study allows, due to the results that follow what was previously seen in the literature, to highlight the use of the ML system in the clinic, as it is portable, more convenient and less uncomfortable, unlike the MB systems that were used in the past and are still used clinically. The ML system is less time-consuming, does not involve much calibration and does not require very rigid clothing standardization, which makes investing in this type of system a valuable asset.

In addition to the more noticeable advantages, it was also possible to study the accuracy of the ML system, which proved to be robust in various clothing scenarios. This versatility further enhances the practicality of this system in a wide range of applications, particularly in those where clothing standardization is not feasible.

Despite obtaining results that follow what is seen in literature, there were some limitations in this study. One of the main limitations was lack of clothing standardization in the SSC condition, thereby enhancing the possibility of a less accurate POSE estimation. Secondly, as data collection was always conducted in a laboratory environment, there was a natural light restriction, which might have caused some influence in the recorded videos. Finally, there was a limitation regarding the currently acceptable angle threshold, since there might be some studies that would benefit more precision.

In summary, the results were positive and within expectations and clothing did not appear to be a limitation, considering the similarities of data obtained under different clothing conditions, which increases the robustness of this system, increasing the possibility of validation, although further studies would be necessary for this.

These studies should deepen some characteristics: a less controlled environment, in which more variables would be introduced into the system, thus testing the system to the maximum; other types movements, either more complex or with higher frequency, such as jumping or squatting and, finally, clothing that really overlaps because, although it is important to understand what type of clothing introduces minimal disturbance in the outputs – finding the condition considered to be closer to reality – it is also important to test various types of clothing, namely winter clothes, such as long coats, snow boots, i.e., clothes that might influence the most the detection of the lower limb joints.

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Appendices

Appendix I - Informed Consent (1)

CÓDIGO DO PARTICIPANTE _____

CONSENTIMENTO INFORMADO LIVRE E ESCLARECIDO

Título do projeto: Validação de um Sistema de análise de movimento sem marcadores para avaliar a marcha em idosos

Pessoa responsável pelo projeto: Vera Moniz-Pereira

Equipa de investigação: Andreia Carvalho, António P Veloso, Filomena Carnide, Katarzyna Micielska, Rita Fernandes, Sílvia Cabral, Vera Moniz-Pereira

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Este documento, designado **Consentimento, Informado, Livre e Esclarecido**, contém informação importante em relação ao estudo para o qual foi convidado a participar, bem como o que pode esperar se decidir participar no mesmo. Leia atentamente toda a informação aqui contida. Deve sentir-se inteiramente livre para colocar qualquer questão, assim como para discutir com terceiros (amigos, familiares) a decisão da sua participação neste estudo.

Informação geral

A capacidade de realizar tarefas quotidianas (atividades da vida diária), é essencial para manter a independência durante o processo de envelhecimento. É também durante as ações locomotoras que as quedas ocorrem mais. Um dos objetivos dos programas de exercício para pessoas com mais de 65 anos é, por isso, manter a mobilidade.

Os estudos de análise de marcha mostram existe uma influência, tanto da idade, como da capacidade física, na forma como caminhamos. No entanto, ainda não existe completo consenso sobre esta matéria, em parte, por haver ausência de estudos de validação associados a esta problemática.

Neste sentido, este estudo tem como objetivo validar um sistema de análise de movimento para avaliar a forma como pessoas caminham.

Appendix I - Informed Consent (2)

Quais os procedimentos do estudo em que vou participar?

Para garantir a qualidade e segurança do estudo em questão, necessitamos de saber se possui os critérios necessários para poder participar neste projeto de investigação. Neste sentido, esta sessão será apenas para verificar a sua elegibilidade para participar neste estudo. Para isso, gostaríamos de lhe fazer algumas questões sociodemográficas e de saúde (condições clínicas, medicamentos, histórico de quedas, saúde cognitiva, capacidade de realizar atividades diárias).

Qual a duração esperada da minha participação?

A duração desta sessão será de, aproximadamente, 30 minutos.

A minha participação é voluntária?

A sua participação é voluntária e pode recusar-se em participar. Caso decida participar neste estudo é importante ter conhecimento que pode desistir a qualquer momento, sem qualquer tipo de consequência para si. No caso de decidir abandonar o estudo, a sua relação com a Faculdade de Motricidade Humana (FMH) não será afetada. Se for o caso, o seu estatuto enquanto colaborador da FMH será mantido e não sofrerá nenhuma consequência da sua não-participação ou desistência.

Se desejar fazer uma reclamação relacionada com a sua participação neste estudo, deverá contactar o Conselho de Ética para a Investigação da Faculdade de Motricidade Humana (etica@fmh.ulisboa.pt).

Quais os possíveis benefícios da minha participação?

Este estudo irá permitir melhorar a forma de avaliar a mobilidade em pessoas com mais de 65 anos e contribuir para melhorar o conhecimento acerca do efeito da idade na forma como caminha. Consequentemente estará a contribuir para melhorar os programas de

Appendix I - Informed Consent (3)

intervenção (por exemplo, programas de exercício) que têm como objetivo a prevenção da incapacidade e a melhoria da mobilidade em pessoas com mais de 65 anos.

Quais os possíveis riscos da minha participação?

Uma vez que as atividades em que vai participar envolvem o preenchimento de questionários, não são expectáveis quaisquer riscos ou desconforto a partir das questões a colocar.

Há cobertura por uma companhia de seguros?

Não sendo expectáveis quaisquer riscos ou desconforto adicionais aos que está sujeito no seu dia a dia, não está prevista a cobertura de riscos por apólice de seguro.

Como é assegurada a confidencialidade dos dados?

A informação obtida neste estudo é confidencial e não será revelada a pessoa alguma, exceto à equipa responsável por este estudo. Os resultados do estudo serão tratados e apresentados de forma inteiramente **anónima**. A confidencialidade dos dados será garantida substituindo o seu nome por um código, conhecido exclusivamente pelos investigadores. Este código consta no canto superior direito da primeira página deste documento. Para além de ser retirado o seu nome, na base de dados eletrónica não constará qualquer informação que permita a sua identificação direta ou indireta (por exemplo, contacto telefónico ou endereço de email). Após a recolha, os dados em papel serão armazenados em armário fechado, devidamente codificados, no Laboratório de Biomecânica e Morfologia Funcional e as respetivas bases de dados eletrónicas num servidor dedicado e com acesso restrito, do mesmo Laboratório. Caso não se verifique a sua elegibilidade para participar neste estudo, todos os seus dados registados (em papel e eletronicamente) serão destruídos.

Appendix I - Informed Consent (4)

O que acontecerá aos dados quando a investigação terminar?

Com a sua autorização e em caso de elegibilidade para o estudo, os dados brutos da base de dados eletrónica passarão a fazer parte da base de dados do Laboratório de Biomecânica e Morfologia Funcional e poderão ser posteriormente usados exclusivamente para fins de investigação, sendo sempre garantido o seu anonimato. Caso contrário, os dados serão apagados do servidor.

Como irão os resultados do projeto ser divulgados e com que finalidades?

Os resultados deste projeto irão ser utilizados apenas para fins de investigação, estando planeado a publicação de uma tese de doutoramento, uma tese de mestrado e de três artigos científicos. Em nenhuma circunstância será possível a sua identificação durante a apresentação dos dados.

Em caso de dúvidas ou de urgência quem devo contactar?

Para qualquer questão relacionada com a sua participação neste estudo, por favor, contactar os investigadores Andreia Carvalho e Vera Moniz-Pereira. Nessa situação, faremos o nosso melhor para responder às suas questões. Poderá contactar-nos através do seguinte endereço eletrónico: caminhar.fmh@gmail.com ou telefone: 214149100

Muito obrigado pela sua colaboração e tempo dispensado!

Appendix I - Informed Consent (5)

Projeto de investigação: Validação de um Sistema de análise de movimento sem marcadores para avaliar a marcha em idosos

Assinatura do Consentimento Informado, Livre e Esclarecido

Li (ou alguém leu para mim) o presente documento e estou consciente do que esperar quanto à minha participação neste projeto (Validação de um Sistema de análise de movimento sem marcadores para avaliar a marcha em idosos). Tive a oportunidade de colocar todas as questões e as respostas esclareceram todas as minhas dúvidas. Assim, aceito voluntariamente participar nesta sessão e declaro ainda que autorizo, caso se verifique a minha elegibilidade, a ser contactado para as sessões de teste.

Contacto: _____

Foi-me dada uma cópia deste documento.

Data: _____

Nome do participante **Assinatura do participante**

Investigador/Equipa de Investigação

Os aspetos mais importantes deste estudo foram explicados ao participante ou ao seu representante, antes de solicitar a sua assinatura. Uma cópia deste documento ser-lhe-á fornecida.

Data: _____

Nome da pessoa que obtém o consentimento **Assinatura da pessoa que obtém o consentimento**

Appendix II - Eligibility Questionnaire (1)

Verificação de critérios de inclusão/exclusão

Data: ___/___/_____Hora de início:___:___ CÓDIGO DO PARTICIPANTE: _____

Quantos anos tem? _____ Sexo: F ☐ M ☐

Qual a sua nacionalidade? _____ Qual a sua naturalidade? _____

Se for de outro país, há quanto tempo vive em Portugal? _____Não Aplicável ☐

Quais são as suas habilitações literárias?

Ensino Primário ou inferior		Ensino Básico Completo		Ensino Secundário Completo		Ensino Superior Completo	

Quantos anos de escolaridade concluiu? _____

Quanto pesa? _____ Quanto mede? _____

Vive num Lar ou Casa de Repouso? Não☐ Sim ☐

De entre as atividades que vou enunciar gostaria de saber se as consegue realizar de forma independente (sem ajuda)	**Não**	**Sim**
Tratar das suas necessidades pessoais, como vestir-se sozinho(a)		
Tomar banho sozinho(a) na banheira ou chuveiro		
Andar na rua 100 metros		

Utiliza algum **auxiliar de marcha** (canadiana, bengala, etc)? Não☐ Sim ☐

Se sim, especifique o equipamento que utiliza: _____

Foi sujeito à colocação de uma **prótese** em alguma articulação do membro inferior? Não ☐ Sim ☐

Se sim, especifique onde: _____

Nos **últimos 6 meses** acedeu aos serviços de saúde por algum sintoma (dor/desconforto) ou patologia dos membros inferiores (ancas, joelhos, pernas, pés...)? Não ☐ Sim ☐

Se sim, especifique: _____

Como descreveria a dor que sente neste momento nos membros inferiores

Sem dor ☐ Dor Ligeira ☐ Dor moderada ☐ Dor intensa ☐ Dor máxima ☐

Essa dor afeta a sua capacidade de caminhar?

Não Aplicável ☐ Não ☐ Sim ☐

Appendix II - Eligibility Questionnaire (2)

Alguma vez lhe foi <u>diagnosticado</u> algumas das condições clínicas seguintes? (Se sim, especifique o ano do diagnóstico e a medicação associadas)			
Condição clínica		**Ano do diagnóstico**	**Medicação associada (nome de cada)**
Ataque cardíaco	Não☐ Sim☐		
Angina de Peito	Não☐ Sim☐		
Hipertensão	Não☐ Sim☐		
Acidente Vascular Cerebral	Não☐ Sim☐		
Cancro	Não☐ Sim☐		
Doença vascular periférica	Não☐ Sim☐		
Diabetes	Não☐ Sim☐		
Neuropatias	Não☐ Sim☐		
Insuficiência respiratória	Não☐ Sim☐		
Doença de Parkinson	Não☐ Sim☐		
Doença de Alzheimer	Não☐ Sim☐		
Esclerose múltipla	Não☐ Sim☐		
Poliomielite/Síndrome Pós-pólio	Não☐ Sim☐		
Epilepsia	Não☐ Sim☐		
Outra condição neurológica:	Não☐ Sim☐		
Osteoporose	Não☐ Sim☐		
Artrite reumatoide	Não☐ Sim☐		
Osteoartrose	Não☐ Sim☐		
Fratura nos membros inferiores	Não☐ Sim☐		
Outra condição músculo-esquelética:	Não☐ Sim☐		

Appendix II - Eligibility Questionnaire (3)

Problemas de visão não corrigidos	Não☐ Sim☐		
Problemas do ouvido interno	Não☐ Sim☐		
Ataxia	Não☐ Sim☐		
Depressão	Não☐ Sim☐		
Doença mental	Não☐ Sim☐		
Doenças endócrinas	Não☐ Sim☐		
Outra(s)	Não☐ Sim☐		

Nos **últimos 6 meses** acedeu aos serviços de saúde por alguma das condições clínicas mencionadas anteriormente? Não ☐ Sim ☐

Se sim, especifique: _____

Atualmente, alguma(s) das condições clínicas, que mencionou anteriormente, afeta a sua capacidade de caminhar?

Não Aplicável ☐ Não ☐ Sim ☐

Se sim, qual? _____

Score **MoCA**: _____

Hora final:___:___

Lista para controlo de critérios de inclusão e exclusão

Critérios de inclusão	**Não**	**Sim**
Capaz de falar e ler em Português Europeu e preencher o CILE		
Tem 65 ou mais anos		
Vive de forma independente na comunidade (Consegue realizar ABVD)		
Caminha 100m sem ajuda (de outra pessoa ou de auxiliares de marcha)		

Critérios de exclusão	**Não**	**Sim**
Condição clínica que afete a capacidade de caminhar		
Toma medicação que afeta a capacidade de caminhar		
Tem dor/sintoma nos membros inferiores que afeta a capacidade de caminhar		
Resultado MOCA (avaliação cognitiva) < 23		
IMC>30kg/m^2		

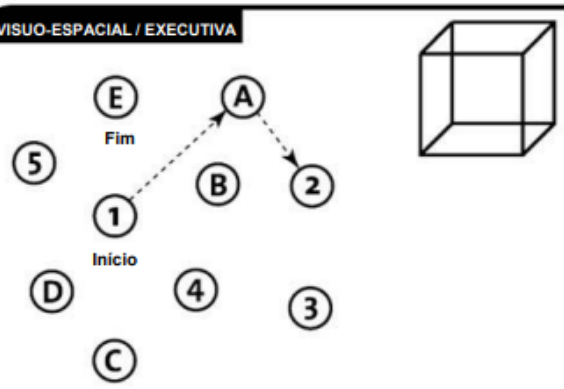
Appendix III - Montreal Cognitive Assessment (1)

MONTREAL COGNITIVE ASSESSMENT (MOCA)

VERSÃO PORTUGUESA – 7.1 VERSÃO ORIGINAL

Nome: _____ **Idade:** _____
Género: _____ **Data de Nascimento:** _____
Escolaridade: _____ **Data de Avaliação:** _____

VISUO-ESPACIAL / EXECUTIVA — **Pontos**



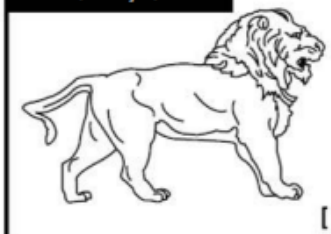
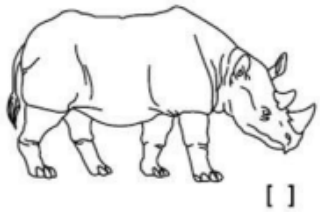
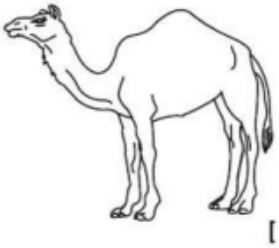
Copiar o cubo

[ ] [ ] — /5

Desenhar um Relógio (onze e dez) (3 pontos)

[ ] Contorno [ ] Números [ ] Ponteiros

NOMEAÇÃO

[ ] [ ] [ ] — /3

MEMÓRIA — Sem Pontuação

Leia a lista de palavras. O sujeito deve repeti-la. Realize dois ensaios. Solicite a evocação da lista **5 minutos mais tarde.**

	Boca	Linho	Igreja	Cravo	Azul
1º ensaio					
2º ensaio					

ATENÇÃO — /2

Leia a sequência de números. (1 número/segundo)
O sujeito deve repetir a sequência. [ ] 2 1 8 5 4
O sujeito deve repetir a sequência na ordem inversa. [ ] 7 4 2

Leia a série de letras (1 letra/segundo). O sujeito deve bater com a mão cada vez que for dita a letra A. Não se atribuem pontos se ≥ 2 erros. — /1

[ ] F B A C M N A A J K L B A F A K D E A A A J A M O F A A B

Subtrair de 7 em 7 começando em 100. [ ] 93 [ ] 86 [ ] 79 [ ] 72 [ ] 65 — /3

4 ou 5 subtracções correctas: **3 pontos;** 2 ou 3 correctas: **2 pontos;** 1 correcta: **1 ponto;** 0 correctas: **0 pontos**

LINGUAGEM — /2

Repetir: Eu só sei que hoje devemos ajudar o João. [ ] O gato esconde-se sempre que os cães entram na sala. [ ]

Fluência verbal: Dizer o maior número possível de palavras que comecem pela letra "P" (1 minuto). [ ] _____ (N ≥ 11 Palavras) — /1

ABSTRACÇÃO — /2

Semelhança p.ex. entre banana e laranja = fruta [ ] comboio - bicicleta [ ] relógio - régua

EVOCAÇÃO DIFERIDA — /5

	Deve recordar as palavras SEM PISTAS	Boca	Linho	Igreja	Cravo	Azul	
		[ ]	[ ]	[ ]	[ ]	[ ]	Pontuação apenas para evocação **SEM PISTAS**
Opcional	Pista de categoria						
	Pista de escolha múltipla						

ORIENTAÇÃO — /6

[ ] Dia do mês [ ] Mês [ ] Ano [ ] Dia da semana [ ] Lugar [ ] Localidade

© Z.Nasreddine MD

Examinador: _____

TOTAL /30

Versão Portuguesa: Freitas, S., Simões, M. R., Santana, I., Martins, C. & Nasreddine, Z. (2013). *Montreal Cognitive Assessment (MoCA): Versão 1.* Coimbra: Faculdade de Psicologia e de Ciências da Educação da Universidade de Coimbra.

Appendix IV - Characterization Questionnaire (1)

CÓDIGO DO PARTICIPANTE: _____

Antes de responder ao questionário, por favor preencha a data e a hora de início do mesmo:

Data:___/___/___ Hora de início:____:____

Dados Sociodemográficos

Qual o seu Conselho de Residência? _____

Qual é a sua situação profissional?

A trabalhar ☐ Desempregado(a) ☐ Reformado(a) ☐ Doméstica(o) ☐

Dados de Saúde

No **último ano,** sofreu alguma queda, incluindo um evento em que tenha tropeçado, ou escorregado, perdido o equilíbrio e caído no chão, ou noutra superfície, com um nível mais baixo em relação ao que se encontrava? _____Se sim, quantas vezes caiu? _____

E nos últimos **3 meses,** quantas vezes caiu? _____

Por favor, assinale a opção que melhor descreve a intensidade de dor nos membros inferiores que sente **NESTE MOMENTO**

Sem dor ☐ Dor Ligeira ☐ Dor moderada ☐ Dor intensa ☐ Dor máxima ☐

Essa dor afeta a sua capacidade de caminhar?

Não Aplicável ☐ Não ☐ Sim ☐

Appendix IV - Characterization Questionnaire (2)

Dados de Prática de Atividade Física

Nos últimos 3 meses, participou numa sessão de exercício ou atividade física? ☐ Não ☐ Sim

Se sim, por favor especifique na tabela que se segue:

(1) o(s) tipo(s) de aula(s)/atividade(s) que pratica (exemplo: caminhadas, hidroginástica, Tai Chi, yoga, natação, etc.);

(2) se essa atividade foi prescrita por um profissional de exercício físico;

(3) a duração e a frequência semanal dessa(s) atividade(s) **relativamente aos últimos 3 meses**;

(4) se considera que a atividade mencionada é exigente (intensa) o suficiente para causar um aumento percetível da frequência respiratória e da frequência cardíaca.

Tipo de sessão/Atividade	Esta atividade foi prescrita por um profissional de exercício físico?	Duração de cada sessão/Atividade	Número de aulas por semana	Esta aula/atividade é exigente o suficiente para causar um aumento percetível da frequência respiratória e da frequência cardíaca?
	Não ☐ Sim☐			Não ☐ Sim☐
	Não ☐ Sim☐			Não ☐ Sim☐
	Não ☐ Sim☐			Não ☐ Sim☐
	Não ☐ Sim☐			Não ☐ Sim☐
	Não ☐ Sim☐			Não ☐ Sim☐

Em alguma das atividades que mencionou anteriormente participa em competições (ex. corridas de 5km)? Não ☐ Sim ☐

Se sim, em qual (quais)?: _____

Por favor indique a hora em que terminou o preenchimento deste questionário:
Hora final:____:____
Muito obrigado pela sua colaboração e tempo dispensado!

DURAÇÃO TOTAL (min):_____

Appendix V – Composite Physical Function Scale (1)

CÓDIGO DO PARTICIPANTE:_____

Antes de responder ao questionário, por favor preencha a data e a hora de início do mesmo:

Data:___/___/___ Hora de início:____:____

COMPOSITE PHYSICAL FUNCTION SCALE – PORTUGUÊS (CPF-PT)

Instruções: Indique por favor a sua capacidade para realizar as seguintes atividades, colocando um circulo na resposta adequada. A sua resposta deve indicar se consegue realizar estas atividades, e não se as realiza atualmente.

	Consigo realizar por mim próprio sem ajuda	Consigo realizar com ajuda	Não consigo realizar
a. Tratar das suas necessidades pessoais, como vestir-se sozinho(a)	2	1	0
b. Tomar banho sozinho (a) na banheira ou chuveiro	2	1	0
c. Andar na rua (100 ou 200 metros)	2	1	0
d. Realizar tarefas domésticas leves – tais como um ou mais dos seguintes exemplos: cozinhar, limpar o pó, lavar a loiça, varrer um passeio	2	1	0
e. Subir e descer um lance de escadas	2	1	0
f. Fazer as próprias compras/ recados (andar aproximadamente 500 metros).	2	1	0
g. Levantar e transportar 5 kg (Um saco de compras).	2	1	0
h. Andar um quilómetro.	2	1	0
i. Andar um quilómetro e meio.	2	1	0
j. Levantar e transportar 10 kg (Uma mala de viagem média ou grande ou dois sacos de compras ou dois garrafões de água)	2	1	0
k. Realizar tarefas domésticas pesadas – tais como um ou mais dos seguintes exemplos: esfregar o chão, aspirar, varrer folhas.	2	1	0
l. Realizar atividades extenuantes – tais como um ou mais dos seguintes exemplos: caminhadas intensas, cavar o jardim, mover objetos pesados, andar de bicicleta, ginástica aeróbica, exercício extenuante, etc.	2	1	0

Por favor preencha a hora em que terminou o preenchimento deste questionário:

Hora final:____:____

Muito obrigado pela sua colaboração e tempo dispensado!

DURAÇÃO TOTAL (min):_____

Appendix VI – EQ5D Questionnaire (1)

Questionário de saúde

Versão Portuguesa para Portugal

(Portuguese version for Portugal)

Appendix VI – EQ5D Questionnaire (2)

Sob cada título, assinale o quadrado que melhor descreve como a sua saúde está HOJE.

MOBILIDADE

Não tenho problemas em andar ❑

Tenho alguns problemas em andar ❑

Tenho de estar na cama ❑

CUIDADOS PESSOAIS

Não tenho problemas com os meus cuidados pessoais ❑

Tenho alguns problemas em lavar-me ou vestir-me ❑

Sou incapaz de me lavar ou vestir sozinho/a ❑

ATIVIDADES HABITUAIS *(ex. trabalho, estudos, atividades domésticas, atividades em família ou de lazer)*

Não tenho problemas em desempenhar as minhas atividades habituais ❑

Tenho alguns problemas em desempenhar as minhas atividades habituais ❑

Sou incapaz de desempenhar as minhas atividades habituais ❑

DOR / MAL-ESTAR

Não tenho dores ou mal-estar ❑

Tenho dores ou mal-estar moderados ❑

Tenho dores ou mal-estar extremos ❑

ANSIEDADE / DEPRESSÃO

Não estou ansioso/a ou deprimido/a ❑

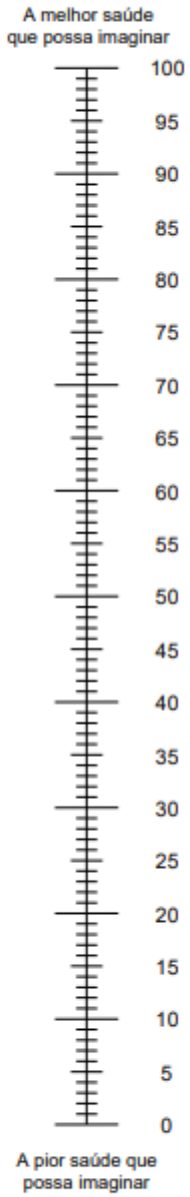
Estou moderadamente ansioso/a ou deprimido/a ❑

Estou extremamente ansioso/a ou deprimido/a ❑

Appendix VI – EQ5D Questionnaire (3)

- Gostaríamos de saber o quanto a sua saúde está boa ou má HOJE.
- A escala está numerada de 0 a 100.
- 100 significa a melhor saúde que possa imaginar.
  0 significa a pior saúde que possa imaginar.
- Assinale com um X na escala de forma a demonstrar como a sua saúde se encontra HOJE.
- Agora, por favor escreva o número que assinalou na escala na caixa abaixo.

A SUA SAÚDE HOJE = ☐



Appendix VII – Python code developed to automatically detect the optimal cutoff frequency (1)

```
# 1 - Import libraries
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
from scipy.signal import butter, filtfilt
from kneed import KneeLocator  # For finding the "elbow" in the
residuals plot
from PyQt5.QtWidgets import QApplication, QFileDialog  # For GUI file
selection
import sys
from scipy.interpolate import interp1d  # For interpolation of data
points

# 2 - Butterworth low-pass filter function
def butter_lowpass_filter(data_values, cutoff, fs, order=2):
    nyquist = 0.5 * fs  # Nyquist frequency (half of the sampling
frequency)
    normal_cutoff = cutoff / nyquist  # Normalize the cutoff frequency
    if not (0 < normal_cutoff < 1):
        raise ValueError(f"Invalid cutoff frequency: {cutoff}. It must
be between 0 and {nyquist}.")
    b, a = butter(order, normal_cutoff, btype='low', analog=False)  #
Design the Butterworth filter
    y = filtfilt(b, a, data_values)  # Apply the filter to the data
    return y  # Return the filtered signal

# 3 - File selection function
def select_file():
    app = QApplication(sys.argv)  # Create a Qt application
    options = QFileDialog.Options()  # Set file dialog options
    options |= QFileDialog.ReadOnly  # Set the dialog to read-only
mode
    file_path, _ = QFileDialog.getOpenFileName(None, "Select ASCII
File", "", "ASCII Files (*.txt);;All Files(*)", options=options) # Set
the type of wanted data format
    app.exit()  # Exit the Qt application
    return file_path  # Return the selected file path
```

```
# 4 - Save filtered data
def save_filtered_data(filtered_data, original_file_path,
suffix="_filtered"):
    output_file_path = original_file_path.replace(".txt",
f"{suffix}.txt")  # Creating the new file name
    pd.DataFrame(filtered_data).to_csv(output_file_path, sep='\t',
index=False)  # Saving filtered data in csv format
    print(f"Filtered data saved to: {output_file_path}")

# 5 - Clean and process data
def clean_data(data_column):
    data_values = pd.to_numeric(data_column,
errors='coerce').dropna().values  # Convert and clean the data
    if len(data_values) == 0:
        raise ValueError(f"No valid numeric data available in column
after cleaning.")  # Verify the data
    return data_values

# 6 - Load and process the data
file_path = select_file()  # Open file dialog to select a file
if not file_path:
    raise ValueError("No file selected. Please select an ASCII file.")
# Check if a file was selected

# Read the file contents
data = pd.read_csv(file_path, delimiter='\t')

# Filter columns that contain the string 'mean' (so that we don't have
to deal with the std deviation columns)
mean_columns = [col for col in data.columns if 'mean' in col.lower()]
# Get columns containing 'mean'
if not mean_columns:
    raise ValueError("No columns containing 'mean' found in the
file.")  # Check if any such columns exist

# Sampling frequency and ranges of cutoff frequencies
fs = 85  # Sampling frequency in Hz
cutoff_frequencies_range1 = np.linspace(6, 8, 100)  # Cutoff freqs for
6-8 Hz range
cutoff_frequencies_range2 = np.linspace(8, 22, 100) # Cutoff freqs for
8-22 Hz range
```

```
# Store residuals and optimal cutoff frequencies
optimal_cutoff_frequencies = {}
all_sum_residuals = []
all_sum_residuals_extended = []

# 7 - Loop through each column
for col in mean_columns:
    data_values = clean_data(data[col])
    sum_residuals_range1 = []  # Residuals for 6-8 Hz range
    sum_residuals_range2 = []  # Residuals for 8-22 Hz range

    # Apply filter for the first range (6-8 Hz)
    for cutoff in cutoff_frequencies_range1: # We are going to filter
the signal with multiple values
        try:
            filtered_signal = butter_lowpass_filter(data_values,
cutoff, fs) #Apply the filter in the 6-8hz range
            residuals = data_values - filtered_signal  # Define the
residuals
            sum_of_squares = np.sum(residuals ** 2)  #Square the
residuals
            sum_residuals_range1.append(sum_of_squares)  #Sum the
square of the residuals
        except ValueError as e:
            print(e)  # Print error if invalid cutoff frequency
            sum_residuals_range1.append(np.nan) # Append NaN if
there's an error

    # Apply filter for the second range (8-22 Hz)
    for cutoff in cutoff_frequencies_range2:
        try:
            filtered_signal = butter_lowpass_filter(data_values,
cutoff, fs)  #Apply the filter in the 8-22hz range
            residuals = data_values - filtered_signal # Define the
residuals
            sum_of_squares = np.sum(residuals ** 2)  #Square the
residuals
            sum_residuals_range2.append(sum_of_squares) #Sum the
square of the residuals
        except ValueError as e:
```

```
            print(e)  # Print error if invalid cutoff frequency
            sum_residuals_range2.append(np.nan)  # Append NaN if
there's an error

    # Clean NaNs in both ranges
    sum_residuals_range1 = np.array(sum_residuals_range1)   #
necessary for efficient numerical operations and array manipulations
    valid_indices_range1 = ~np.isnan(sum_residuals_range1) # Identify
valid (non-NaN) indices
    valid_cutoff_frequencies_range1 =
cutoff_frequencies_range1[valid_indices_range1] # Filter valid cutoff
frequencies; Only the indices where valid_indices is True are kept
    sum_residuals_range1 = sum_residuals_range1[valid_indices_range1]
#Only sum the residuals where the index is valid

    sum_residuals_range2 = np.array(sum_residuals_range2)
    valid_indices_range2 = ~np.isnan(sum_residuals_range2)
    valid_cutoff_frequencies_range2 =
cutoff_frequencies_range2[valid_indices_range2]
    sum_residuals_range2 = sum_residuals_range2[valid_indices_range2]

    # Store sum of residuals for plotting
    all_sum_residuals.append(sum_residuals_range1)
    all_sum_residuals_extended.append(sum_residuals_range2)

    # 8 - Use KneeLocator to find optimal cutoff frequency
    kneedle = KneeLocator(valid_cutoff_frequencies_range1,
sum_residuals_range1, curve='convex', direction='decreasing')   #
Initialize KneeLocator
    optimal_cutoff_frequency = kneedle.elbow   # Finding the
elbow/knee (OCF)
    if optimal_cutoff_frequency is not None:
        optimal_cutoff_frequencies[col] = optimal_cutoff_frequency  #
Store optimal frequency for each column

# Calculate overall optimal cutoff frequency
overall_optimal_cutoff_frequency =
np.nanmean(list(optimal_cutoff_frequencies.values()))  # Mean of
optimal frequencies across columns
```

```
print(f'\nThe overall optimal cutoff frequency is around
{overall_optimal_cutoff_frequency:.2f} Hz.')

# 9 - Apply the filter with the overall optimal cutoff frequency and
save filtered data
filtered_signals = {} # Create an empty dictionary to store filtered
signals
for col in mean_columns:
    data_values = clean_data(data[col])
    filtered_signal = butter_lowpass_filter(data_values,
overall_optimal_cutoff_frequency, fs) # Apply a low-pass Butterworth
filter using the OCF
    filtered_signals[col] = filtered_signal

# 10 - Plot elbow graph
mean_sum_residuals_range1 = np.nanmean(all_sum_residuals, axis=0) #
Calculate the mean of the residuals for the first range, ignoring NaN
values
mean_sum_residuals_range2 = np.nanmean(all_sum_residuals_extended,
axis=0) # Calculate the mean of the residuals for the extended range,
ignoring NaN values

extended_cutoff_frequencies = np.linspace(0.1, 22, 1000) # Cutoff
freqs for 0.1-22 Hz range
interpolation =
interp1d(np.concatenate([valid_cutoff_frequencies_range1,
valid_cutoff_frequencies_range2]),
                            np.concatenate([mean_sum_residuals_range1,
mean_sum_residuals_range2]),
                            kind='linear', fill_value='extrapolate') #
Interpolate the sum of residuals across valid cutoff frequencies using
linear interpolation

extended_sum_residuals = interpolation(extended_cutoff_frequencies) #
Apply interpolation to the extended cutoff frequencies
extended_sum_residuals = np.clip(extended_sum_residuals, a_min=0,
a_max=None)  # Clip the residual values to ensure they are non-
negative
```

```
threshold_at_optimal = np.interp(overall_optimal_cutoff_frequency,
cutoff_frequencies_range1, mean_sum_residuals_range1) # Interpolate to
find the threshold at the OCF

plt.figure(figsize=(10, 6))
plt.plot(extended_cutoff_frequencies, extended_sum_residuals,
color='green', linestyle='-') # Plot the average sum of residuals for
the min extended range of cutoff frequencies
plt.axvline(x=overall_optimal_cutoff_frequency, color='blue',
linestyle='--', label='Optimal Cutoff Frequency') # Add a vertical
line at the overall optimal cutoff frequency
plt.axhline(y=threshold_at_optimal, color='red', linestyle='--',
label='Threshold') # Add an horizontal for the threshold
plt.xlabel('Cutoff Frequency (Hz)')
plt.ylabel('Sum of Residuals')
plt.title('Elbow Graph for Optimal Cutoff Frequency')
plt.legend()
plt.grid(True)
plt.xlim([0, 22])
plt.ylim([0, np.max(extended_sum_residuals)])
plt.show()

# Save the filtered data
save_filtered_data(filtered_signals, file_path) # Save the filtered
signals to a specified file path
```

Appendix VIII – Amplitude of the moments

JOINT	PLANE	CLOTHING CONDITION				DIFFERENCES	RELATIVE DIFFERENCE
		MC		SSC		MC - SSC	
		$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	
HIP	SAGITTAL	1.42	0.25	1.46	0.22	-0.04	-2.88%
	FRONTAL	0.98	0.17	1.11	0.15	-0.13	-13.61%
	AXIAL	0.25	0.05	0.28	0.06	-0.04	-15.45%
KNEE	SAGITTAL	0.94	0.22	0.95	0.20	-0.01	-0.68%
	FRONTAL	0.50	0.11	0.58	0.10	-0.08	-16.31%
	AXIAL	0.27	0.07	0.29	0.06	-0.01	-5.49%
ANKLE	SAGITTAL	1.52	0.15	1.53	0.14	-0.01	-0.82%
	FRONTAL	0.26	0.07	0.28	0.08	-0.01	-4.30%
	AXIAL	0.16	0.04	0.18	0.04	-0.02	-12.71%