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Biomechanical gait pattern changes associated with functional fitness levels and falls in the elderly

Dissertação elaborada com vista à obtenção do Grau de Doutor em Motricidade Humana na Especialidade de Biomecânica

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“Não faço tudo o que amo, mas amo tudo o que faço”
“I do not do everything I love, but I love everything I do”
(Gabriel o Pensador)

Para a minha avó Carlota,
uma das primeiras mulheres licenciadas em Educação Física em Portugal,
a melhor aluna do seu curso, uma avó maravilhosa, uma mulher extraordinária.
O meu exemplo, a minha inspiração.

To my grandmother Carlota,
one of the first women who graduated in Physical Education in Portugal,
the best student of her course, a wonderful grandmother and an extraordinary woman.
She was and is my role model and my inspiration.

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Resumo

A presente dissertação objetiva o aprofundamento do conhecimento sobre os determinantes das quedas na população idosa portuguesa, com especial enfoque nas alterações biomecânicas nos padrões de marcha associadas ao declínio funcional característico desta população. A abordagem metodológica preconizada para a análise do problema compreende duas fases complementares: uma primeira fase, que englobou dois estudos epidemiológicos com o objetivo de estabelecer os fatores determinantes de quedas na população idosa portuguesa; uma segunda fase, onde foram considerados três estudos experimentais (laboratoriais), com o propósito de determinar a influência de diferentes níveis de aptidão funcional nos padrões de marcha desta população. Os resultados demostraram que as quedas resultam da interação de diversos fatores de risco, destacando-se os seguintes: género, parâmetros de aptidão funcional e de saúde. De relevar que o fenómeno de queda se revelou independente da idade, mesmo quando analisada a sua associação com os fatores determinantes em grupos etários mais avançados (≥75 e ≥80 anos). Neste sentido, nos estudos subsequentes, foram analisados os padrões de marcha de subgrupos de idosos recrutados do grupo de participantes dos estudos anteriores e estratificados em função do seu nível de aptidão funcional. Observou-se então que os idosos com baixos níveis de aptidão funcional adotavam estratégias consistentes de redistribuição dos momentos de força articulares dos membros inferiores, aquando da execução de diferentes tarefas locomotoras (marcha, subir e descer escadas). Considerando o sucesso demonstrado das intervenções sustentadas em programas de atividade física para a prevenção de quedas e incapacidade, as alterações biomecânicas dos padrões de marcha observadas poderão constituir um importante suporte informacional para os profissionais de saúde e exercício que trabalham com a população idosa.

Palavras-chave: Idosos, Quedas, Aptidão funcional, Momentos de força articulares, Acelerações induzidas.

Abstract

This thesis aimed to provide a better understanding on the determinant factors for falling in Portuguese older adults, with a special emphasis on the biomechanical changes in gait patterns associated with the functional fitness decline in this population. Our methodological approach to this problem encompassed two different levels of analysis: in the first part two epidemiological studies were conducted in order to establish the determinant factors for falling within the Portuguese older adults; in the second part three laboratory-based studies were performed in order to determine the influence of functional fitness levels on elderly gait patterns. Falls were shown to result from the interaction of many risk factors. Within these, gender, functional fitness level and health parameters were found to be the strongest fall determinants. Interestingly, age was not a determinant factor for falling, even within very old individuals (≥75 years or ≥80 years). Therefore, in the subsequent studies, the gait patterns of a subgroup of older adults, who had participated in the epidemiological studies, were characterized according with their functional fitness levels. The results showed that older subjects with a lower functional fitness level score, consistently re-distribute lower limb joint moments while performing different locomotor tasks (walking, stair ascent and stair descent). Because the success of physical activity interventions aiming at falls and disability prevention is dependent on subgroup characterization, these biomechanical gait pattern changes may yield important information for the health and exercise professionals working with the elderly.

Keywords: Elderly, Falls, Functional fitness, Joint moments, Induced accelerations.

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List of Abbreviations

ADLs	Activities of daily living
CD	Chronic diseases
CoM	Centre of mass
CS	Chair stand test (SFT)
ES	Effect size
F/EF	Episodic fallers
FAB	Fullerton advanced balance scale
FAB4	Step up and over a bench (FAB)
FAB5	Tandem walk along a line (FAB)
FAB6	Stand on one leg from (FAB)
FAB7	Stand on a foam with eyes closed (FAB)
FF	Functional fitness
FOF	Fear of falling
GC	Gait cycle
GO	Global optimization
GOR	Global optimization restricted
GRF	Ground reaction force
HHP	Hearing health perception
HFFL	High functional fitness level group
HP	Health perception
IAA	Induced acceleration analysis
LFFL	Low functional fitness level group
MI	Moving index (YPAS)
NF	Non fallers
PA	Physical activity
Pose	Segments' position and orientation
RF	Recurrent fallers
RMS	Root mean square
ROM	Range of motion
SA	Stair ascent
SD	Stair descent
SFT	Senior fitness test
SI	Standing index (YPAS)
SO	Segment optimization
STA	Soft tissue artifact
STI	Sitting index (YPAS)
UG	8 foot and go test (SFT)
VHP	Visual health perception
VI	Vigorous index (YPAS)
WI	Walking index (YPAS)
YPAS	Yale physical activity survey

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General Introduction

CHAPTER

1.1 Background

Thirty to forty percent of the community dwelling older adults over 65 years fall at least once each year (Todd & Skelton, 2004; Lord, Sherrington, Menz, & Close, 2007a; World Health Organization, 2007). Further, fall rates are reported to increase with ageing, reaching approximately 50% in elderly who are over 80 years of age (Todd & Skelton, 2004). More than an incidence issue, falling is a serious problem among older adults, who are more susceptible to injury due to the higher prevalence of clinical conditions like osteoporosis and reduced bone density. Thus, within this population, even a mild fall may have very serious consequences. Falls have been related to the increase of morbidity and mortality within the older subjects, and may also be the first indicator of an undetected illness (Todd & Skelton, 2004; World Health Organization, 2007). Furthermore, even non-injurious falls appear to be determinant for functional decline, social withdrawal, anxiety and depression, and long term placement in a skilled-nursing facility (Todd & Skelton, 2004; Tinetti & Williams, 1997, 1998; Stel, Smit, Pluijm, & Lips, 2003; Voermans, Snijders, Schoon, & Bloem, 2007).

The burden induced by falls not only affects the elderly and their families' quality of life, but has also associated costs for the health care system, which are reported to be increasing throughout the world, due to the increase of life expectancy (World Health Organization, 2007). As so, fall prevention became a primary public health concern, and many studies have been done to determine the main risk factors for falling (e.g. Graafmans et al., 1996; Pluijm et al., 2006; Stalenhoef, Diederiks, Knottnerus, Kester, & Crebolder, 2002; Tromp et al., 2001; Yamashita, Noe, & Bailer, 2012).

The problem of falls has shown to be the result of the interaction of many risk factors, categorized in four dimensions by the World Health Organization (World Health Organization, 2007): biological, behavioral, environmental and socioeconomic (Figure 1.1). The biological risks factors comprise the individual characteristics related with the human body, including non-modifiable factors, like age, gender and race, and factors that may be modified, such as the decline in physical capacity. The behavioral factors are related with human actions, emotions and daily choices (sedentary behavior and excess alcohol use, for example) and are also potentially modifiable. Environmental risk factors include home hazards and hazardous features in public environment (narrow steps, slippery surfaces of stairs, looser rugs and so on). These factors are not by themselves the direct cause for falling. Instead, falls occur due to the interaction between individuals' physical conditions and the surrounding environment, to which they are exposed. Finally, socioeconomic risk factors are associated with the social conditions and the economic status of the individual (examples: low income, lack of social interactions and limited access to health and social services).

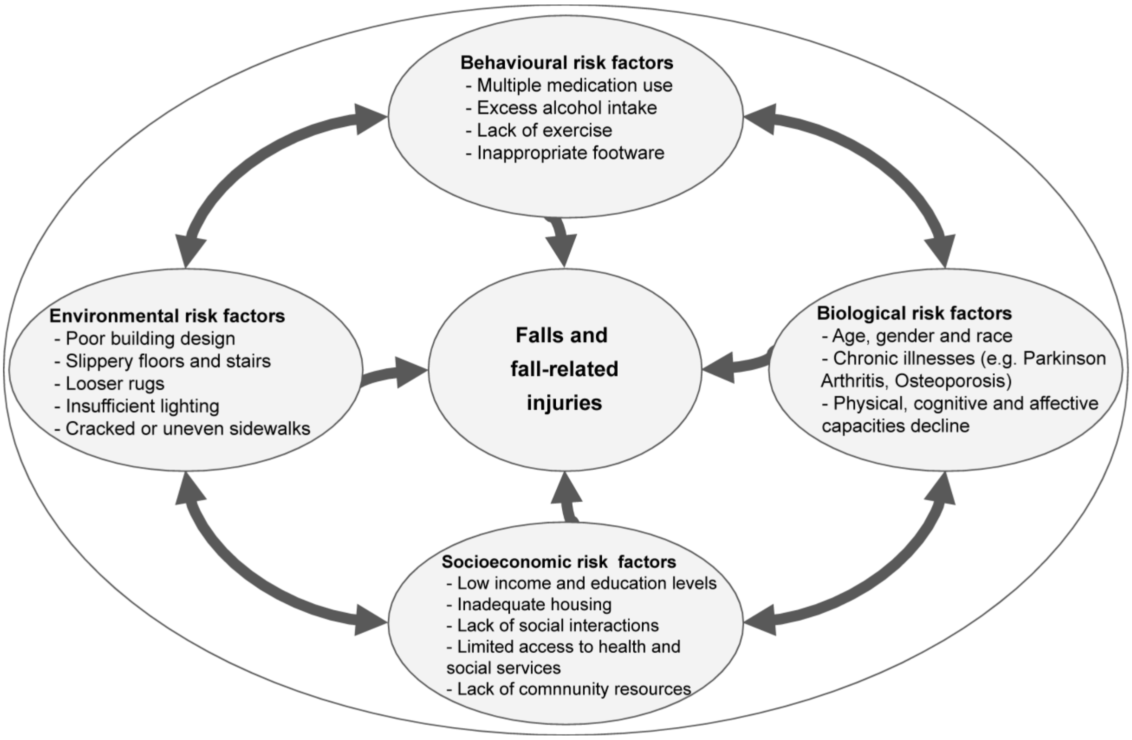

Figure 1.1: Risk factor model for falls in older age (World Health Organization, 2007)

Although falls are a result of the interaction of multiple factors, specific physical capacity related factors, such as muscle weakness and problems with gait and balance, have been identified as particularly important risk factors for falling (Rubenstein, 2006). Since the mentioned factors are related to physical function decline, which is strongly associated with inactivity rather than age and/or disease alone (Collins, Rooney, Smalley, & Havens, 2004; Spirduso, Francis, & MacRae, 2005; U.S. Department of Health and Human Services, 1996; Visser, Pluijm, Stel, Bosscher, & Deeg, 2002), this will have important consequences for a pro-active approach of fall prevention. In fact, the Fall Prevention Model established by the World Health Organization (World Health Organization, 2007) is built within the Active Ageing Policy Framework (World Health Organization, 2002), which aims to extend the healthy life expectancy (i.e. the years lived without disability) and the quality of life for all people during the ageing process. The key goal in this framework is to maintain autonomy and independence through life by sustaining an active lifestyle (both in terms of physical activity, as well as through the engagement in social, cultural, civic and other activities) (World Health Organization, 2002).

This interaction between lifestyle behaviors, physical function, falls and disability is shown on the disability conceptual model proposed by Spirduso et al 2005 (Figure 1.2). By combining all factors that have been related to disability in previous predictive models (Lawrence & Jette, 1996; Morey, Pieper, & Cornoni-Huntley, 1998; Nagi, 1991; Verbrugge & Jette, 1994), this model expands the view of disability, as the sole consequence of pathology (Nagi, 1991), to a more complex model.

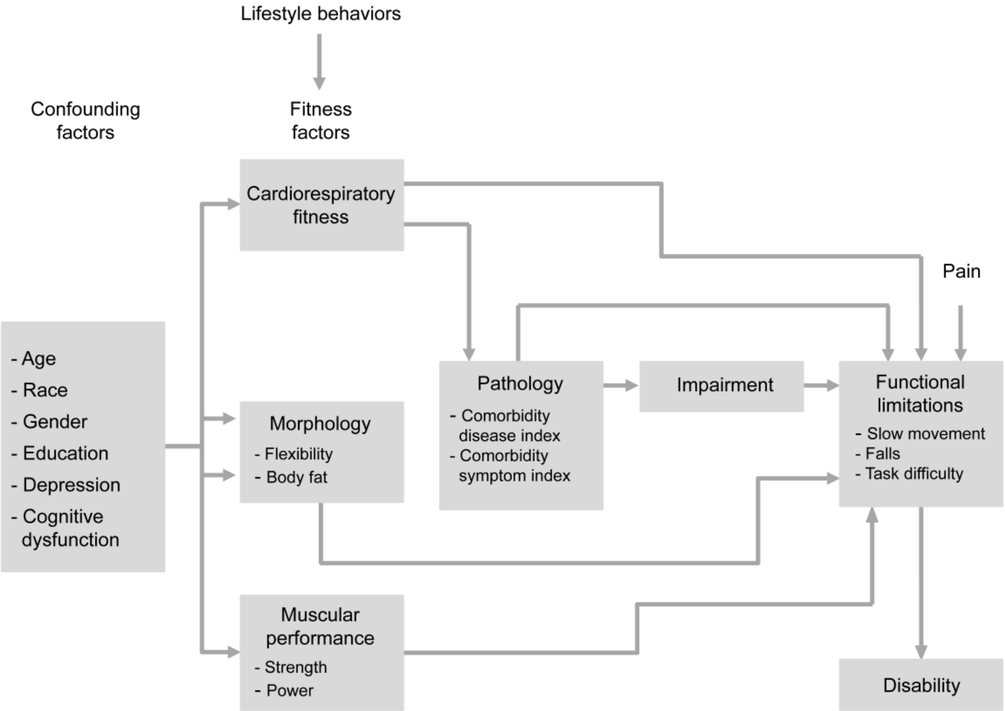

Figure 1.2: Disability conceptual model (Spirduso et al., 2005)

In this model, physical capacity factors[1] are directly related to falls and functional limitations, even on the absence of pathology. Age, race, gender, education, depression and cognitive dysfunction, are included as confounding factors, due to their influence on physical capacity factors. Lifestyle behavioral factors are also considered, showing that the path towards disability should not be assumed as inevitable, but can be reversed by changing health and physical activity habits (Spirduso et al., 2005).

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[1] Due to the variety terms co-existing in the literature (Rikli & Jones, 1999; Spirduso, Francis, & MacRae, 2005; World Health Organization, 2007), in the scope of this thesis physical capacity factors embrace the terms fitness factors and physical parameters

Because of the role of physical function on falls and disability, the measurement of the physiological declines that precede the loss of function became a priority when dealing with community dwelling older adults (Rikli & Jones, 1997, 1999). To this effect, and based on the disability models, Rikli and Jones (1997, 1999) proposed a functional ability framework so that the physical capacity factors necessary to perform certain functions, and essential to accomplish common daily activities, could be identified (Figure 1.3).

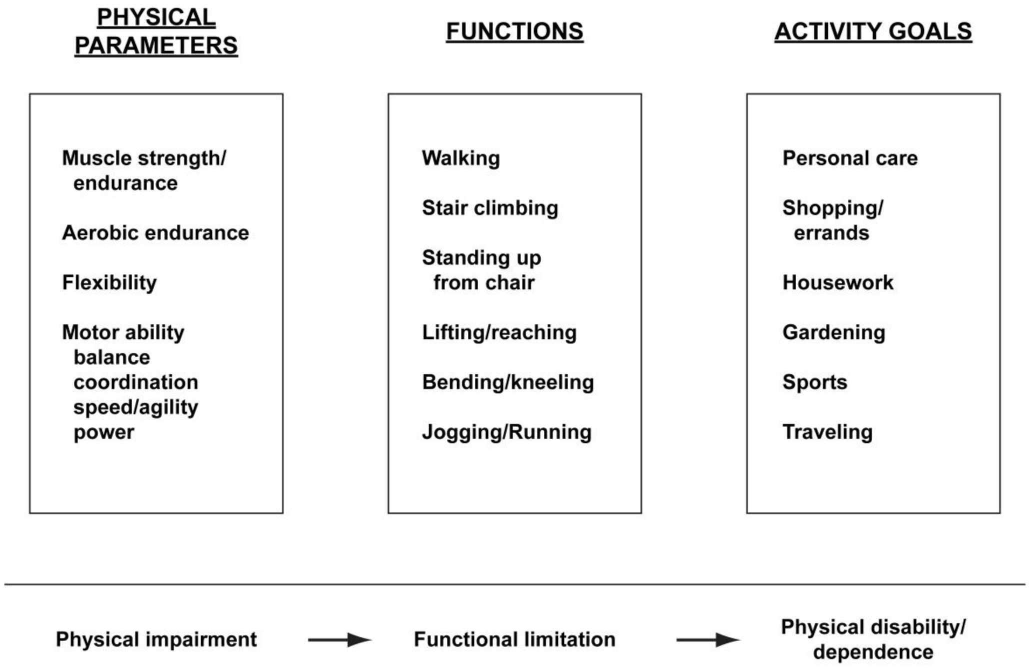

Figure 1.3: A functional ability framework (Rikli & Jones, 1997, 1999)

Within this framework, the authors also defined functional fitness as “having the physiologic capacity to perform normal daily activities safely and independent without the undue fatigue” (Rikli & Jones, 1999; pp133). The expression “without undue fatigue” is used to integrate the concept of physiological reserve and thus emphasize the need of having an adequate reserve of the physical capacity factors (e.g. muscle strength, aerobic endurance, balance) in order to perform the correspondent daily activities. The majority of these activities require the ability to move from a place to another, independently and safely, which is defined as mobility (Rantakokko, Mänty, & Rantanen, 2013). Elderly physical capacity decline, namely muscle strength decline, is shown to be particularly high in lower limb muscles, leading to problems in mobility and difficulties in performing daily activities (Vandervoort, 2002). Therefore, it is not surprising that older adults report difficulties in gait activities performance, especially when dealing with stairs, and that most falls occur during these activities (Berg, Alessio, Mills, & Tong, 1997; Startzell, Owens, Mulfinger, & Cavanagh, 2000).

In exercise and rehabilitation contexts, mobility limitations can be measured through self report, which is based on the subjects' self perception of mobility, or through performance tests, in which the examiner rates the subject's performance during a specific task, therefore providing a more objective measure of mobility (Rantakokko et al., 2013). Nevertheless, to have a better understanding of the mechanisms underlying the functional changes in gait activities, a more complex approach is needed. Through instrumented gait analysis it is possible to quantify the mobility changes associated to a determined disorder/condition, as well as to determine the neuromuscular-skeletal parameters causing those changes (Simon, 2004). This assessment technique is shown to offer a reliable assessment of gait performance (Wilken, Rodriguez, Brawner, & Darter, 2012). In older adults, instrumented gait analysis may yield important information regarding the biomechanical mechanisms of balance control underlying the performance of gait activities, and thus help to pin-point useful changes related to functional impairments and falls (Winter, 1991).

It is fairly difficult to compare the results of the studies concerning the biomechanical changes in elderly gait patterns, since they differ highly regarding the data collection equipment used, the biomechanical model chosen and the normalization process of the data. Even though, there are some consistent findings in the literature, especially in what concerns temporal-distance and/or kinematic parameters while walking. When compared with younger adults, older individuals were shown to walk with a slower velocity, a shorter stride length and an increased stance time (namely, double support time) (DeVita & Hortobagyi, 2000; Prince, Corriveau, Hébert, & Winter, 1997; Winter, Patla, Frank, & Walt, 1990). A decrease in ankle and knee flexion/extension range of motion and an increase of hip flexion/extension range of motion and hip flexion are also consistent kinematic changes related with ageing (DeVita & Hortobagyi, 2000; Kerrigan, Todd, Della Croce, Lipsitz, & Collins, 1998; Prince et al., 1997). Furthermore, although kinetic changes in elderly walking patterns are less studied, a less vigorous push off, reflected through a reduction in the peak of the anterior ground reaction force and of the plantaflexor joint moment, seems to be a consistent characteristic of older adults gait patterns (DeVita & Hortobagyi, 2000; Prince et al., 1997; Winter et al., 1990). Studies regarding elderly changes in stair walking patterns are scarce and some of them are focused only on the negotiation of a single step (Begg & Sparrow, 2000; T Hortobágyi & DeVita, 1999; Lark, Buckley, Bennett, Jones, & Sargeant, 2003; Lark, Buckley, Jones, & Sargeant, 2004), while others are centered on the behavior of one or two lower limb joints (Tibor Hortobágyi, Mizelle, Beam, & DeVita, 2003; Reeves, Spanjaard, Mohagheghi, Baltzopoulos, & Maganaris, 2008, 2009). Nevertheless, it is interesting to note that both during level and stair walking older adults, when compared with their younger counterparts, seem to redistribute lower limb joint moments by consistently applying a lower plantarflexor joint moment (DeVita & Hortobagyi, 2000; Novak & Brouwer, 2011; Reeves et al., 2008, 2009). Further studies are needed to have more consistent findings regarding the behavior of other lower limb joints.

Another issue is that the majority of the mentioned studies commonly compare healthy independent older adults with younger counterparts, which are expectable different groups. Additionally, older adults are an heterogeneous group in terms of physical function, and even within community dwelling older adults, a widely range of capacities can be found (Spirduso et al., 2005). This issue was already stressed out by Kressig et al. (2004), who affirmed that one of the problems, when comparing the results of studies involving older adults, is the difficulty in accurately define their functional capabilities. Lord, Sherrington, Menz, & Close (2007b) also point out the need of further research, especially in gait activities involving obstacles (e.g. dealing with stairs), in order not only to determine gait pattern compensations in the elderly, but also to identify the physiological factors responsible for those compensations.

The main aim of this thesis is to provide a better understanding on the determinant factors for falling in Portuguese older adults, with a special emphasis on the biomechanical changes in gait patterns associated with functional fitness decline in this population. Our methodological approach to this problem encompasses two different levels of analysis: in the first part two epidemiological studies were conducted in order to establish the determinant factors for falling within the Portuguese older adults (1); in the second part three laboratory-based studies were performed in order to determine the influence of functional fitness levels on elderly gait patterns (2).

1.2 Thesis goals and overview

Although the identification of risk factors and determinants of falls is one of the pillars of the World Health Organization Falls Prevention Model (World Health Organization, 2007), information about the fall determinants within the Portuguese older population is scarce. Therefore, the aim of the first part of this thesis (chapters 2 and 3) was to determine the risk factors for falling in Portuguese older adults.

Specifically, the cross-sectional study “Falls in Portuguese older people: procedures and preliminary results of the study Biomechanics of locomotion in the elderly”, presented on chapter 2 of this thesis, aimed: (1) to present preliminary results regarding the field procedures (physical activity and functional fitness assessments) followed in the epidemiological studies; (2) to present a preliminary characterization of Portuguese older people regarding sociodemographic, health, physical activity and functional fitness parameters; and (3) to identify, the independent contribution of those parameters as determinants for falling in Portuguese older adults.

In order to gain a better insight about fall determinants, the study “Using a multifactorial approach to determine fall risk profiles in Portuguese older adults” (chapter 3) was performed. This approach allowed us to go further on the establishment of fallers (episodic and recurrent) risk profiles in the Portuguese population by adjusting the models for possible confounders.

Considering that the decline in physical capacity is particularly determinant for falling (Rubenstein, 2006), and that further research is needed concerning gait pattern compensations in the elderly, especially in activities involving obstacles (e.g. dealing with stairs) (Lord et al., 2007b), the second part of this thesis (chapters 4 to 6) aimed to determine the influence of functional fitness levels on elderly gait patterns.

When performing a biomechanical gait analysis, one essential step for the computation of joint kinematics and kinetics is the choice of the model used to determine the position and orientation of the body segments (segments’ pose). From the different sources of error affecting segments’ pose estimation, soft tissue artifact (STA) is considered the most critical (Andriacchi & Alexander, 2000). When testing older adults, the effects of STA are especially critical, due to the decrease in muscle and skin stiffness and the increase in fat mass that occurs with ageing. The technical note showed on chapter 4 (“Sensitivity of joint kinematics and kinetics to different pose estimation algorithms and joint constraints in the elderly”) aimed to study the influence of different optimization methods used to compensate for STA on joint kinematics and kinetics. This study was essential for choosing the most appropriate kinematic model to carry out the following study.

Joint moments of force, computed with traditional inverse dynamics methods, are central parameters when performing a biomechanical analysis because they are the causes of the movement pattern. The aging process has been associated with a lower limb joint moment redistribution both during level (DeVita & Hortobagyi, 2000) and stair walking (Novak & Brouwer, 2011). However, there is still some controversy about the kinetic strategies adopted by the elderly during these tasks. The study “Gait patterns in the elderly: the influence of functional fitness level”, presented on chapter 5, aimed to contribute for the characterization of sagittal and frontal lower limb joint moment patterns in three different functional tasks (level walking, stair ascent and stair descent) within a group of older adults; and to verify the influence of subjects’ functional fitness level in those task patterns.

Although the inverse dynamics approach for the quantification and description of joint moment patterns is a valuable tool to perform a biomechanical analysis, the cause-effect relation between kinetics and kinematics, when using this method, is inferred by comparison with normative data. The mentioned approach also assumes that the generated net moments crossing a joint are the primary controllers of the movement at that joint, but it was already shown that the joint moments produced by muscles that span a certain joint will generate acceleration in all body joints (Zajac & Gordon, 1989). Induced acceleration analysis is an interpretative method based on the principles outlined by Zajac and Gordon (1989), which allows the direct quantification of joint moments (and/or individual muscles) contribution to the acceleration of each body joint (and/or center of mass). This technique has proven to be a powerful clinical assessment tool (Goldberg & Kepple, 2009; Siegel, Kepple, & Stanhope, 2006) and thus, has been gaining popularity within the biomechanics research community. Chapter 6 is a preliminary study whose purpose was to quantify the potential changes in the contributions of lower limb joint moments and gravity to center of mass forward progression and support in elderly gait patterns, using induced acceleration analysis.

In the final chapter of this thesis (chapter 7) the main findings of each study are summarized and discussed, as well as the general methodological issues concerning those studies. Recommendations for future research are also provided.

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2

Falls in Portuguese older people:

Procedures and preliminary results of the study Biomechanics of Locomotion in the Elderly

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CHAPTER

Abstract

Aim: The aims of this study were to: (1) present preliminary results about the evaluation of the procedures (physical activity and functional fitness tests) followed in the baseline period of our research program; (2) present a preliminary characterization of Portuguese older people regarding sociodemographic, health, physical activity and functional fitness variables; (3) identify, within those parameters, the ones which are determinant to predict falls in Portuguese older adults.

Material and Methods: 647 subjects aged over 65 years were randomly recruited in Lisbon and Tagus Valley area. Trained interviewers administered: (1) a standardized questionnaire that included sociodemographic, health and falls parameters; (2) YPAS questionnaire for PA and (3) six FF tests (30sec Chair-Stand and 8 foot Up&Go from SFT battery and items 4-7 from FAB Scale).

Reproducibility and convergent validity of the FF and PA tests were determined by ICC and Pearson correlations. Logistic regression analysis was used to model fall occurrence considering three different fall groups (non-fallers (NF: 0 falls), episodic fallers (EF: 1 fall) and recurrent fallers (RF: >1 fall).

Results: FF and PA tests showed to have a good convergent validity and reproducibility, giving us confidence about the results obtained.

Approximately 37% of the elderly tested fell during the previous year. From these, 41% were RF. Our results showed that age is not a risk factor for falling and that health and FF variables are the most determinant factors to assess fall risk.

Conclusion: According to the results, falls might not be an inevitable consequence of age, but instead, mainly associated with poor health and functional fitness. Moreover, PA seems to play a key role in this process, not only because a higher level of PA will lead to a better functional fitness level, but also because PA was found to be a protective factor for both episodic and recurrent falls.

Key Words: Elderly, Falls, Functional Fitness, Physical Activity, Health.

2.1 Introduction

The increase of life expectancy in the industrialized countries has raised new public health issues derived from the increment of the number of years lived by the elderly. Thus, improving elderly functional status and minimizing their disability burden, became a primary concern (Anderson & Hussey, 2000; World Health Organization, 2007). Among other things, elderly quality of life depends on their ability to perform activities of daily living (ADLs). In this sense, it is important to determine the mechanisms that can improve functionality and, consequently, quality of life in the elderly (Oztürk, Simşek, Yümin, Sertel, & Yümin, 2011).

Inactivity is one of the factors that can lead to the decline in physical and psychological functions, therefore affecting the ability of people to perform ADLs. This potential impairment is especially critical for older adults (Collins, Rooney, Smalley, & Havens, 2004), whose activity levels are extremely low. Many older adults who have become increasingly sedentary may be performing ADLs at their maximum capacity being, therefore, at risk of losing independence, becoming disabled and also, at risk of falling (Gu & Conn, 2008; Shumway-Cook et al., 2009).

Fall-related morbidity and mortality rates are referred to as one of the most common and serious problems faced by the elderly (Hausdorff, Rios, & Edelberg, 2001; Hornbrook et al., 1994). About 40% of the community-living population aged over 65 years will fall at least once each year, and about 1 in 40 of them will be hospitalized (Rubenstein, 2006). Nevertheless, the problem of falls in the elderly is clearly more complex than a high incidence issue. Young children and athletes have higher fall rates than older adults (Mertz, Lee, Sui, Powell, & Blair, 2010) but, as older people have higher incidence of chronic diseases (CD), like osteoporosis, reduced bone density and age-related physiological changes, the likelihood of an injury increases, making even a relatively mild fall particularly dangerous (Rubenstein, 2006).

Although most falls do not cause serious injury, 5% of older people suffer major injuries such as fractures, head trauma and other musculoskeletal and soft tissue injuries (van Dieën, Pijnappels, & Bobbert, 2005). Moreover, fall rates and their associated complications are reported to rise steadily with age, being about two times higher for persons aged over 75 years (Rubenstein, 2006; van Dieën et al., 2005).

Thus, identifying old people who are at risk of falling seems to be a key step to establish interventions aiming at the prevention or the delay of physical frailty of that population.

Many studies have been done (e.g. Chan et al., 2007; Graafmans et al., 1996; Neyens et al., 2006; Pluijm et al., 2006; Todd & Skelton, 2004; Voermans, Snijders, Schoon, & Bloem, 2007) to identify the risk factors for falling. Among others, the most referenced risk factors for falling are: age, gender, specific chronic diseases, impaired mobility, balance and gait, muscle weakness, sedentary behaviour, cognitive impairment, fear of falling, visual impairment, medication intake, health perception and history of falling.

Although there is a general agreement regarding to what are the main risk factors for falling, the mentioned studies were done using different tools, procedures and variables definitions (e.g fall, level of physical activity or functional level definitions) that are not always well clarified, making therefore difficult the comparison between studies. Moreover, no study was done to verify these relations in Portuguese older adults.

Therefore, this paper aims to: (1) present preliminary results about the evaluation of the procedures (physical activity (PA) and functional fitness (FF) tests) followed during baseline period of the project "Biomechanics of Locomotion in the Elderly: Determinants in Fracture Risk Reduction"; (2) present a preliminary characterization of Portuguese older people regarding sociodemographic, health, PA and FF parameters and (3) identify, within the previous mentioned variables, the ones which are determinant to predict falls in Portuguese older adults.

2.2 Materials and Methods

Sample Recruitment

The first stage of this project has enrolled 647 from 870 subjects, aged 65 years or older, recruited in Lisbon and Tagus Valley area. The subjects were randomly selected from day care centres, senior schools, gyms and health promotion community events. To obtain a representative sample, a multistage stratified sampling design was used.

The institutions were selected within a 50 km distance from the Faculty of Human Kinetics, Technical University of Lisbon. The choice of this area for sample recruitment was done, not only due to geographic proximity, but also because the selected area allowed us to establish a cohort of representative elderly subjects from the Lisbon region by encompassing people from both urban and country side areas.

The mentioned institutions were selected randomly from a list available on the website of the Directorate-General of Health (Ministry of Health).

The general inclusion criteria were: to be 65 years of age or older, to correctly understand the Portuguese language, to be autonomous, to not have dementia, cognitive and cerebrovascular impairments and to not be recovering from an acute illness. For Functional Fitness (FF) tests, the following inclusion criteria were added: to be able to walk independently and/or without assistance of a walking aid and not to have a hip or knee prosthesis.

Immediately prior to data collection, all participants were informed about the study, accepted to participate and signed the informed consent. The Ethics Committee of Faculty of Human Kinetics, Technical University of Lisbon, approved all the study protocols.

Health and Falls interview

Trained examiners administered a structured and standardized questionnaire, by interview, that included sociodemographic characteristics, health, vision and hearing perception status, medical history (medical visits, hospitalizations, surgeries), medication intake (total and number for each disease, with specification of the drug name) fear of falling (FOF), activity avoidance due to FOF, fall prevalence (in the previous year) and falls characteristics (location, circumstances and consequences of, at most, 3 of the reported falls). A fall was defined as “an unexpected event in which the participant comes to rest on the ground, floor or lower level” (Lamb, Jørstad-Stein, Hauer, & Becker, 2005). The mean duration of the interview was 12 minutes.

Physical activity interview

Physical activity was assessed by interview, following the health questionnaire, with the Yale Physical Activity Questionnaire – YPAS (Dipietro, Caspersen, Ostfeld, & Nadel, 1993). This tool reports to a typical week during the month prior to evaluation and is divided in two parts:

(1) *YPAS activity checklist* allows to obtain detailed information about the type, duration (Hrs/week) and intensity (Kcal/min) of the typical activities carried out by the elderly (housework, exercise, caretaking, yard work and recreational activities).

(2) *YPAS activity scores* allow to assess an index of intensity of five distinct PA dimensions: (a) the *vigorous index* (VI) combines the frequency and the duration engaged in activities that cause large increases in breathing rate and heart rate, sweating or leg fatigue; (b) the *walking index* (WI) reports the frequency and the duration of walking activities that last at least 10 minutes without stopping or making an vigorous effort; (b) the *moving index* (MI) comprehends the time spent daily in activities with movement while standing, including walking, (c) the *standing index* (SI) evaluates the daily time spent in activities while standing but without movement; and, (d) the *sitting index* (STI) assesses daily time spent in the seated position. Partial scores are multiplied by the specific weighting factor to calculate the individual indexes and then summed to determine the summary index of activity (SumI).

The mean duration of interview was 13 minutes. The subjects who answerd the interview and fulfilled the inclusion criteria were then invited to participate in the FF assessment.

Functional Fitness Assessment

Several FF tests for older adults have been developed and reported (Berg, Wood-Dauphinee, & Williams, 1995; Duncan, Weiner, Chandler, & Studenski, 1990; Rikli & Jones, 1999; Rose, Lucchese, & Wiersma, 2006). Among these, we have selected 6 for this study (30sec Chair-Stand (CS) and 8 foot Up and Go (UG) from Senior Fitness test (Rikli & Jones, 1999) and items 4 to 7 from Fullerton Advance Balance Scale (Rose et al., 2006)), based on their reported ability to discriminate fallers and detect age functional decline in community-dwelling older adults (Hernandez & Rose, 2008; Rose, Jones, & Lucchese, 2002), as well as their feasibility in clinical and exercise field. The first two tests (CS and UG) assess lower limb strength, power and mobility, while the last four measure static (FAB6 – stand on one leg – and FAB7 – stand on a foam with eyes closed) and dynamic (FAB4 – step up and over a bench – and FAB5 – tandem walk along a line) balance. Besides the referred tests, during FF assessment, height and weight were also collected for Body Mass Index (BMI) calculation.

Before testing, a demonstration was performed by the examiner and the subjects completed one or two practice trials.

At the end of the each session, participants received feedback, through a written report, concerning their test results.

The duration of FF assessment was on average approximately 12 minutes.

Examiners Training

For all the tests, forty examiners were trained by the research team over a total period of 51 hours (33 hours of theoretical and practical training and 18 hours of field assessments).

The examiners received an instruction manual for field data collection containing: (1) a script with the questions included in both questionnaires and the most common difficulties of the subject when responding to the questionnaires; (2) basic instructions on conducting the interview; (3) basic FF test instructions, according to the respective authors method (Rikli & Jones, 1999; Rose et al., 2006).

All examiners were supervised while interviewing and applying FF test to older subjects, who kindly offered to be tested, by at least two members of the research team. At the end of the work sessions, a verbal feedback was given to each examiner.

Examiners were also asked to classify the performance of the same older subject in all FF tests, presented through video recording during one of the classes. These results were compared between examiners, in order to perform an inter-observer analysis, and with the assessment made by two research team members, experts in Health & Exercise, to assess the convergent validity of these tests. For the UG and the CS tests the convergent validity was also assessed by comparing examiners assessment with accelerometer data (xyzPlux triaxial accelerometer sensor, with a dynamic range of ±3g) that was collected from 33 elderly subjects during the field assessments.

Besides answering the PA questionnaire, 98 of the subjects worn uniaxial accelerometers (Actigraph Model 7194) and the results were compared to assess the convergent validity of the questionnaire. Furthermore, the reproducibility of this test was assessed using the test-retest results of 31 subjects.

Statistical analysis

Reproducibility and convergent validity for PA and FF field tests were determined respectively by Intra-class correlation (ICC-parallel; one-way random effect model; 95%CI) and Pearson's correlation coefficient.

A cross-sectional study was designed and the subjects were divided in three different groups according to fall prevalence: non-fallers (NF), subjects who did not report any falls during the previous year, episodic fallers (EF), those who reported to have fallen only once during the previous year, and recurrent fallers (RF), the ones that fell twice or more times during the previous year. Statistical analysis was done according to these groups.

The characterization of Portuguese older adults in matters of sociodemographic, health, PA and FF variables was performed through basic descriptive statistics.The identification of main factors for falling in Portuguese older adults was evaluated via Mantel–Haenszel chi-square, t-Student or Mann-Whitney tests, with the significance of the results set at $p<0.05$. The Spearman correlation coefficient was also used to investigate associations among quantitative independent variables. Finally, binary logistic regression analysis was used to model fall occurrence (NFvsF, FvsRF and FvsRF). Because risk factors must be easily and quickly measurable, for use in clinical/exercise settings, independent variables were dichotomized throughout their median value, as normality could not be assumed by Kolmogorov-Smirnov test for continuous variables. BMI was the only exception, being classified as good between 22.0 and 26.9 Kg/m^2 and poor for results ≥27.0 Kg/m^2 (Cervi, Franceschini, & Priore, 2005). Values below its median were classified as “poor level”, and values equal or greater than the median were classified as “good level”, with the exceptions of the number of medications, the sitting index and the 8 foot Up and Go test.

All the analyses were performed using PASW 18.0.

2.3 Results

Reproducibility and convergent validity of Functional Fitness and Physical activity tests

The reproducibility results indicate significantly high inter-examiners correlations for all FF tests. The inter-observer ICC for each item ranged from 0.588 to 0.965 while the ICC for average measures ranged from 0.938 to 0.998. According to the literature (Szklo, 2000; Pynsent, 2001), our results show a very good reproducibility for most of FF testes. The exceptions were observed for CS and FAB5 tests, which had a satisfactory level of reproducibility.

The Pearson correlation coefficients associating both CS and U&G tests and accelerometry were strong and highly significant (CS: 0.83, U&G: 0.92, p<0.001), confirming the good results for convergent validity of these tests.

The test-retest results for YPAS questionnaire were very good for SI (ICC=0.76) and MI (ICC=0.79). For other indexes the results were satisfactory with ICC ranging from 0.620 to 0.73 (Pynsent, 2001; Szklo, 2000). The results of the convergent validity using accelerometry (Copeland & Esliger, 2009) showed a positive correlation among active indexes (0.307<rho<0.373; 0.004<p<0.001) and a negative correlation with the SIT (rho=-0.469; p<0.001).

Sociodemographic parameters

Eight hundred and seventy older subjects over 65 years accepted to participate in the field assessments over a year testing period. From those, 642 subjects were included in the study analysis. The recruitment results were very satisfactory; the sample represents 0.05% of the elderly population in Portugal and ~7.1% of the elderly living in Lisbon and Tagus Valley region. Besides, the sample size highly exceeds the minimum number needed (379 elderly, for EES=0.5, power=80%, α=0.05 and considering an annual prevalence of falls of about 40% in national population (Moniz-Pereira, Viana Andre, Machado, Carnide, & Veloso, 2010)) to ensure a representative sample of the Lisbon population.

As only a few determinant factors were found for distinguishing episodic fallers from recurrent fallers, the respective results are not presented in the tables. However, when these differences are found, a reference is done in the text.

Participants' sociodemographic characteristics are summarized on Table 2.1.

Table 2.1: Sample characterization: main demographic parameters and their associations among groups: non-fallers (NF), episodic fallers (EF) and recurrent fallers (RF).

	NF n=405 n (%)	EF n=140 n (%)	RF n=97 n (%)	NF vs EF OR (95%CI)	NF vs RF OR (95%CI)
Female	268 (66.2)	107 (76.4)	73 (75.3)	1.47 (1.04-2.08) §	1.44 (0.85-1.00)
Marital status (married)	221 (55.1)	55 (23.6)	44 (46.8)	0.63 (0.47-0.85) §	0.74 (0.52-1.06)
Living alone	104 (26.0)	46 (33.6)	38 (40.5)	1.30 (0.97-1.76)	1.63 (1.13-2.34) §
Living in own home	331 (81.7)	119 (87.5)	80 (85.1)	0.80 (0.47-1.36)	0.97 (0.54-1.73)
Basic education level	247 (65.5)	80 (63.0)	59 (60.8)	1.48 (0.88-2.47)	1.93 (1.04-3.72)¥
	$\bar{X}$±sd ($\tilde{X}$)	$\bar{X}$±sd ($\tilde{X}$)	$\bar{X}$±sd ($\tilde{X}$)	OR (95%CI)	OR (95%CI)
Age	74.3 ± 6.5 (73.0)	75.0 ± 6.3 (74.0)	74.8 ± 6.6 (73.0)	1.35 (0.92-1.99)	1.05(0.73-1.50)
Retirement age	60.5 ± 6.9 (62.0)	59.4 ± 7.8 (61.0)	59.0 ± 7.4 (60.5)	1.26 (0.83-1.90)	1.36 (0.84-2.19)

§ p<0.05; ¥ p<0.001
Reference category "good level", defined by value higher than median parameter
OR (95%CI) - Odds Ratio (95% Confidence Intervals)

From the total sample, 405 (63.1%) of subjects didn’t’ fall during the previous year, 140 (21.8%) reported one fall and 97 (15.1%) reported to have fallen twice or more throughout the same period. Five participants did not report their fall status.

Their mean age was 74.5 ± 6.4 years and about 22% were older than 80 years. No differences were found for age between fall groups.

The majority of the participants were female (69.9%). Near half of the sample was married (58%) and about 84.3% lived in their own home. More than 60% of participants had only the basic education level and the mean age for retirement was approximately 60 years. The results also showed that women, when compared to men, presented a risk of falling about 40% higher and that to be married is a protective condition for falling. Moreover, subjects who had only the basic education level had also a higher probability to be recurrent fallers.

Falls and Health parameters

Falls occurred mainly in outdoor settings for both EF (59.8%) and RF (59.3%). Most of the falls occurred while walking (EF = 50%, RF = 60.8%) and climbing stairs (EF = 13.6%, RF = 21.6%) and the more prevalent perceived causes were to stumble (EF = 28%, RF = 25%) and to slip (EF = 23.6%, RF = 42.3%). Among fallers, 57% had an injury as a result of the fall, and 14.4% resulted in fractures. The percentage of injuries as a result of falls was higher among RF (EF = 57.3%; RF = 68.6%), although the frequency of fractures was slightly higher in the F group (F=17.4%; RF=13.7%). Logistic regression analysis showed no statistically significant associations between fall prevalence and the circumstances and consequences of the falls.

Health parameters results are presented on table 2.2. The most determinant risk factors for falling were health perception (HP), visual HP, Fear-of-falling (FOF) and medication intake.

Non-fallers (NF) have better health perception (HP) and visual HP than EF and RF, and both of the factors increase the risk of falling by approximately 50% and the risk of recurrent falling by ~140%. FOF showed to be determinant only for F, when compared with NF. However it is interesting to note that the activity avoidance due to FOF was a determinant for RF, when compared with NF.

Table 2.2: Health parameters and its association among groups: non-fallers (NF), episodic fallers (EF) and recurrent fallers (RF)

	NF	EF	RF	NF vs EF	NF vs RF
	n=405	n=140	n=97		
	n (%)	n (%)	n (%)	OR (95%CI)*	OR (95%CI)*
Health Perception Status (HPS)	172 (43.7)	42 (30.4)	20 (20.6)	1.54 (1.12-2.12)§	2.47 (1.57-3.91)$^{¥}$
Visual Health Perception (VHP)	255 (65.4)	70 (51.9)	38 (39.2)	1.51 (1.31-2.01)§	2.35 (1.63-3.38)$^{¥}$
Hearing Health Perception (HHP)	64 (48.0)	17 (44.7)	14 (60.7)	1.15 (0.55-2.36)	1.56 (0.716-3.38)
Chronic diseases					
Psychiatric	98 (25.7)	41 (32.3)	30 (65.9)	1.38 (0.90-2.13)	1.49 (0.91-2.46)
Cardiovascular	242 (63.5)	86 (67.7)	57 (64.8)	1.09 (0.61-1.93)	1.21 (0.79-1.85)
Allergies	7 (1.8)	4 (3.1)	3 (3.4)	1.74 (0.50-6.04)	1.89 (0.49-7.44)
Musculoskeletal	47 (12.3)	16 (12.6)	17 (19.3)	1.02 (0.56-1.88)	1.70 (0.92-3.74)
Diabetes	42 (11.0)	22 (17.3)	10 (11.4)	1.69 (0.97-2.96)	1.035 (0.50-2.15)
Colesterol	78 (19.3)	29 (22.8)	21 (21.6)	1.15(0.71-1.87)	1.22 (0.71-2.11)
FOF	62 (44.3)	27 (69.2)	13 (56.5)	2.83(1.33-6.04)§	1.64 (0.67-3.98)
Activity avoidance due to FOF	21 (17.1)	11 (30.6)	8 (42.1)	2.14 (0.91-5.00)	3.53 (1.29-9.84)§
	$\bar{X}$±sd ($\tilde{X}$)	$\bar{X}$±sd ($\tilde{X}$)	$\bar{X}$±sd ($\tilde{X}$)	OR (95%CI)	OR (95%CI)
Medical consultation (previous month)	0.71 ± 0.90 (1.00)	0.67 ± 0.80 (1.00)	0.77 ± 0.99 (1.00)	1.17 (0.76-1.86)	1.28 (0.76-2.18)
Medication (more than 6 months)	3.10 ± 2.41 (3.00)	3.32 ± 2.40 (3.00)	3.54 ± 1.92 (3.00)	1.25 (0.84-1.85)	2.24 (1.37-3.67)§

§ $p<0.05$; ¥ $p<0.001$
Reference category “good level”, defined by value higher than median parameter
OR (95%CI)- Odds Ratio (95% Confidence Intervals)

Regarding the prevalence of chronic diseases (CD), more than 60% of the subjects had cardiovascular disease (64.5%), followed by psychiatric disorders (28.4%) and high cholesterol (21.4%). However, no statistical differences were found between fall groups. The same was observed for the number of medical visits during the previous month. On the other hand, medication intake was shown to be a strong risk factor for recurrent falling. Further, differences were also found for this variable between EF and RF, having the latest group about 80% more risk of falling (OR=1.80; 95%CI 1.02-3.15).

Physical activity parameters

Table 2.3 shows the main results obtained for PA variables. In general, NF presented higher partial activity scores than EF and RF and the differences between groups were statistically significant. Moreover, all poor activity scores were correlated and risk factors for episodic falling and/or recurrent falling. Specifically, having a poor VI (i.e. 0 min) showed to be a determinant factor for episodic falling, moving less than 3-5 hr/day

(MI) was a determinant factor for RF, while a poor WI (walking less than 30 min per day) and/or SI (standing less than 3-5 hr/day) were risk factors for both EF and RF.

Table 2.3: Physical Activity parameters and their association among groups: non-fallers (NF), episodic fallers (EF) and recurrent fallers (RF)

Index	NF n=405 $\bar{X}$±sd ($\tilde{X}$)	EF n=140 $\bar{X}$±sd ($\tilde{X}$)	RF n=97 $\bar{X}$±sd ($\tilde{X}$)	NF vs EF OR (95%CI)*	NF vs RF OR (95%CI)*
Vigorous	13.1 ± 17.0 (0.0)	9.3 ± 13.7 (0.0)	9.8 ± 14.4 (0.0)	1.51 (1.02-2.25)§	1.45 (0.94-2.31)
Walking	19.6 ± 15.0 (16.0)	16.09±15.32 (16.00)	13.02±15.36 (8.00)	1.59 (1.07-2.36)§	2.59 (1.64-4.11)$^{¥}$
Moving	9.2 ± 3.4 (9.0)	8.2 ± 3.7 (9.0)	8.0 ± 4.1 (6.0)	1.45 (0.97-2.16)	2.17 (1.37-3.43)$^{¥}$
Standing	6.4 ± 2.3 (6.0)	5.7 ± 2.5 (6.0)	5.7 ± 2.8 (6.0)	1.83 (1.21-2.76)§	2.37 (1.49-3.78)$^{¥}$
Sitting	2.3 ± 1.0 (2.0)	2.6 ±1.0 (2.0)	2.7 ± 1.0 (3.0)	1.21 (0.80-1.83)	2.07 (1.05-4.10)§
Total	50.8 ± 27.5 (46.0)	42.2 ± 25.8 (36.5)	39.3 ± 26.6 (34.0)	1.33 (0.90-1.96)	1.56 (0.96-2.43)

§ $p<0.05$; ¥ $p<0.001$
Reference category “good level”, defined by value higher than median parameter
OR (95%CI)- Odds Ratio (95% Confidence Intervals)

On the other hand, it is also important to highlight that RF had the highest inactivity score (SIT index) and that these differences were significant when compared to NF, showing that with the increase of the number of hours of inactivity (>6 hours/day), the risk of falling recurrently doubles.

Functional Fitness parameters

The results of FF tests are presented on Table 2.4.

The risk of falling recurrently, when compared to not falling, doubles for subjects who have a poor FF level, independently of the test chosen. Further, for some of the tests (CS, FAB4 and FAB7), this risk is even higher.

The risk of falling, when compared to non-falling, also increases, although with less extent, for those who have poor results in almost all of the FF tests, with the exception of FAB7 and BMI tests.

Table 2.4: Functional Fitness parameters and their association among groups: non-fallers (NF), episodic fallers (EF) and recurrent fallers (RF)

	NF n=405 $\bar{X}$±sd ($\tilde{X}$)	EF n=140 $\bar{X}$±sd ($\tilde{X}$)	RF n=97 $\bar{X}$±sd ($\tilde{X}$)	NF vs EF OR (95%CI)*	NF vs RF OR (95%CI)*
CS (x/30s)	15.6 ± 5.4 (16.0)	13.7 ± 5.7 (14.0)	12.6 ± 6.01 (13.0)	1.67 (1.14-2.51)§	2.51 (1.57-4.00) ¥
U&G (sec)	6.2 ± 3.1 (5.4)	7.0 ± 3.7 (6.1)	7.6 ± 4.6 (6.0)	2.23 (1.48-3.36)¥	1.85 (1.16-2.95) §
FAB4	3.6 ± 1.4 (4.0)	3.2 ± 1.4 (4.0)	3.0 ± 1.5 (4.0)	2.34 (1.38-3.97)§	3.10 (1.76-5.46) ¥
FAB5	2.7± 1.3 (3.0)	2.2 ± 1.5 (2.0)	2.0 ± 1.6 (2.0)	1.87 (1.26-2.77)§	1.84 (1.17-2.90)§
FAB6	2.6 ± 1.4 (3.0)	2.0 ± 1.4 (2.0)	1.8 ± 1.4 (2.0)	2.29 (1.52-3.43) ¥	2.28 (1.39-3.57) ¥
FAB7	3.1 ± 1.2 (4.0)	2.8 ± 1.4 (3.0)	2.5 ± 1.6 (3.0)	1.39 (0.91-2.11)	1.96 (1.23-3.13) §
BMI (kg/m^2)	27.7 ± 4.4 (27.3)	28.8 ± 5.3 (28.1)	29.5 ± 5.2 (28.9)	1.15 (0.78-1.70)	2.01 (1.25-3.23)§

§ p<0.05; ¥ p<0.001
Reference category “good level”, defined by value higher than median parameter
OR (95%CI)- Odds Ratio (95% Confidence Intervals); CS- Chair-stand test; U&G- 8 foot Up and Go; FAB4 – step up and over a bench; FAB5 – tandem walk along a line; FAB6– stand on one leg; FAB7– stand on a foam with eyes closed; BMI- Body mass index.

2.4 Discussion

As far as we know, this is the first population-based study that has characterized a cohort of Portuguese older subjects and identified fall risk factors in this population using in situ methods that were not exclusively questionnaires.

The identification of the referred variables requires validated instruments for the elderly population, as those that were used in this study, without implying a burden to the examiners. The low burden was expressed by the mean time of 35min for the application of the 3 batteries per subject.

The assessment of a sample with this dimension is only possible with a large team available on the field. As so, we trained 40 examiners and the reproducibility results were classified as good to very good for both the FF and the PA parameters. The convergent validity of these tools also showed good results for field application. These results give us high confidence in the collected data that is discussed on the following paragraphs.

Our results showed that approximately 37% of the elderly tested fell during the previous year. From these, 41% were RF. These results were similar to the ones reported in the literature (Tinetti & Speechley, 1989).

On the contrary of what has been reported (Todd & Skelton, 2004), in our study, age was not a risk factor for falling or recurrent falling. Interestingly, the same result was obtained using a different cut off value (≥80 years old), instead of the median, to dichotomize this variable (OR F=1.05; 95% CI 0.661-1.657; OR RF=1.041 CI 0.612-1.769). Thus, falling seems to be not an inevitable consequence of ageing.

Old age is sometimes called a woman’s problem, based on the increasing ratio of women to men on old age groups and on their greater vulnerability for disability (Orfila et al., 2006; Todd & Skelton, 2004). This fact was verified in our results, in which the percentage of women is ~70% and women have 40% more probability to suffer an episodic fall than men.

Being married was identified as protective factor for episodic falls, while living alone as a risk factor for recurrent falling, which also has been reported in the literature (Lord, Sherrington, Menz, & Close, 2007). Furthermore, being married remains a protective factor for falling even when comparing NF with those who have fallen one or more times during the previous year (OR 0.597, 95% CI 0.432-0.826).

Poor educational level was identified as a risk factor for recurrent falls. These results can be supported by the growing evidence that persons with lower levels of education (as indicator for socioeconomic status) are much more likely to have lower levels of functionality, increased number of CD, and decreased health related quality of life, tendency for isolation and weak self-esteem (Collins et al., 2004; Dunn, Rudberg, Furner, & Cassel, 1992).

Although relations were found between the sociodemographic parameters mentioned above and fall risk, the parameters that were more strongly correlated with falls were health and FF.

The health impairments that occur during the aging process are often related to poor HP status (Liao, McGee, Cao, & Cooper, 2001). In our study, HP showed a significant association with fall risk, being consistently higher for RF. Another interesting result was the association between VHP and fall groups, showing the same relation with fall risk that was obtained for HP (OR F= 1.51; OR RF= 2.35). Visual age–related decline is a normal process in older people that is expressed by the decreasing of visual acuity, glare sensibility, dark adaptation, accommodation and depth perception. All these factors are reported to be associated with visual health and risk factors for falling (Ivers, 2000; Lord et al., 2007). While visual health limitations may be more directly associated by the elderly to difficulties in performing daily tasks, particularly the ones involving locomotion, the same might not be true for hearing health limitations, if they are not related to inner ear pathologies. This could be a possible explanation for the fact that no association was found between perceived hearing health status and falls in this study.

Other factor found to be determinant for falling was FOF, increasing the risk of falling episodically by ~180%. Previous studies (Hadjistavropoulos, Delbaere, & Fitzgerald, 2011; Lach, 2005) have also reported this fact. Furthermore, ~70% of the subjects who have reported FOF, had higher probability to avoid certain ADLs and a 3.5 times higher risk of falling recurrently.

Finally, the number of medications, independently the chronic condition, showed a positive association with RF, having those who took 3 or more drugs per day, a two times higher risk for falling recurrently, when compared with NF. Effectively, advanced age can be associated with an increase in the number of diseases, which implies the increase of medication intake and an higher diversity of the prescribed drugs, factors that have been both reported as risk factors for falling, although with a different cut-off value for number of medications (> 4 drugs per day) (Lord et al., 2007; Robbins et al., 1989; Todd & Skelton, 2004). Chronic diseases, namely musculoskeletal diseases, have not been identified as determinant for either episodic or recurrent falls. The fact that all the tested elderly were autonomous may explain this result, since the identified chronic diseases might not necessarily represent a limitation in daily tasks performance.

As mentioned, FF variables, together with the health variables, were highly correlated to fall risk. A bad performance, on any of the applied tests, highly increases recurrent falling risk. The same is verified for the risk of falling episodically, with the exception of FAB7 and BMI scores. These results are extremely relevant because they reinforce that falls are not an inevitable consequence of ageing and that by improving functional fitness, we can prevent falls in older adults.

Physical activity plays a key role on the improvement of functionality (Cress et al., 1999). Nevertheless, the relation between PA and fall risk is not yet well clarified. Some studies state that the increase of PA levels decreases fall risk (Heesch, Byles, & Brown, 2008; Mertz et al., 2010), while other studies showed that higher PA rates (Chan et al., 2007) and, specially, higher vigorous PA rates increase fall risk (Talbot, Musiol, Witham, & Metter, 2005). Our results showed that the increase o PA levels, independent of the intensity, decreases the risk of falling both episodically and recurrently. The only exception was VI, that was only a protective factor for episodic falling. However, as the majority of our subjects (~70%) did not practise vigorous PA, more studies should be done to clarify this relation. Furthermore, being sedentary (number of hours seated/day) showed to highly increase the risk of falling recurrently (~110%), a fact that reinforces the importance of PA for fall prevention.

2.5 Conclusion

To the extent of our knowledge, this is the first population-based study that has characterized a cohort of Portuguese older subjects and identified, within a wide variety of factors, the ones that can increase fall risk in this population.

Our results showed that age is not a risk factor for falling and that health and FF variables are the most determinant factors to assess fall risk in Portuguese older adults. This means that falls might not be an inevitable consequence of age and therefore, by improving functional fitness and health it is possible to prevent falls in older adults. PA seems to play a key role in this process, not only because a higher level of PA will lead to a better functional fitness, but also because PA, of light to moderate intensity, was found to be a protective factor for both episodic and recurrent falls. Moreover, sedentary behaviour was found to be a strong risk factor for falling recurrently, reinforcing the PA role in fall prevention.

Considering these results, in the future it would be important to validate a tool for Portuguese older adults, based on the found risk factors for falling, that would be (1) feasible to apply in a clinical/exercise setting and (2) able to establish a link between the intervention process and the assessment.

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CHAPTER

3

Using a multifactorial approach to determine fall risk profiles in Portuguese older adults

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Abstract

Aim: The aim of this study was to use a multifactorial approach to characterize episodic and recurrent fallers risk profiles in Portuguese older adults.

Materials and Methods: To accomplish the mentioned purpose, 1416 Portuguese older adults over 65 years were tested with three different field measurements: 1) health and falls questionnaire; 2) Physical Activity questionnaire and 3) a set of functional fitness tests.

The subjects were divided in three different groups according to fall prevalence: non-fallers, subjects who did not report any falls during the previous year, episodic fallers, those who reported to have fallen only once during the previous year, and recurrent fallers, the ones that fell twice or more times during the previous year.

Episodic and recurrent fallers risk profiles were established using multifactorial logistic regression models in order to avoid confounding effects between the variables.

Results: The results showed that age was not a risk factor for either episodic or recurrent falling. In addition, health parameters were shown to be the factors distinguishing recurrent from episodic fallers. This may imply that, compared to episodic falls, recurrent falls are more associated with a higher presence of chronic conditions and are less likely to occur due to external factors. Furthermore, being a woman, having fear of falling and lower functional fitness levels were determinant factors for both episodic and recurrent falls. It is also important to note that, although total physical activity was only related with episodic falling, promoting physical activity and exercise may be the easiest and cheapest way to improve functional fitness and health levels and therefore, its role in fall prevention should not be underestimated.

Conclusions: The results of this study reinforce the importance of using a multifactorial approach, not only focusing on cognitive-behavioral factors, but also on promoting physical activity and healthy lifestyles, when assessing fall risk or planning an intervention aiming at fall prevention within the older population.

Keywords: Elderly, Fall, Risk profiles, Multifactorial approach.

3.1 Introduction

Falls are a major health concern faced by the elderly population in the industrialized countries. The rate of community living older adults who fall at least once each year varies between 30% and 40%, depending on the study (Lord, Sherrington, Menz, & Close, 2007; Todd & Skelton, 2004; World Health Organization, 2007). It is also reported that this rate increases with ageing, reaching approximately 50% in old people over 80 years (Todd & Skelton, 2004). Furthermore, the higher incidence of chronic diseases, like osteoporosis and reduced bone density, characteristic of the elderly population, increases the likelihood of an injury, making even a relatively mild fall particularly dangerous (Rubenstein, 2006). It is stated that 20% to 30% of those who fall suffer injuries that reduce mobility and independence as well as increase the risk of premature death (Todd & Skelton, 2004). Moreover, even a non-injurious fall may have important consequences like functional fitness decline, social withdrawal, anxiety and depression, fear of falling, and an increased use of medical services (Stel, Smit, Pluijm, & Lips, 2003; Tinetti & Williams, 1998; Todd & Skelton, 2004; Voermans, Snijders, Schoon, & Bloem, 2007). Therefore, older adults who have fallen, regardless of whether they have experienced an injurious fall, are at greater risk of becoming institutionalized (Tinetti & Williams, 1997).

Because of the mentioned consequences to the elders and their families' quality of life, as well as the generated increase in health costs, the implementation of fall preventive strategies is a primary public health concern. These preventive strategies will be more efficient if the risk prediction models are developed separately for homogeneous subpopulations (Yamashita, Noe, & Bailer, 2012). In fact, it has been reported that in what concerns fall prevention there is no one-size-fits-all intervention (Rose, 2008). Instead, it is recommended that the characteristics of the intervention should be decided by the clinicians and practitioners according with the fall risk level of their patients (Rose, 2008). As so, and because the risk profile of an episodic faller may be different from the one of a recurrent faller (Graafmans et al., 1996), the success of the intervention will depend on our ability in identify and distinguish older people who are at risk of episodic and recurrent falling from those with no fall risk.

Being a multifactorial problem, several risk factors have been reported and related to falls (Chan et al., 2007; Graafmans et al., 1996; Lord et al., 2007; Pluijm et al., 2006; Rubenstein, 2006; Stalenhoef, Diederiks, Knottnerus, Kester, & Crebolder, 2002; Stel, Pluijm, et al., 2003; Todd & Skelton, 2004; Tromp et al., 2001; Voermans et al., 2007; World Health Organization, 2007; Yamashita et al., 2012). Among others, the most referenced are: age, gender, specific chronic diseases, impaired mobility, balance and gait, muscle weakness, sedentary behaviour, cognitive impairment, fear of falling, visual impairment, medication intake, health perception and history of falling. In a preliminary study (Moniz-Pereira, Carnide, Machado, André, & Veloso, 2012), we have verified, in a cohort of 647 Portuguese older subjects from Lisbon and Tagus Valley region, that falls might not be an inevitable consequence of ageing and that health, functional fitness and physical activity parameters were the most determinant factors for both episodic and recurrent falls. However, in the mentioned study, we have analyzed the contribution of each risk factor independently, without identifying possible confounding effects between them.

Since data on the Portuguese older population relative to this matter is scarce, it seems urgent to characterize both episodic and recurrent fallers risk profiles in this population. Thus, the purpose of this study was to use a multifactorial approach to determine and characterize both episodic and recurrent fallers risk profiles in Portuguese older adults.

3.2 Materials & Methods

Sample

Participants were community-dwelling older adults from the Biomechanics of Locomotion in the Elderly Project (PTDC/DES/72946/2006) that were recruited from 18 Portuguese municipalities, from Lisbon & Tagus Valley area and centre national regions (Lisbon, Cascais, Oeiras, Amadora, Odivelas, Sintra, Mafra, Loures, Almada, Setúbal, Nazaré, Rio Maior, Santarém, Cartaxo, Azambuja, Samora Correia, Torres Vedras, Benavente), and different contexts, including exercise classes, day care centres, senior schools and health promotion public community events. Sample recruitment was done using a multistage approach as described elsewhere (Moniz-Pereira et al., 2012). A total of 1416 older adults, from a total of 1723, aged 65 years and older were enrolled in this study, between May 2010 and September 2012. Exclusion criteria were to have a neurologic condition (Dementia, Parkinson or stroke), not being able to comprehend Portuguese Language and not being able to walk independently or with a walking aid. Prior to data collection, all participants were informed about the study, accepted to participate and signed the informed consent. The Ethics Committee of Faculty of Human Kinetics, Technical University of Lisbon, approved the study protocol.

Measures and Procedures

In order to assess the risk factors for falling, three different field measurements were used: two questionnaires (one regarding health and falls parameters (HFQ) and another concerning physical activity (PA) levels) and a set of functional fitness (FF) tests. A more detailed description of the study design and the validation of the procedures has been published elsewhere (Moniz-Pereira et al., 2012).

Briefly, the questionnaires were administered through an interview, conducted by trained examiners. The HFQ included questions regarding sociodemographic characteristics, health, vision and hearing perception status, medical history (medical visits, hospitalizations, surgeries), medication intake (total and number for each disease, with specification of the drug name), fear of falling (FOF), activity avoidance due to FOF, fall prevalence (in the previous year) and falls characteristics (location, circumstances and consequences of, at most, 3 of the reported falls). A fall was defined as “an unexpected event in which the participant comes to rest on the ground, floor or lower level” (Lamb, Jørstad-Stein, Hauer, & Becker, 2005). PA levels were assessed by the Yale Physical Activity Survey (YPAS) questionnaire (Dipietro, Caspersen, Ostfeld, & Nadel, 1993), which reports a typical week of activity during the month prior to evaluation. The questionnaire provides an index of intensity, duration and frequency of five distinct physical activity dimensions: 1) vigorous activity (vigorous index) - activities lasting more than 10 minutes which cause large increases in breathing rate and heart rate, sweating or fatigue in the legs; 2) walking (walking index) – walking for at least 10 minutes without stopping or making a vigorous effort; 3) movement (movement index) – all activities involving movement carried out while standing, including walking, 4) standing (stand index) - activities in the standing position without movement; and, 5) sitting (sitting index) - activities performed in a seated position. Each of the partial scores, corresponding to each of the physical activity intensities, is multiplied by the specific weighting factor in order to calculate the partial indexes, and then summed to determine the summary index of PA (Total PA).

Finally, FF assessment included a set of strength and balance tests, as well as the measures of body height and mass for body mass index (BMI) computation. Lower limb strength, power and coordination assessment, was done through the 8 foot Up-and-Go (UG) test (involves getting out of a chair, walking to 2,44m and turning around a shaped elevated mark and returning to the chair in the shortest time possible) and the Chair-Stand (CS) test (involves counting the number of times within 30s that an individual can rise to a full stand from a seated position, without pushing off with the arms) from the Senior Fitness Test (SFT) battery (Rikli & Jones, 1999). Balance was assessed through items 4 – step up and over (FAB4) , 5 – tandem walk (FAB5), 6 – stand on one leg (FAB6) and 7 – stand on foam eyes closed (FAB7), of FAB Scale (Rose, Lucchese, & Wiersma, 2006). FF tests were selected based on their reported ability to discriminate fallers and detect age functional decline (Hernandez & Rose, 2008; Rikli & Jones, 1999; Rose, Jones, & Lucchese, 2002), as well as their feasibility on clinical and exercise field (in what concerns space, time and equipment requirements). Examiners were trained to administer all tests, following the authors' instructions (Rikli & Jones, 1999; Rose et al., 2006). At the end of the screening session, participants received feedback, through a written report, concerning their test results.

Statistical Analysis

Subjects were divided in three different groups according to fall prevalence: non-fallers (NF), subjects who did not report any falls during the previous year; episodic fallers (EF), those who reported to have fallen only once during the previous year, and recurrent fallers (RF), the ones that fell two or more times during the previous year. Statistical analysis was done according to these groups using PASW Statistics 18.0 with the level of significance set at $p<0.05$.

The variables were divided in four groups: demographic parameters (gender, marital status, living alone, living own home and education level); health parameters (general, visual and hearing health perceptions, total medication intake, fear of falling (FOF), activity avoidance due to FOF and surgeries in the previous year); PA parameters (vigorous, walking, movement, standing and sitting indexes and total PA) and FF parameters (BMI and 6 FF tests). The results from FF tests were also recoded into two other different variables: the balance score, obtained through the sum of FAB4, FAB5, FAB6 and FAB7 test results, from the FAB scale (Rose et al., 2006), and total functional fitness score (TFFS), computed by summing the balance score with the CS and UG test results, from the SFT battery (Rikli & Jones, 1999). Considering that the SFT battery tests results involve different measure units from those of the balance tests, in order to obtain the TFFS, we transformed the first two test results (TUG and CS) in an ordinal scale similar to the one used in the balance tests. This was done by calculating the quartiles of the results of the CS and the UG tests, after adapting for gender, following the original national norms established by the authors of the tests (Rikli & Jones, 1999).

Descriptive statistics was used to determine the central tendency parameters for scale variables (mean, standard deviation and median) and relative frequency of the nominal ones, allowing the characterization of the sample.

The main outcome was the number of falls, which was stratified in the following comparisons' groups: non-fallers vs. episodic fallers and non-fallers vs. recurrent fallers.

As risk factors must be easily and quickly measurable, continuous or ordinal variables were dichotomized throughout their median value. Apart from UG test, medication number and sitting time, in which a "good level" was considered if subjects scored below the median value, for the other variables, a "good level" was considered if subjects showed results equal or greater than the median/cut-off value. Further, there was a group of variables wherein specific cut-off values were applied. For general, visual and hearing health perceptions, the cut off value was 4 (in a scale from 1 – very bad – to 5 – excellent); FOF was classified as "no" if the participant answer "never", or "yes" if they answered "sometimes", "often" or "always"; and BMI was dichotomized using the proposed cut-off values to define overweight ($BMI \geq 27 Kg/m^2$) in the older population (Cervi, Franceschini, & Priore, 2005). The need for using different BMI cut off values when studying the elderly, instead of the ones established for adults, has been suggested in recent studies (Cervi et al., 2005; Heiat, National Institutes of Health (NIH: the NIH Consensus Conference on Health Implications of Obesity in 1985), United States Department of Agriculture (the 1990 Department of Agriculture's Dietary

Guidelines for Americans), & National Heart, Lung, and Blood Institute, 2003; Heiat, Vaccarino, & Krumholz, 2001). It is reported that older individuals, especially the ones over 60 years, suffer a decrease in height and lean mass, as well as an increase in fat mass, which has an impact on BMI by approximately 1.5 kg/m^2 in men and 2.5 kg/m^2 in women (Sorkin, Muller, & Andres, 1999). Furthermore, studies focused on the identification of risk factors of morbidity and mortality, regardless of the disease, also suggest a higher BMI cut-off value (27kg/m^2) for elderly subjects (Heiat et al., 2003, 2001).

Differences between groups for the independent variables were verified using the Chi-Square test. Variables that were significantly different between groups were then included in the bivariate logistic regression models (Enter method) so that determinant factors for episodic and recurrent falling could be identified, when compared with non-falling.

Afterwards, multivariate logistic regression models (backward- conditional method) were built, using the previously identified determinant factors for falling and recurrent falling, in order to identify any possible confounding effect between them. Interactions were calculated based on conditional parameter estimates of the final logistic regression models. The goodness-of-fit of the models was assessed with the Homer-Lemeshow test, which allows to verify if the differences between the observed and predictive values are small, as well as if there is no systematic contribution of the differences to the error structure of the model (Archer, Lemeshow, & Hosmer, 2007). Additionally, the concordance of predictive values with actual outcomes was verified through the determination of the area under the Receiver-Operator Characteristic curve (AUC-ROC). In this curve, sensitivity is plotted against specificity, with the test having a perfect discrimination if the AUC-ROC is 100% (Zweig & Campbell, 1993).

3.3 Results

Sample and fall groups' characterization

From a total of 1723 subjects, 1416 met all the inclusion criteria (~82.2%), being therefore included in the study analysis. This sample size represents 0.7% of the Portuguese older subjects and is considered to be appropriate to study the problem of falls in Portugal (n=1370, defined from an estimated effect size (ES) equal to 0.5, power 80%, alpha of 0.05 and a prevalence of falls of 40% (Suresh & Chandrashekara, 2012).

From the 1416 participants, 38% fell during the previous year and within these, 61% fell once (EF) and 39% fell twice or more times (RF). Furthermore, within the participants who fell, 43% suffered an injury and 11% of these injuries were fractures.

The characterization of each sample group is summarized on Table 3.1, as well as the differences between groups. With the exception of general health perception, no differences were found between EF and RF and therefore, differences between these fall groups are not shown.

Participants had a mean age of 73.0±5.6 years ($\tilde{x}$ =72.0y) and 35% of them had over 75 years. No differences between fall groups were found for age. Furthermore, even when using a higher cut-off value (≥75yr and ≥80 yr), instead of the median, the results remained the same, with no differences found between NF and both episodic (X^2_{75y}=2.60, p=0.11; X^2_{80y}=0.38, p=0.54) and recurrent fallers (X^2_{75y}=3.01, p=0.08; X^2_{80y}=0.13, p=0.72). About 75% of the subjects in the total sample were women. In the NF group 70% of the participants were women, which was a significantly lower percentage comparing with the proportion of women found in EF and RF groups. Still regarding the demographic parameters, when compared with NF, a significantly higher percentage of EF were single and lived alone.

Considering health parameters, NF reported the highest percentage of good general, visual and hearing health perceptions, and the lowest percentage of medication intake, fear of falling and activity avoidance due to FOF.

For the total amount of physical activity, NF were found to be more active than both episodic and recurrent fallers. On the other hand, looking at the partial scores, differences were only found between non-fallers and recurrent fallers, having this last group a more sedentary behaviour (RF walked and moved less and spent more time in a seated position than NF). Further, no differences were found between both fall groups and non-fallers for the time spent in vigorous activities, nor the time spent standing.

Table 3.1: Sample characterization: Demographic, health, PA and FF parameters (absolute and valid frequency) and their associations among groups (non-fallers (NF), episodic fallers (EF) and recurrent fallers (RF))

	NF n=889 n(%)	EF n=325 n(%)	RF n=202 n(%)
Demographic parameters			
Age (≥72years)	463 (52.1)	187 (57.5)	116 (57.4)
Gender (Female)	623 (70.1)	266 (81.8)*	174 (86.1)*
Marital status (Single)	527 (59.3)	163 (50.2)*	111 (56.1)
Living alone	230 (25.9)	107 (33.7)*	58 (29.3)
Living own home	783 (88.1)	294 (90.5)	174 (88.8)
Education level (4th grade)	340 (59.6)	108 (56.8)	80 (63.0)
Health parameters			
General health perception (poor)	532 (59.8)	223 (69.0)*	162 (80.2)*
Visual health perception (poor)	308 (34.9)	132 (41.1)*	119 (58.9)*
Hearing health perception (poor)	254 (40.1)	104 (43.5)	70 (50.7)*
Medication (n≥3/day)	511 (59.6)	210 (67.5)*	158 (79.4)*
FoF (yes)	553 (62.2)	229 (70.5)*	170 (84.2)*
Activity avoidance due to FoF (yes)	59 (18.2)	38 (25.9)	37 (33.0)*
Surgery (yes)	104 (11.8)	40 (12.4)	28 (13.9)
PA parameters			
Vigorous (< 10 min/week)	538 (60.5)	214 (65.8)	133 (65.8)
Walking (<150 min/week)	366 (41.2)	148 (45.5)	108 (53.5)*
Movement (< 5h/day)	250 (28.2)	90 (27.7)	79 (39.1)*
Standing (< 5h/day)	407 (45.8)	161 (49.5)	97 (48.0)
Sitting (≥ 6h/day)	664 (74.7)	241 (74.2)	166 (82.2)*
Total PA(<40 scale points)	396 (44.5)	172 (54.1)*	110 (56.7)*
FF parameters			
FAB4 (<4 scale points)	108 (12.1)	52 (16.0)	62 (30.7)*
FAB5 (<3 scale points)	278 (31.3)	124 (38.2)*	92 (45.5)*
FAB6 (<2 scale points)	211 (23.7)	106 (32.6)*	85 (42.1)*
FAB7 (<4 scale points)	496 (55.8)	155 (47.7)	115 (56.9)*
Balance score (<13 scale points)	360 (41.9)	168 (54.0)*	126 (66.3)*
CS (times/30s) ¥	340 (38.3)	198 (39.5)	99 (49.5)*
UG (sec) ¥¥	458(51.5)	189 (58.2)*	127 (62.9)*
TFFS (<17 scale points)	375 (43.7)	168 (54.0)*	124 (66.0)*
BMI (≥27.0 kg/m^2)	526 (59.2)	218 (67.1)*	139 (68.8)*

*$p<0.05$

¥ adjusted for gender: female: <15x/30s; male: <16x/30s

¥¥ adjusted for gender: female: ≥5,67s; male: ≥5,13s

FoF: fear of falling; PA: Physical activity; UG: 8 foot Up-and-Go test; CS: Chair-Stand test; FAB4: step up and over test; FAB5: tandem walk test; FAB6: stand on one leg FAB7: stand on foam eyes closed; TFFS: Total functional fitness score; BMI: Body mass index

Finally, almost all FF tests revealed statistical differences between groups (NF vs EF and NF vs RF), showing a consistent decrease in functional fitness for both episodic and recurrent fallers. Additionally, a higher BMI was found for EF and RF, when compared with NF. However, it is important to note that the average BMI of the total sample was 28.5±4.5 Kg/m^2 (x̃=28.1 Kg/m^2), with 63% of the individuals scoring over 27 Kg/m^2.

Fall risk profiles

The results obtained from the bivariate logistic regression models, presented on Table 3.2, are in accordance with the previous mentioned results.

Table 3.2: Bivariate logistic regression models for episodic and recurrent fallers

	Episodic Fallers OR (95% CI)**	Recurrent fallers OR (95% CI)**
Demographic parameters		
Gender (Female)	1.93 (1.40-2.64)*	2.65 (1.74-4.06)*
Marital status (single)	1.51 (1.17-1.96)*	1.16 (0.85-1.80)
Living alone	1.41 (1.07-1.86)*	1.17 (0.84-1.65)
Health parameters		
General health perception (poor)	1.50 (1.14-1.96)*	2.72 (1.88-3.94)*
Visual health perception (poor)	1.30 (1.03-1.69)*	2.68 (1.96-3.66)*
Hearing health perception (poor)	1.15 (0.85-1.56)	1.54 (1.06-2.23)*
Medication (≥3 med/day)	1.41 (1.07-1.85)*	2.61 (1.80-3.78)*
Fear of falling (yes)	1.45 (1.10-1.91)*	3.23 (2.16-4.82)*
Activity avoidance due to FoF (yes)	1.57 (0.98-2.49)	2.22 (1.37-3.60)*
PA parameters		
Walking (<150 min/week)	1.20 (0.93-1.54)	1.64 (1.21-2.23)*
Movement (< 5h/day)	0.98 (0.74-1.30)	1.65 (1.20-2.27)*
Sitting (≥ 6h/day)	1.03 (0.77-1.38)	1.56 (1.06-2.31)*
Total PA(<40 scale points)	1.42 (1.09-1.83)*	1.57 (1.15-2.15)*
FF parameters		
FAB4 (<4 scale points)	1.38 (0.96-1.97)	3.20 (2.23-4.59)*
FAB5 (<3 scale points)	1.36 (1.04-1.77)*	1.84 (1.35-2.51)*
FAB6 (<2 scale points)	1.56 (1.18-2.06)*	2.33 (1.70-3.21)*
FAB7 (<4 scale points)	1.15 (0.89-1.49)	1.67 (1.23-2.27)*
Balance score (<13 scale points)	1.63 (1.26-2.12)*	2.73 (1.97-3.80)*
CS (times/30s) ¥	1.03 (0.80-1.34)	1.58 (1.56-2.15)*
UG (sec) ¥¥	1.48 (1.14-1.91)*	1.80 (1.31-2.46)*
TFFS (<17 scale points)	1.42 (1.09-1.85)*	2.29 (1.64-3.16)*
BMI (≥27.0 kg/m^2)	1.41 (1.08-1.84)*	1.52 (1.10-2.11)*

*p<0.05

**OR (95% CI)- Odds Ratio (95% Confidence intervals for OR)

¥ adjusted for gender: female: <15x/30s; male: <16x/30s

¥¥ adjusted for gender: female: ≥5,67s; male: ≥5,13s

FoF: fear of falling; PA: Physical activity; UG: 8 foot Up-and-Go test; CS: Chair-Stand test; FAB4: step up and over test; FAB5: tandem walk test; FAB6: stand on one leg FAB7: stand on foam eyes closed; TFFS: Total functional fitness score; BMI: Body mass index

The risk of falling episodically doubles for women and the risk of falling recurrently is even higher. Further, living alone and being single are risk factors for episodic falling, showing the importance of social conditions for the determination of the episodic fallers risk profile.

Health and FF parameters showed to be the most determinant for episodic and especially recurrent falls. When compared with NF, the risk of falling episodically increased between approximately 30% and 60%, while risk of recurrent falling may be up to 3 times higher, for those with poorer health and functional fitness.

Finally, being less active (i.e. having a lower total PA score) may increase the risk of episodic falling and recurrent falling by approximately 40% and 60%, respectively. Moreover, to spend less time in moderate and light PA (less than 5 hours in movement and standing activities) and to spend more time in a seated position (more than 6 hours per day) are risk factors for RF.

Multivariate logistic regression models are shown on Table 3.3. To avoid collinearity, variables that were contained in global scores (*e.g.* Balance score and TFFS or sitting index and total PA) were not placed in the models at the same time. The best models, i.e. the ones with better discriminative power (measured by the AUC-ROC) were selected to be presented.

Table 3.3: Multivariate logistic regression models for episodic and recurrent fallers

	Episodic Fallers OR (95% CI)	Recurrent fallers OR (95% CI)[¥]
Gender (female)	1.52 (1.07-2.16)	1.84 (1.14-2.96)
General health perception (poor)		1.66 (1.08-2.57)
Visual health perception (poor)		1.63 (1.14-2.34)
Medication (n≥3 med/day)		2.06 (1.14-3.14)
Fear of falling (yes)	1.36 (1.00-1.86)	2.50 (1.35-3.14)
Total PA (<40 scale points)	1.36 (1.01-1.77)	
Balance score (<13 scale points)	1.41 (1.06-1.89)	
TFFS (<17 scale points)		1.48 (1.03-2.13)
Models fit indicators		
Hosmer-Lemshow (p)	3.99 (0.86)	9.37 (0.31)
ROC Curve (CI 95%)	62.0 (0.51-0.65)	72.9 (0.69-0.77)

[¥] OR (95% CI)- Odds Ratio (95% Confidence intervals for OR)

PA: Physical activity; TFFS: Total functional fitness score

According to these models, gender, FOF, total PA and balance score are determinant factors for episodic falls. Likewise, recurrent falls are also determined by gender and FOF, and further by health parameters (general and visual health perceptions and medication intake) and functional fitness level. All factors included in the models presented higher *odds ratios* for RF than for F.

The Homer-Lemeshow goodness-of-the-fit test for logistic regression was not significant for both models (p>0.05), indicating that the models fit the data well. The area under the ROC curve (AUC) of the two models shows moderate discriminative properties, with about 60% of the subjects classified correctly as fallers and 70% of the subjects classified correctly as recurrent fallers.

3.4 Discussion

The purpose of this study was to use a multifactorial approach to determine and characterize both episodic and recurrent fallers risk profiles in Portuguese older adults. In order to accomplish that goal we have tested 1416 community-dwelling older adults from 18 Portuguese municipalities, representing about 0.7% of national elderly population. Our results are in agreement with what we have found before in smaller cohort of Portuguese older adults (Moniz-Pereira et al., 2012) and allowed us to go further on the establishment of fallers (episodic and recurrent) risk profiles in the Portuguese population by adjusting the models for possible confounders.

An important result of our study is that falls seem not to be an inevitability of ageing, as age was not found to be a risk factor for both episodic and recurrent falls, even if the cut-off value used represents the very old individuals (≥75yr and ≥80yr), instead of the sample median. This fact, together with the importance of functional fitness in determining falls (both episodic and recurrent), indicates that these events may be prevented and allows the definition of effective intervention programs, tailored to different risk profiles.

Among the other demographic parameters, being single and living alone were risk factors for episodic falling, while being a woman was a risk factor for both falling episodically and recurrently. Other studies (Graafmans et al., 1996; Pluijm et al., 2006;

Todd & Skelton, 2004) have also identified these demographic parameters as risk factors for falling, although they tend to lose importance when entered in a multivariate model. In our study, gender was the only demographic parameter that remained in the multivariate models, determining both episodic and recurrent falls. Nevertheless, this result may not be explained only by gender *per se*, but also be a consequence of the higher prevalence of disability and chronic conditions present in elderly women (Orfila et al., 2006).

In what concerns health parameters, bivariate models show that almost all of them were associated with both episodic and recurrent falls. The association of different health parameters, not only with falls, but also with functional fitness decline, is not new (Collins, Rooney, Smalley, & Havens, 2004; Hartikainen, Lönnroos, & Louhivuori, 2007; Lord et al., 2007; Todd & Skelton, 2004). However, it is interesting to note that, when adjusting for confounders' effects, with the exception of FOF, all the other health parameters (specifically, general and visual health perceptions and medication intake) were only determinant for the recurrent fallers' profile. This fact may indicate that, compared to episodic falls, recurrent falls are more associated with comorbidities and are less likely to occur due to external factors. Further, the strong presence of FOF in both models should be highlighted, not only because of the known vicious circle linking this variable with activity avoidance, balance performance and falls (Hadjistavropoulos, Delbaere, & Fitzgerald, 2010), but also because this indicates the need of having a cognitive-behavioural approach in fall prevention programs.

Similarly, having a lower level of FF, either measured through the balance or the total score, was a determinant factor for both episodic and recurrent falls. It is important to note that all FF tests were predictors for both episodic and recurrent falls, but the combined scores (Balance and total scores) led to models with better predictive power, reinforcing the need for a multidimensional approach when dealing with falls. These results are in accordance with the literature where, although different FF measures have been used, having poor FF is reported to be a strong predictor for falls, especially for recurrent falls (Chan et al., 2007; Graafmans et al., 1996; Pluijm et al., 2006; Stalenhoef et al., 2002; Tromp et al., 2001). Actually, muscle weakness, problems with gait and balance have been referred as the most important risk factors for falling (Rubenstein, 2006). In our sample, lower functional fitness levels were associated especially with recurrent falling, even within subjects without FOF, fact that reinforces the relevance of the inclusion of these measures in both fall risk assessment tools and intervention programs.

Finally, the total PA score was associated with both falling and recurrent falling, while walking, movement and sitting scores were associated only with recurrent falling in the bivariate models. Nevertheless, when inputted in the multivariate models, total PA was the only parameter that remained, being only determinant for episodic falls. The relation between PA and falls is still not clear and, even though recent evidence shows that regular PA significantly reduces falls (specially injurious falls) in older people (Thibaud et al., 2012), there is still controversy whether higher PA levels associated with lower functional fitness levels could lead to a higher propensity for falling (Chan et al., 2007; Peeters, Schoor, Pluijm, Deeg, & Lips, 2009). In our study, being more active, especially in what concerns light and moderate PA, was not only negatively correlated with falls frequency, but also positively correlated with FF level ($p \leq 0.001$). Moreover, PA health benefits for older people, namely the effect of slowing the decline in mobility performance, are widely known (U.S. Department of Health and Human Services, 1996; Visser, Pluijm, Stel, Bosscher, & Deeg, 2002), and therefore, its role in fall prevention should not be underestimated.

A limitation of this study was that falls were assessed retrospectively, which can generate an underestimation of these events, as falls are easily forgotten (Fleming, Matthews, & Brayne, 2008; Ganz, Higashi, & Rubenstein, 2005) unless they have serious physical consequences. Other limitation of this cross-sectional study was the impossibility to establish cause-effect time-based relationships between the independent variables and the outcome. These facts may limit our conclusions regarding the potential of the tested variables to predict episodic and recurrent falls. Nevertheless, the fact that the results of this study are in agreement with the ones from other prospective studies, as well as the representative dimension of our sample, give us confidence about the strength of our results.

3.5 Conclusion

In this study we have tested 1416 Portuguese older adults above 65 years and used a multifactorial approach to determine and characterize episodic and recurrent fallers' risk profiles in this population. Our results showed that age was not a risk factor for either episodic or recurrent falling. In addition, health parameters were shown to be the factors distinguishing recurrent from episodic fallers. This may imply that, compared to episodic falls, recurrent falls are more associated with comorbidities and are less likely to occur due to external factors. Furthermore, being a woman, having fear of falling and lower functional fitness levels were determinant factors for both episodic and recurrent falls. These factors appear to be related since women in our sample had a poorer FF level and more FOF, when compared with men. Moreover, although total physical activity was only related with episodic falling, promoting physical activity and exercise may be the easiest and cheapest way to improve functional fitness and health levels and therefore, its role in fall prevention should not be underestimated.

Concluding, the results of this study reinforce the importance of a multifactorial approach, not only focusing on cognitive-behavioral factors, but also on promoting physical activity and healthy lifestyles, when assessing fall risk or planning an intervention aiming at fall prevention within the older population.

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Conflicts of Interest

The authors declare that they have no conflict of interests associated with this paper.

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4

Sensitivity of joint kinematics and kinetics to different pose estimation algorithms and joint constraints in the elderly

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CHAPTER

Abstract

The purpose of this research was to study the sensitivity of lower limb joint kinematics and kinetics, calculated during different functional tasks (walking, stair descent and stair ascent) in a sample of older adults, to different pose estimation algorithms and models' joint constraints. Three models were developed and optimized differently: in one model, each segment had 6 degrees of freedom (segment optimization, SO), while in the other two, global optimization was used, with different joint constraints: 1) GO, allowing all joint rotations; 2) GOR, allowing three rotations at the hip, one at the knee (flexion/extension) and two at the ankle (dorsi/plantar flexion and eversion/inversion). The results showed that joint angles are more sensitive to the model's constraints than joint moments and, the more restrictive the model, the higher the differences between models, especially for the frontal and transverse planes (max. RMS difference during gait: 11.7º (64%) vs 0.12 Nm/Kg (35.4%). Additionally, except for knee abduction/adduction angle, differences between SO and GO models were relatively low. Since GO avoids the non anatomical dislocations sometimes observed in SO, choosing this model seems to be reasonable for future studies with a similar sample and study design.

Keywords: Modeling, Optimization, Degrees of freedom, Soft tissue artifact, Locomotion.

4.1 Introduction

Segments’ pose estimation from external markers is affected by several sources of error, from which soft tissue artifact (STA) is considered to be the most critical (Andriacchi & Alexander, 2000). STA effects on the lower limb landmarks can be larger than 10 mm, especially in the thigh (Peters, Galna, Sangeux, Morris, & Baker, 2010). Further, STA has a frequency content similar to the actual bone movement and is also subject and task dependent, rendering difficult its quantification and compensation (Leardini, Chiari, Della Croce, & Cappozzo, 2005). The effects of STA are especially critical when testing older subjects, due to the decrease in muscle and skin stiffness and the increase in fat mass that occur with ageing.

Different STA compensation methods, such as optimization techniques, have been proposed (Leardini et al., 2005). In segmental optimization methods, each segment is tracked independently and its pose is computed finding the optimal fit, in a least-squares sense, between the model determined and the measured markers coordinates (Challis, 1995; Spoor & Veldpaus, 1980). Because this method treats each segment independently (i.e. doesn’t apply any joint constraints), STA errors can affect the segment pose estimation and generate non anatomical displacements at the joints (Selbie, 2011). Contrarily, in global optimization methods, joint constraints are applied to overcome these unrealistic joint translations, and the best fit is determined considering the entire limb or body at each frame, instead of each segment independently (Lu & O’Connor, 1999). Consequently, these solutions depend highly on joint constraints (Duprey, Cheze, & Dumas, 2010).

Despite the controversy about the reliability of global optimization methods in minimizing STA (Andersen, Benoit, Damsgaard, Ramsey, & Rasmussen, 2010; Stagni, Fantozzi, & Cappello, 2009), kinematic models with joint constraints are commonly used in biomechanical analysis. Since STA is subject and task specific and its effects might be especially critical in older people, the purpose of this research was to study the sensitivity of lower limb joint kinematics and kinetics, measured during different functional tasks (walking, stair descent and stair ascent) in a sample of older adults, to different pose estimation algorithms and models’ constraints.

4.2 Methods

Sample

A convenience sample (7 women and 2 men) was selected from the Biomechanics of Locomotion in the Elderly Project (PTDC/DES/72946/2006) (Moniz-Pereira, Carnide, Machado, André, & Veloso, 2012). Subjects had a mean age of 72.2 years (SD ± 4.0 y) and were able to independently walk and ascend and descend a flight of stairs without using the handrail. None of them had neurologic or orthopedic conditions that affected their gait pattern. All participants signed an informed consent. The Ethics Committee of Faculty of Human Kinetics, Technical University of Lisbon approved the study protocol.

Data collection procedures

When performing the functional tasks (walking, stair ascent and stair descent), participants were barefoot and wore tight black shorts and t-shirts. Anthropometric measures included mass, stature and trochanteric height. The marker set was based on the calibrated anatomical system technique (Cappozzo, Catani, Della Croce, & Leardini, 1995), using a digitizing pointer for the anterior superior iliac spine markers.

Kinematic and kinetic data was collected with 8 infrared, high speed optoelectronic cameras (Oqus 300, Qualisys AB, Sweden) working at 200 Hz and synchronized in time and space with two force plates (9281B and 9283U014, Kistler, Switzerland).

For the stairs trials, a wooden staircase with three steps was built. Each step had 15 cm of height and 27 cm of depth. The last step was extended (80 cm depth) in order to avoid deceleration during stair climbing. One of the force platforms was imbedded on the floor in front of the staircase, while the first step was covering and securely fixed to the second force plate. This step was built ensuring an extreme rigidity of the structure. Each force platform was independent of the surrounding wooden pieces to ensure adequate measures.

Participants were asked to walk at their comfortable pace. Prior to data collection, training trials were allowed so that subjects became familiarized with each task. Five trials from each task were collected and the order of the tasks (walking and stairs) was randomized.

Data processing

Three lower limb models were built for each subject. All models had seven segments (feet, shanks, thighs and pelvis). Most of the inertial parameters were computed based on Hanavan (1964), while segment masses were determined according to Dempster (1955). Segment lengths were defined using the respective proximal and distal anatomical landmarks, i.e., the knee and ankle joint centers were the mid-point of the epicondyles and the mid-point of the malleoli, respectively (Robertson, 2004, pp 151-153). The hip joint centers were computed using the pelvis markers, through a regression equation proposed by Bell, Pedersen, & Brand (1990).

The differences between the three models were either the pose estimation algorithm used and/or the models' constraints. For one model, the optimal fit was determined for each segment, which was considered independent and with six degrees of freedom (segment optimization, SO) (Spoor & Veldpaus, 1980). In the other two models, global optimization was used, following Lu and O'Connor's method (Lu & O'Connor, 1999), with different joint constraints: 1) allowing all joint rotations (X, flexion/extension; Y, abduction/adduction; and Z, internal/external rotation), but restraining all joints' translations (GO); 2) allowing three rotations at the hip, one at the knee (flexion/extension) and two at the ankle (dorsi/plantar flexion, and external/internal rotation), while also restraining all joints' translations (GOR).

From the five trials collected from each task, three were processed. These movement trials were associated to each of the three models. A fourth order Butterworth 10Hz low pass filter was used for both kinematic and kinetic data. Lower limb joint angles (using a XYZ Cardan sequence consistent with Grood & Suntay (1983)) and moments (determined through inverse dynamics and normalized to subjects' body mass) were computed and expressed relatively to the proximal segment. Thus, flexion/extension rotations occurred around the medio-lateral axis of the proximal segment, abduction/adduction rotations around a floating axis and external/internal rotations around the distal segment longitudinal axis. Both joint angles and moments were normalized to a full right limb stride cycle.

All data processing was performed in Visual 3D software (Professional Version v4.80.00, C-Motion, Inc, Rockville, USA).

Data analysis

Root mean square (RMS) differences between the three methods were computed for each joint angle and moment curves for each subject. These differences were also normalized to the signal amplitude and averaged for the nine subjects. To assess the relevance of these differences (i.e. the sensitivity of the variables to the models), RMS differences were also determined within and between subjects to obtain intra and inter subject variability.

4.3 Results

To illustrate the results, the walking task is used. However, the results for the stairs tasks may be consulted in Appendix 1.

In general, variables in the sagittal plane and joint moments, irrespectively of the plane of motion, were less sensitive to the chosen kinematic model (Figures 4.1B and 4.2B).

RMS differences between methods were consistently higher when comparing GOR with both SO and GO. The exceptions were hip flexion/extension angles, hip joint moments, and ankle joint angles and moments in the sagittal plane, where differences were homogenous and lower than intersubject variability between all methods. Additionally, although RMS differences for hip joint abduction/adduction angles, knee angles in the sagittal plane and knee moments, were sometimes higher than intersubject variability, the curve patterns had a good agreement between methods (figures 4.3 and 4.4). On the contrary, RMS differences for hip joint angles in the transverse plane, knee and ankle joint moments in the frontal plane, and ankle joint angles and moments in the transverse plane, were particularly critical between GOR and the other models and the curve patterns agreement was poorer.

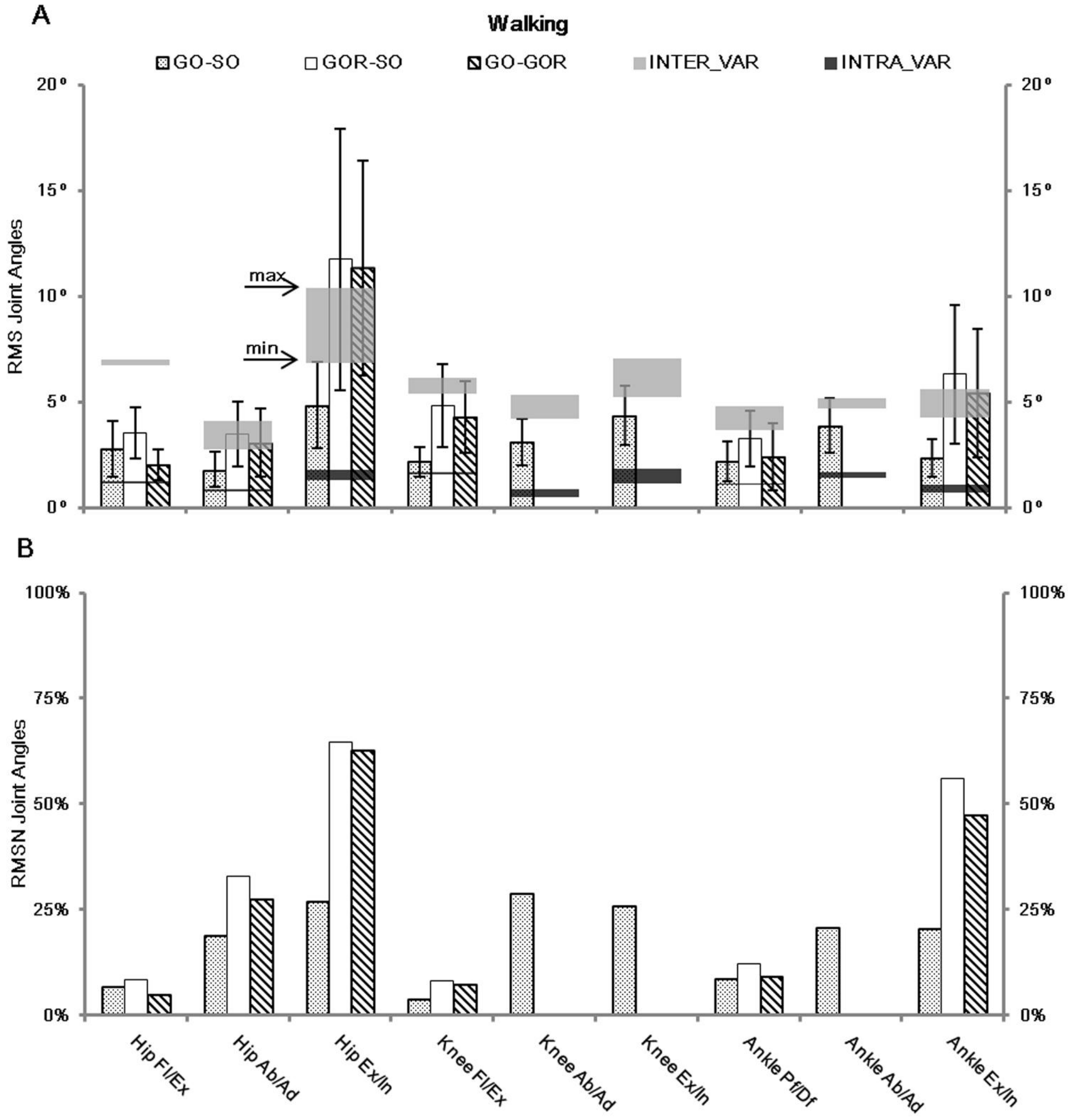

Figure 4.1: Joint angles root mean square (RMS) (A) and normalized RMS (RMSN) (B) differences between methods for the walking task (Fl/Ex, Ab/Ad, Ex/In and Pf/Df stand for flexion/extension, abduction/adduction, external/internal rotations and plantar/dorsiflexion). Maximum and minimum intersubject variability (INTER_VAR) is represented by the gray shadow, while maximum and minimum intrasubject variability (INTRA_VAR) is represented by the black shadow.

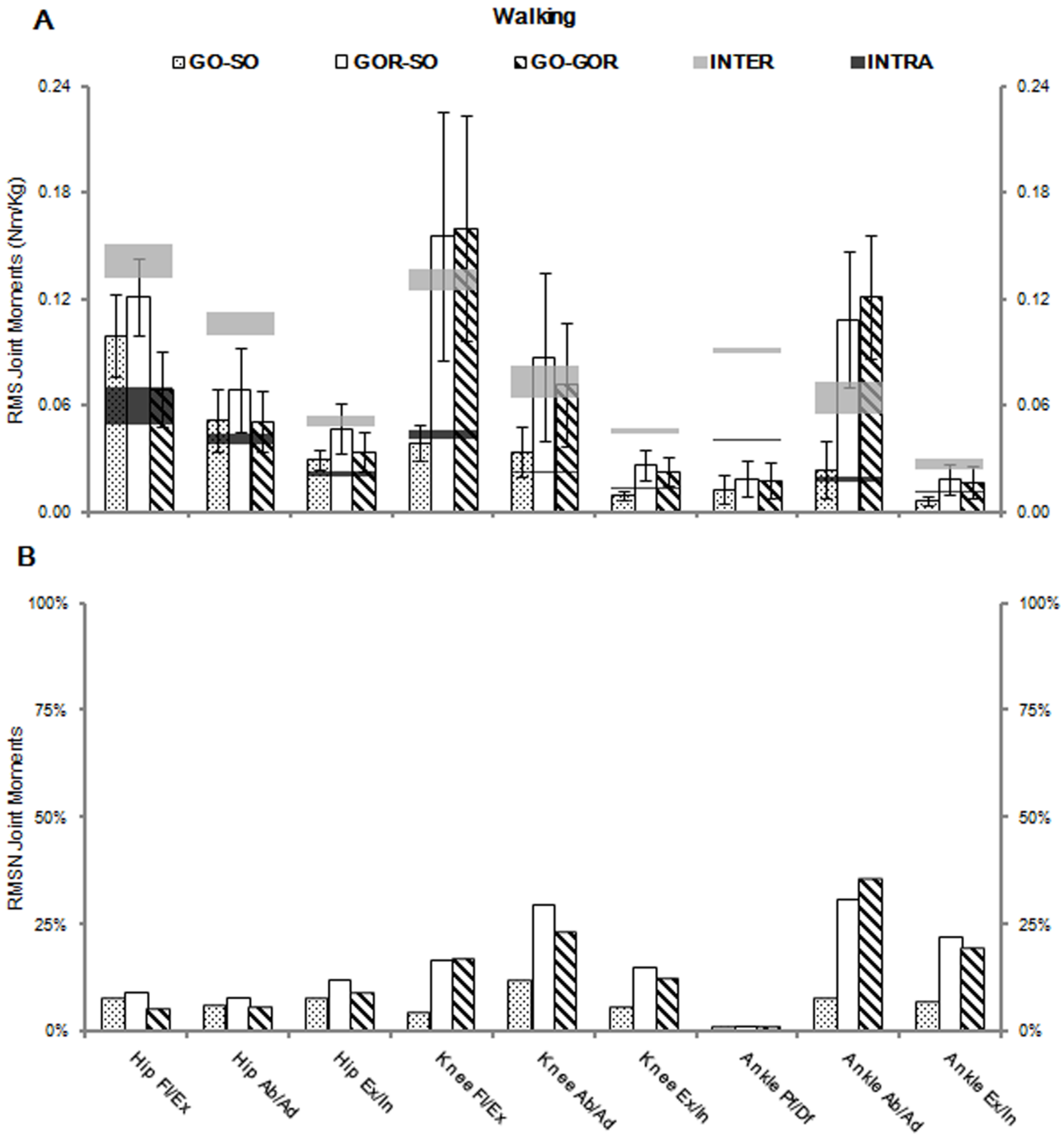

Figure 4.2: Joint moments root mean square (RMS) (A) and normalized RMS (RMSN) (B) differences between methods for the walking task (Fl/Ex, Ab/Ad, Ex/In and Pf/Df stand for flexion/extension, abduction/adduction, external/internal rotations and plantar/dorsiflexion). Maximum and minimum intersubject variability (INTER_VAR) is represented by the gray shadow, while maximum and minimum intrasubject variability (INTRA_VAR) is represented by the black shadow.

RMS differences between SO and GO remained within intersubject variability for most variables and tasks (figures 4.1A and 4.2A). The largest differences were found for: hip joint angles in the transverse plane, knee joint angles in the frontal and transverse planes, and ankle joint angles in the frontal and transverse planes. The high standard deviation of these differences also indicates that the influence of the method varies according to subjects' characteristics. Moreover, with the exception of knee abduction/adduction angles, the agreement between the curve patterns was relatively good between these two methods, even for the variables that showed higher differences (figures 4.3 and 4.4).

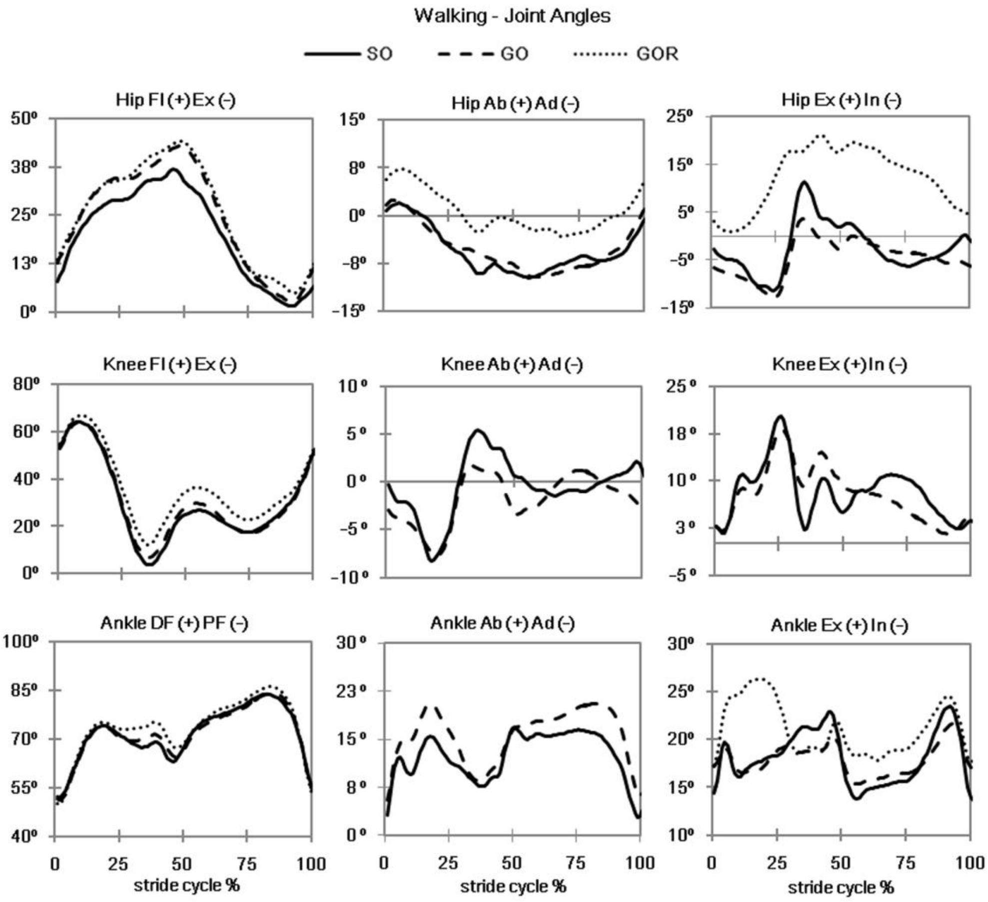

Figure 4.3: Joint angular displacements, of one of the subjects, for the 3 different methods during a walking stride cycle (from right foot off to right foot off). Fl/Ex, Ab/Ad, Ex/In and Pf/Df stand for flexion/extension, abduction/adduction, external/internal rotations and plantar/dorsiflexion.

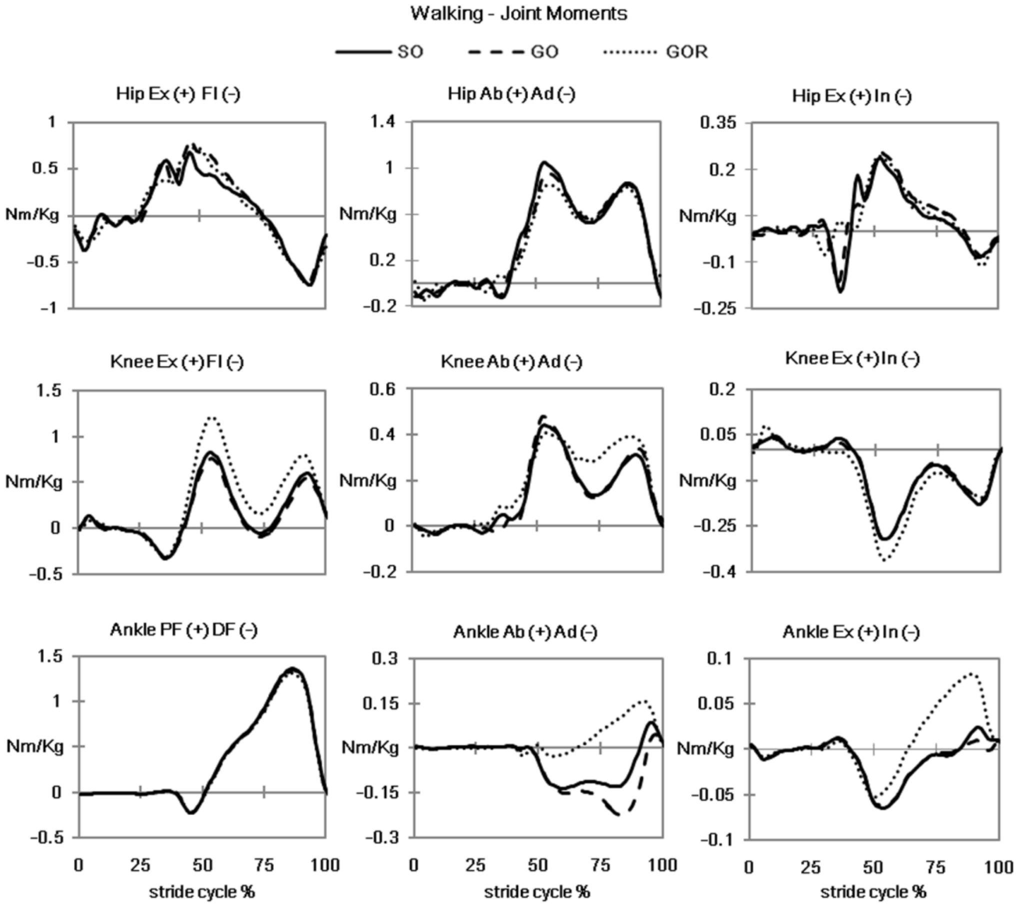

Figure 4.4: Joint moments, of one of the subjects, for the 3 different methods during a walking stride cycle (from right foot off to right foot off). Fl/Ex, Ab/Ad, Ex/In and Pf/Df stand for flexion/extension, abduction/adduction, external/internal rotations and plantar/dorsiflexion.

4.4 Discussion

The purpose of this study was to verify the sensitivity of lower limb joint kinematics and kinetics, measured during different functional tasks (walking, stair ascent and stair descent) in a sample of older adults, to different pose estimation algorithms and models' constraints. In order to accomplish this goal, three models were built and optimized differently for each participant and the RMS differences between the models were computed.

A limitation of this study is the lack of *in-vivo* data. Nevertheless, one should note that these procedures are highly invasive and therefore have very limited applicability, particularly when dealing with older subjects. As such, the aim of this study was not to identify which method describes better the joint kinematics and kinetics during locomotor tasks, but rather to provide further knowledge on the effect of different pose estimation methods on these data and thus the foundation for a more sound decision making process. Likewise, the conclusions of this study should be taken carefully when using different rotation sequences and different joint axis orientations, as these choices may produce different results.

The results showed that joint angles are more sensitive to the kinematic model than joint moments and that, the more restrictive the model is, the higher are the differences between methods, especially for the frontal and transverse planes. Furthermore, with the exception of knee abduction/adduction joint angles, differences between SO and GO models were relatively small, and the curve patterns had a good agreement between methods and with the literature (Andriacchi, Andersson, Fermier, Stern, & Galante, 1980; Bovi, Rabuffetti, Mazzoleni, & Ferrarin, 2011; DeVita & Hortobagyi, 2000; McFadyen & Winter, 1988; Nadeau, McFadyen, & Malouin, 2003; Novak & Brouwer, 2011; Reeves, Spanjaard, Mohagheghi, Baltzopoulos, & Maganaris, 2008, 2009; Winter, 1991).

Hip internal/external rotation angle showed a higher dispersion between methods, especially between GOR and both GO and SO. This variability, already mentioned by some authors (Duprey et al., 2010; Richards, 2008), was accompanied by a higher intra and intersubject variability, and therefore might have been, not only generated by the model constraints, but due to individual differences in pelvis positioning and femoral rotation (Richards, 2008, pp 63). Knee joint motion, other than in the sagittal plane, and especially in the frontal plane, revealed also higher differences. Although there is almost no data reported for the angles on frontal and horizontal planes in the elderly, the problem of obtaining reliable angular displacements in these planes, measured through external markers, is not new for healthy young adults (Benoit et al., 2006; Reinschmidt et al., 1997). In contrast, knee joint moments in the frontal and transverse planes were much more consistent between methods and, even though the RMS differences were higher than those observed for the sagittal plane, the curve patterns remained consistent between methods and participants and were in accordance with the literature (Nadeau et al., 2003; Novak & Brouwer, 2011). At the ankle, the differences were also higher in the frontal and transverse planes, especially in the latter and when comparing GOR with the other two models. These data are scarce in the literature for elderly subjects. Nevertheless, frontal plane curve patterns, especially joint moment curves, obtained in this study had a good agreement with the patterns referred in the literature for healthy young subjects (Andriacchi et al., 1980; Novak & Brouwer, 2011; Reinschmidt et al., 1997). On the other hand, sagittal plane variables were, in general, the least affected by the model's characteristics, showing consistent amplitudes and patterns, which were in accordance with the literature (Andriacchi et al., 1980; Bovi et al., 2011; DeVita & Hortobagyi, 2000; McFadyen & Winter, 1988; Nadeau et al., 2003; Novak & Brouwer, 2011; Reeves et al., 2008, 2009; Winter, 1991).

These findings should be taken into account together with the goals of a study, when choosing the kinematical model to be applied. If the variables of interest are mainly in the sagittal plane, any of the models can be used since all of them seem to give consistent answers. However, if movement in the frontal and transverse plane, particularly in the knee and ankle joints, is the main concern of the study, GOR may not be appropriate, as it may hide movement that is really occurring, and these data should be analyzed in a conservative way. Given the accordance found between SO and GO, and the importance of frontal plane variables in stairs tasks, it seems that GO is a prudent choice for future studies with a similar sample and study design, as GO avoids the non anatomical dislocations sometimes observed for SO due to STA, which is a major problem in a population such as the elderly.

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Conflict of Interest Disclosure

The authors declare that they have no conflict of interests associated with this paper.

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5

Gait patterns in the elderly: the influence of functional fitness level

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CHAPTER

Abstract

Functional tasks involving locomotion are present in many daily activities, being essential for the maintenance of independence and quality of life in the elderly. Studies have been focused on age changes in gait patterns. However, community dwelling older adults are a highly heterogeneous group in terms of functional fitness. This study aimed to characterize and compare sagittal and frontal lower limb joint moments of force in 3 different functional tasks (level walking, stair ascent and stair descent) within a group of older adults, and to verify the influence of functional fitness level in those patterns. Twenty seven subjects over 60 years participated in this study. Instrumented 3D gait analysis was performed to assess joint moments' profiles. In all tasks, older subjects with a lower functional fitness level score produced higher hip extensor moments and lower ankle plantaflexor moments. Further, in the stairs tasks, knee extensor moments were also reduced for this subgroup. In the frontal plane, the lower functional fitness level subgroup produced smaller hip abductor moments, especially while walking and ascending stairs. These compensations seem to reflect the strategies adopted during these tasks in order to enhance perceived stability and to guarantee a safe clearance of the contralateral limb.

Keywords: Stair walking, Level walking, Joint moments, Lower extremity function, Older adults.

5.1 Introduction

Functional fitness decline, especially in lower-extremity function, has been identified as a predictor of disability in older people living in the community (Guralnik, Ferrucci, Simonsick, Salive, & Wallace, 1995). Strength and balance impairments affect locomotor performance, limiting elderly mobility and thus, their ability to independently and safely carry out daily activities (Rantakokko, Mänty, & Rantanen, 2013). Besides, both lower limb muscle weakness and gait deficits, have shown to be prognostic factors for falling (Rubenstein, 2006), a major problem faced by the elderly.

As a result, studies have been conducted in order to characterize the gait patterns adopted by older people, and to compare those patterns with the ones adopted by their younger counterparts (Winter, 1991; Prince, Corriveau, Hébert, & Winter, 1997; Kerrigan, Todd, Della Croce, Lipsitz, & Collins, 1998; Begg & Sparrow, 2000; DeVita & Hortobagyi, 2000; Reeves, Spanjaard, Mohagheghi, Baltzopoulos, & Maganaris, 2008, 2009; Novak & Brouwer, 2011). In particular, when compared with younger subjects, older adults distribute lower limb joint moments differently both during level (Kerrigan et al., 1998; DeVita & Hortobagyi, 2000) and stair walking (Novak & Brouwer, 2011; Reeves et al., 2008, 2009). The most consistent finding within these studies is that older adults apply smaller plantarflexor joint moments when performing these tasks, showing a less vigorous push off than their younger counterparts. However, for the other lower limb joints, literature shows controversial results. Additionally, studies considering age related changes in the frontal plane of motion are scarce, though it has been indentified that substantial effort in this plane is needed to successfully perform locomotor tasks, especially when dealing with stairs (Kowalk, Duncan, & Vaughan, 1996; Nadeau, McFadyen, & Malouin, 2003).

The mentioned studies focused on determining age effects on gait patterns. However, it has been reported that up to 20% of very old individuals still have a completely normal gait and do not fall despite their age, indicating that balance and gait disorders are certainly not an inevitable consequence of ageing (Voermans, Snijders, Schoon, & Bloem, 2007). Moreover, responsiveness to physical activity interventions is dependent on specific subgroup's characteristics, like functional limitations (van Stralen, de Vries, Bolman, Mudde, & Lechner, 2010). Thus, the characterization of different locomotor tasks in older adults with different functional fitness levels, may yield important information to the success of fall and disability preventive strategies, in both clinical and exercise contexts.

The purposes of this study were to characterize and compare sagittal and frontal lower limb joint moment patterns in three different functional tasks (level walking, stair ascent and stair descent) within a group of older adults and to verify the influence of subjects' functional fitness level in those task patterns.

5.2 Methods

Sample

The study sample included 27 participants. All of them were over 60 years (63 - 84 years), able to independently walk and to ascend and descend a flight of stairs without using the handrail. None of them had any neurologic or orthopedic condition that would affect their gait pattern. Participants signed the informed consent. The Faculty Ethics Committee approved the study protocol.

Data collection

On their first visit, participants answered a health and a physical activity questionnaire and performed 6 functional fitness tests.

In the health questionnaire participants were asked about their demographic data, general health, medication intake (and associated diseases) and fall history. This questionnaire was used to select the eligible participants according to the previously mentioned inclusion criteria. Yale Physical Activity Questionnaire (YPAS) (Dipietro, Caspersen, Ostfeld, & Nadel, 1993) was used to assess their weekly physical activity routines. Finally, functional fitness tests were administered to assess lower limb strength, power and coordination - through the 8 foot Up-and-Go test and the Chair Stand test from Senior Fitness Test battery (Rikli & Jones, 1999) – as well as balance - through items 4 (step up and over), 5 (tandem walk) , 6 (stand on one leg) and 7 (stand on foam eyes closed) of the Fullerton Advanced Balance Scale (Rose, Lucchese, & Wiersma, 2006).

During the second visit, participants performed the locomotor tests. They were barefoot and wore tight black shorts and t-shirts. Anthropometric measures included subjects' body mass, stature and trochanteric height. Thirty passive markers and four marker clusters were used based on the calibrated anatomical system technique (Cappozzo, Catani, Della Croce, & Leardini, 1995). Specifically, six markers were placed on the trunk, one on top of each acromion, one on the C7 spinous process and three on the sternum area (placed so that soft tissue artifact and collinearity was avoided). At the pelvis, two markers were placed on each posterior superior iliac spines and two along each iliac crest. A virtual marker was created in each anterior superior iliac spine using a digitizing pointer. Markers were also placed on the lateral and medial femur epicondyles, the lateral and medial ankle malleoli and on the top of the first and fifth metatarsal heads. Each foot had also one marker on the heel, another laterally in the middle of the foot and a third one between the two metatarsal heads. Finally, the mentioned marker clusters were attached to both thighs and shanks.

Kinematic and kinetic data was collected at 200 Hz using 8 infrared cameras (300, Qualisys AB, Sweden) synchronized in time and space with two force plates (9281B and 9283U014, Kistler, Switzerland).

For the stairs trials, a wooden staircase with three steps was built. Each step was 15 cm high and 27 cm deep. The last step was extended (80 cm depth) to avoid deceleration during stair climbing. The first force platform was embedded on the floor in front of the staircase while the second was covered by the first step. This step was securely fixed to the second force platform and was built ensuring the rigidity of the structure. Each force platform was independent of the surrounding wooden pieces.

Participants were asked to walk at their comfortable pace during all tasks (walking, stair ascent (SA) and stair descent (SD)) and to use a step over step pattern in the stair tasks. Before data collection, practice trials were allowed. Five trials from each task were collected and the order of the tasks (walking and stairs) was randomized.

Data processing

Functional fitness level was determined through a total functional fitness score (with a maximum of 24 points), computed using the results of the previously mentioned functional fitness tests, as described elsewhere (Moniz-Pereira et al., 2013). Two groups were created using the median value of the mentioned score: the low functional fitness level (LFFL) group, which included subjects who scored less than 22 points and the high functional fitness (HFFL) group, which included subjects who scored 22 or more points.

For the biomechanical data, a model with eight segments (feet, shanks, thighs, pelvis and trunk) was built for each participant. Apart from the trunk and pelvis, which had six degrees-of-freedom, all the other segments were allowed to rotate about the 3 axis but translations were restricted using global optimization (Lu & O'Connor, 1999). Most inertial parameters were computed based on Hanavan (1964), whereas segment masses were determined according to Dempster (1955). Segment lengths were defined using the respective proximal and distal anatomical landmarks, i.e., knee joint centre was the mid-point of the epicondyles and ankle joint center the mid-point of the malleolli Robertson (2004). The hip joint centre was computed using the pelvis markers, through a regression equation proposed by Bell, Pedersen & Brand (1990).

From the five trials collected from each task, three right limb cycles were processed. The terminology used to distinguish between different cycle phases was based in the work done by McFadyen & Winter (1988). A fourth order Butterworth low pass filter at 10Hz was used for both kinematic and kinetic data. Computed gait variables included spatial-temporal parameters (stride width, stride velocity, support and swing durations) and lower limb joint moments (determined through inverse dynamics, normalized to subjects' body mass and expressed relatively to the proximal segment). Joint moment peaks and joint rotational impulses were computed for each trial during stance phase only (and/or during the braking – Impulse 1 – and the propulsive – Impulse 2 – phases of the anterior-posterior ground reaction force curve, as described elsewhere (Peterson, Kautz, & Neptune, 2011)) and averaged afterwards for each subject. Although not included in the primary goal of this study, joint angles were also computed, using a XYZ Cardan sequence and expressed relatively to the proximal segment, in order to complement the discussion of the results. Thus, flexion/extension rotations occurred around the medio-lateral axis of the proximal segment, abduction/adduction rotations around a floating axis and external/internal rotations around the distal segment longitudinal axis.

All data processing was performed in Visual 3D (Professional Version v4.80.00, C-Motion, Inc).

Statistical analysis

Statistical analysis was performed in IBM SPSS Statistics 20 and included (1) descriptive statistics of all outcome variables; (2) independent t-tests (or Mann Whitney test) to determine differences between functional fitness groups for basic characterization variables; and (3) a repeated measures ANOVA for kinetic variables with one between subjects factor (functional fitness level) and one within subjects factor (gait task). Although repeated measures ANOVA is known to be robust with respect to assumptions, as long as the design is balanced (Norman & Streiner, 2008), non-parametric statistics and sphericity corrections were also verified, when necessary, in order to confirm the results.

The significance level was set at $p<0.05$ and supplemented by an effect size analysis. Medium effect sizes (i. e. $|d| > 0.5$ and $\eta^2_p > 0.06$ (Cohen, 1988)) were considered as clinically relevant differences.

5.3 Results

The studied sample had a mean age of 71.4 ± 5.4 years, a body mass index of 27 ± 3.2 Kg/m^2 and a functional fitness score of 21.7 ± 3.2 score points. The LFFL group (n = 14) scored on average 20 ± 1.3 (range: 17 – 21) scale points, while the HFFL group (n = 13) scored 23.5 ± 0.8 (range: 22 – 24) scale points. No differences between groups were found for age, body mass index, medication intake, falls or total physical activity time.

There were also no statistically significant differences between groups for temporal distance parameters in all tasks (Table 5.1). However, walking cycle and support durations presented medium to large effect sizes, with the LFFL group having a lower cycle time than the HFFL group. Nevertheless, because support duration was also shorter for this group, the percentage of support duration was similar between the groups.

Table 5.1: Group Means (M) ± SD and effect sizes (ES) for temporal distance parameters during walking, stair ascent and stair descent.

Temporal-distance parameters	Walking			Stair Ascent			Stair Descent		
	LFFL M ± SD (n = 14)	HFFL M ± SD (n = 13)	ES (d)	LFFL M ± SD (n = 14)	HFFL M ± SD (n = 13)	ES (d)	LFFL M ± SD (n = 14)	HFFL M ± SD (n = 13)	ES (d)
Cycle duration (s)	0.96 ± 0.06	1.03 ± 0.11	**0.80***	1.54 ± 0.20	1.54 ± 0.24	0.01	1.31 ± 0.18	1.36 ± 0.25	0.23
Support duration (s)	0.59 ± 0.05	0.63 ± 0.07	**0.66***	0.98 ± 0.16	0.97 ± 0.19	0.02	0.86 ± 0.16	0.87 ± 0.17	0.06
Support duration (%)	61.8 ± 0.8	61.6 ± 1.5	0.17	63.3 ± 2.7	62.9 ± 2.6	0.15	65.7 ± 3.6	64.2 ± 3.0	0.45
Double support duration (%)	23.3 ± 1.5	22.7 ± 2.7	0.00	29.7 ± 3.0	29.1 ± 3.5	0.18	27.7 ± 3.7	27.7 ± 4.9	0.00
Stride width (m)	0.10 ± 0.02	0.10 ± 0.02	0.00	0.11 ± 0.04	0.11 ± 0.02	0.06	0.14 ± 0.03	0.13 ± 0.02	0.39
Stride width normalized to LL (m/m)	0.12 ± 0.02	0.12 ± 0.02	0.00	0.13 ± 0.05	0.12 ± 0.03	0.08	0.16 ± 0.04	0.15 ± 0.02	0.28
Stride velocity (m/s)	1.32 ± 0.13	1.34 ± 0.20	0.12	0.47 ± 0.06	0.48 ± 0.08	0.12	0.52 ± 0.08	0.53 ± 0.10	0.11
Stride velocity normalized to LL (m/s/m)	1.56 ± 0.15	1.51 ± 0.25	0.24	0.56 ± 0.08	0.54 ± 0.09	0.17	0.62 ± 0.10	0.60 ± 0.12	0.18

LFFL = low functional fitness level group; HFFL = high functional fitness level group
* |d| > 0.5 – medium effect size, here considered as clinical relevant differences between group means

With the exception of knee abductor impulse 1, statistically significant differences were found for all variables between tasks (Table 5.2). The highest plantarflexor moment push off peak (2nd peak) was applied in the walking task, followed by SA and SD tasks. However, both SA and SD tasks required higher ankle plantarflexor rotational impulses, especially at the beginning of stance (Figure 5.1). Larger knee extensor moments and rotational impulses were also required while dealing with stairs, when compared with level walking. These differences were mainly seen during the weight acceptance and pull up phases for the SA task (1st peak and Impulse 1), and throughout all stance in SD task (Impulses 1 and 2). At the hip the highest extensor impulses occurred in the SA task, while the highest flexor impulses were observed during walking. Furthermore, hip joint moments in the sagittal plane were very small during SD. In the frontal plane both SA and SD tasks required larger ankle adductor moments (Table 5.2), with the highest difference found between walking and SD during the controlled lowering phase (Impulse 2). Knee joint abductor impulse was only different between walking and SD during this same phase, while hip abductor impulse during stance was higher for both stairs tasks, but especially for SD.

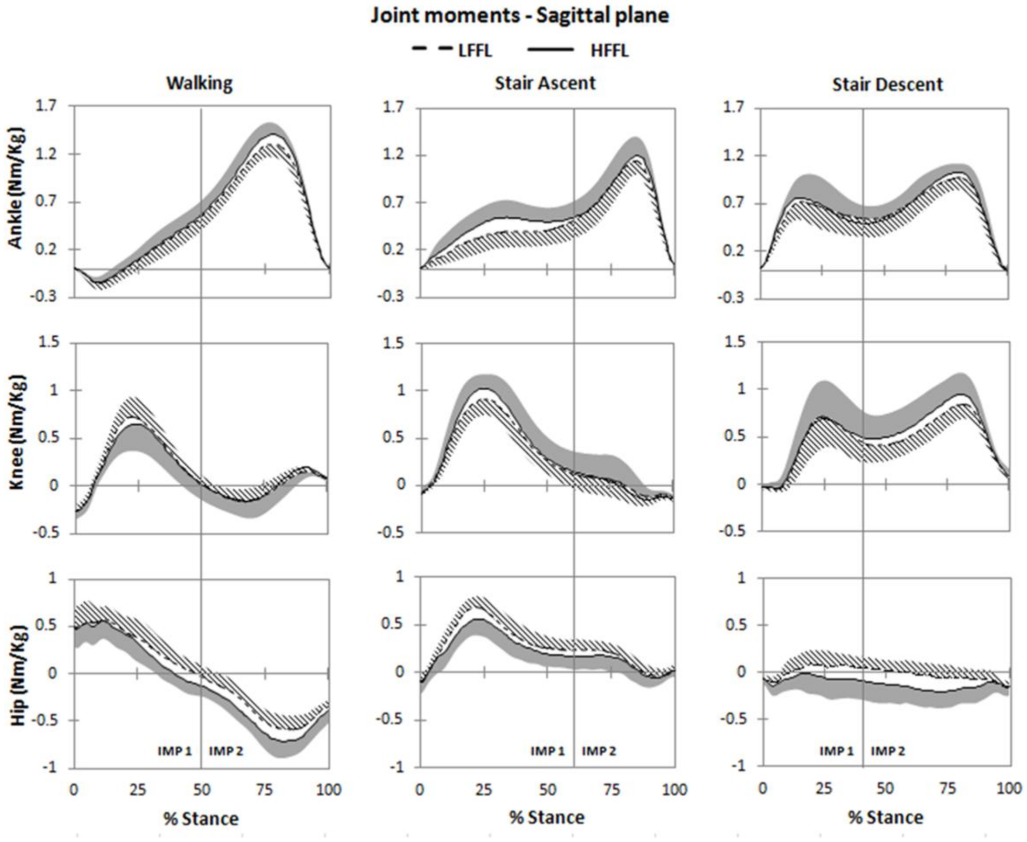

Figure 5.1: Joint moment profiles in the sagittal plane during stance for all tasks. LFFL stands for low functional fitness level group and HFFL stands for high functional fitness level group. The vertical line distinguishes braking and propulsive impulses (impulse 1 and 2, respectively). Positive values represent plantarflexion/extension moments.

Table 5.2: Means ± SD for joint moments and rotational impulses for each task: within subjects effects.

Joint moments (Nm/kg) and rotational impulses (Nm.s/Kg)			**Walking**	**Stair Ascent**	**Stair Descent**	**Within subjects**	
			M ± SD	**M ± SD**	**M ± SD**	**p**	**ES (η^2_p)**
Sagittal plane (Extension / Plantaflexion +; Flexion / Dorsiflexion -)	**Ankle**	**2^{nd} Peak**	1.36±0.13	1.21±0.16	1.04±0.11	**< 0.001***	**0.74**
		Impulse Stance	0.32±0.06	0.52±0.14	0.53±0.10	**< 0.001‡**	**0.74**
	Knee	**1^{st} Peak**	0.70 ± 0.24	1.01 ± 0.17	0.78 ± 0.32	**< 0.001¥**	**0.39**
		Impulse 1	0.096 ± 0.043	0.291 ± 0.076	0.134 ± 0.073	**< 0.001***	**0.79**
		Impulse 2	-0.002 ± 0.031	0.005 ± 0.059	0.300 ± 0.103	**< 0.001ψ**	**0.89**
	Hip	**Impulse 1**	0.086 ± 0.039	0.182 ± 0.055	-0.012 ± 0.060	**< 0.001***	**0.93**
		Impulse 2	-0.124 ± 0.033	0.046 ± 0.045	-0.042 ± 0.061	**< 0.001***	**0.88**
Frontal plane (Abduction +; Adduction -)	**Ankle**	**Impulse 1**	-0.040 ± 0.013	-0.096 ± 0.039	-0.080 ± 0.029	**< 0.001‡**	**0.57**
		Impulse 2	-0.053 ± 0.027	-0.087 ± 0.035	-0.146 ± 0.054	**< 0.001***	**0.80**
	Knee	**Impulse 1**	0.072 ± 0.025	0.069 ± 0.047	0.068 ± 0.042	0.866	0.00
		Impulse 2	0.043 ± 0.025	0.046 ± 0.036	0.112 ± 0.068	**< 0.001ψ**	**0.55**
	Hip	**1^{st} Peak**	0.75 ± 0.12	0.64 ± 0.10	0.81 ± 0.14	**< 0.001***	**0.55**
		Impulse Stance	0.27 ± 0.06	0.34 ± 0.11	0.44 ± 0.11	**< 0.001***	**0.73**

Impulse 1: computed during the time interval of the braking phase of the anterior-posterior ground reaction force curve.
Impulse 2: computed during the time interval of the propulsive phase of the anterior-posterior ground reaction force curve.
* Differences between all tasks;
‡ Differences between walking and both stair ascent and stair descent
¥ Differences between stair ascent and both walking and stair descent
ψ Differences between stair descent and both walking and stair ascent

Differences between functional fitness groups were only statistically significant for hip extensor impulse 2 (Table 5.3). However, the moderate effect sizes found for hip extensor impulse 1 reinforce the result that the LFFL group consistently applied higher hip extensor moments throughout stance in all tasks, when compared with the HFFL group (Figure 5.1). Moderate effect sizes were also found for plantarflexor moment peak (walking and SD) and impulse (walking and SA), which tended to be higher in the HFFL group. Moreover, a large effect size was also found for knee extensor joint moment (1st peak), which was higher for the HFFL group, but only during the SA task (Table 5.3). The HFFL group had also the tendency to have a higher second knee extensor moment peak (LFFL = 0.87 ± 0.15 Nm/Kg; HFFL = 0.98 ± 0.21 Nm/Kg; p = 0.11; d = 0.64) during the SD task (Figure 5.1). Finally, in the frontal plane, the HFFL group presented a higher hip abductor moment peak, especially during walking and SA (Table 5.3 and Figure 5.2).

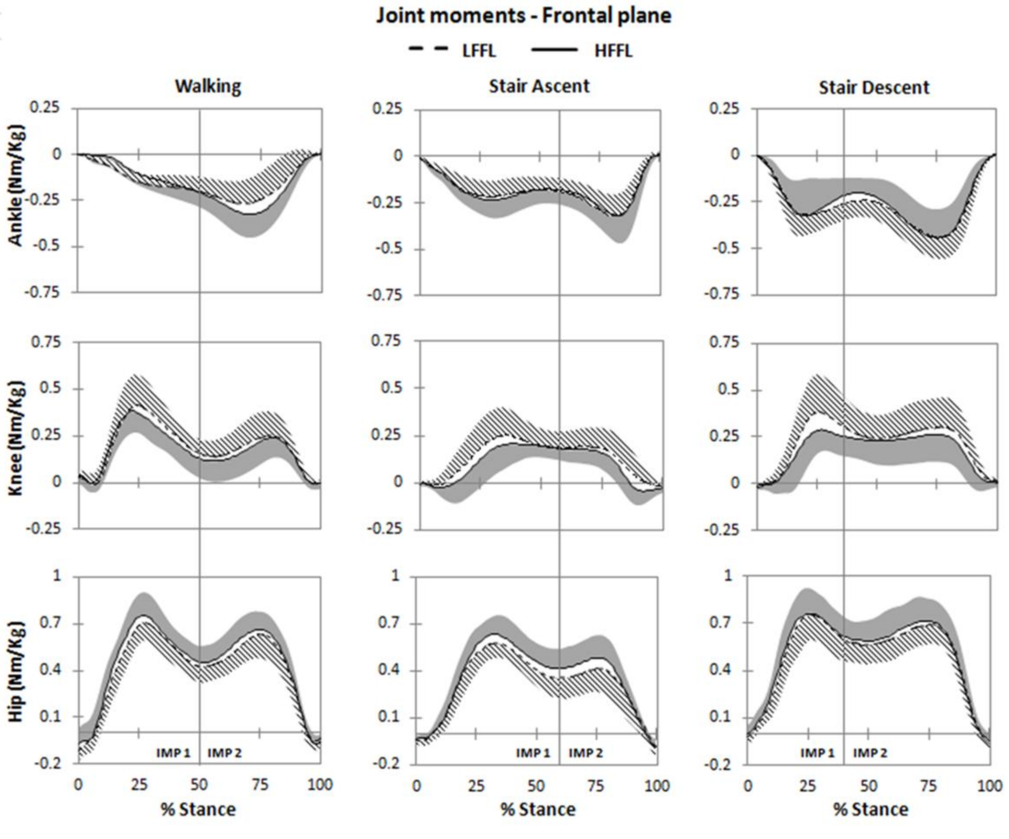

Figure 5.2: Joint moment profiles in the frontal plane during stance for all tasks. LFFL stands for low functional fitness level group and HFFL stands for high functional fitness level group. The vertical line distinguishes braking and propulsive impulses (impulse 1 and 2, respectively). Positive values represent abduction moments.

Table 5.3: Means ± SD and effect sizes (ES) for joint moments and rotational impulses for each task: between groups effects.

Joint moments (Nm/Kg) and rotational impulses (Nm.s/Kg)			Walking			Stair Ascent			Stair Descent			Between groups	
			LFFL M ± SD (n = 14)	**HFFL M ± SD (n = 13)**	**ES (d)**	**LFFL M ± SD (n = 14)**	**HFFL M ± SD (n = 13)**	**ES (d)**	**LFFL M ± SD (n = 14)**	**HFFL M ± SD (n = 13)**	**ES (d)**	**p**	**ES (η^2_p)**
Sagittal plane (Extension / Plantaflexion +; Flexion / Dorsiflexion -)	Ankle	2nd Peak	1.32 ± 0.12	1.41 ± 0.12	**0.75***	1.18 ± 0.13	1.25 ± 0.19	0.43	1.01 ± 0.12	1.08 ± 0.08	**0.68***	0.064	**0.13***
		Impulse Stance	0.30 ± 0.04	0.34 ± 0.06	**0.85***	0.48 ± 0.11	0.55 ± 0.16	**0.52***	0.53 ± 0.10	0.54 ± 0.11	0.10	0.206	**0.06***
	Knee	1st Peak	0.72 ± 0.20	0.69 ± 0.29	0.09	0.94 ± 0.15	1.08 ± 0.15	**0.96***	0.78 ± 0.27	0.78 ± 0.38	0.00	0.573	0.01
		Imp 1	0.095 ± 0.037	0.096 ± 0.051	0.02	0.28 ± 0.06	0.31 ± 0.09	0.4	0.13 ± 0.05	0.14 ± 0.10	0.08	0.524	0.02
		Imp 2	-0.004 ± 0.023	-0.001 ± 0.039	0.09	0.007 ± 0.044	0.004 ± 0.074	0.05	0.28 ± 0.09	0.32 ± 0.12	0.35	0.504	0.02
	Hip	Imp 1	0.092 ± 0.035	0.079 ± 0.043	0.33	0.20 ± 0.05	0.16 ± 0.05	**0.74***	0.010 ± 0.037	-0.035 ± 0.073	**0.79***	0.072	**0.12***
		Imp 2	-0.11 ± 0.03	-0.14 ± 0.03	**0.84***	0.057 ± 0.038	0.035 ± 0.051	0.49	-0.017 ± 0.046	-0.068 ± 0.066	**0.90***	**0.026‡**	**0.18***
Frontal plane (Abduction +; Adduction -)	Ankle	Imp 1	-0.042 ± 0.014	-0.037 ± 0.013	0.37	-0.093 ± 0.038	-0.099 ± 0.040	0.15	-0.083 ± 0.027	-0.076 ± 0.032	-0.24	0.774	0.00
		Imp 2	-0.051 ± 0.014	-0.054 ± 0.014	0.11	-0.090 ± 0.031	-0.084 ± 0.040	0.17	-0.15 ± 0.04	-0.15 ± 0.07	0.00	0.952	0.00
	Knee	Imp 1	0.071 ± 0.029	0.072 ± 0.022	0.04	0.077 ± 0.050	0.062 ± 0.044	0.32	0.074 ± 0.036	0.062 ± 0.047	0.29	0.498	0.02
		Impu2	0.045 ± 0.025	0.042 ± 0.025	0.12	0.050 ± 0.034	0.042 ± 0.038	0.22	0.12 ± 0.07	0.11 ± 0.078	0.13	0.652	0.01
	Hip	1st Peak	0.71 ± 0.09	0.79 ± 0.14	**0.62***	0.60 ± 0.08	0.68 ± 0.10	**0.82***	0.81 ± 0.16	0.82 ± 0.12	0.05	0.180	**0.07***
		Impulse Stance	0.25 ± 0.05	0.29 ± 0.06	**0.72***	0.32 ± 0.10	0.36 ± 0.12	0.35	0.43 ± 0.09	0.45 ± 0.14	0.21	0.309	0.04

LFFL = low functional fitness level group; HFFL = high functional fitness level group; Imp 1: impulse 1 computed during the time interval of the braking phase of the anterior-posterior ground reaction force curve; Imp 2: impulse 2computed during the time interval of the propulsive phase of the anterior-posterior ground reaction force curve.

* $|d| > 0.5$ or $\eta^2_p > 0.06$ – medium effect size, here considered as clinical relevant differences between group means

‡ $p < 0.05$ – statistical significant differences between groups

5.4 Discussion

The purposes of this study were to characterize and compare sagittal and frontal lower limb joint moment patterns in three different functional tasks (level walking, stair ascent and stair descent) within a group of older adults and to verify the influence of subjects' functional fitness level in those task patterns.

Few studies have been done which encompass sagittal and frontal plane lower limb joint moments of force during these locomotor tasks, especially in what concerns the elderly population (Novak & Brouwer, 2011). Also, studies usually are performed in order to find differences between different age groups (young vs old) (DeVita & Hortobagyi, 2000; Kerrigan et al., 1998; Novak & Brouwer, 2011; Reeves et al., 2008, 2009), when changes in gait patterns may be associated with mobility impairments rather than age alone. To our knowledge, this study is the first aiming to analyze the influence of functional fitness level on joint moment patterns within the elderly. The small size of the subgroups (LFFL and HFFL) is a recognized limitation. As so, to better understand the magnitude of the differences found, even if not statistically significant, our analysis was complemented with the computation of effect sizes. Additionally, apart from functional fitness level, the subgroups were homogenous and walked at similar velocities, a fact that strengthens our results. Thus, we believe this study has a significant contribution, not only for the knowledge of the strategies adopted by the elderly while performing different locomotor activities, as well as for the influence of functional fitness level on those strategies.

The present study showed that, in general, the strategies adopted by the elderly subjects in the sagittal plane were similar to the ones reported for young adult subjects when performing these locomotor tasks, although joint moments' magnitudes differed (McFadyen & Winter, 1988; Nadeau et al., 2003; Riener, Rabuffetti, & Frigo, 2002). Specifically, ankle plantarflexor moment peak during the push off was higher for the walking task, while plantarflexor rotational impulses were higher for both SA and SD tasks. Comparing with level walking, when dealing with stairs step length is reduced due to the geometry of the stair case, and therefore there is no need for such a vigorous push off. However, during these tasks higher plantaflexor moments are produced in the first half of the stance in order to propel the body upward or to absorb the energy derived from the lowering of the body (McFadyen & Winter, 1988), and thus higher impulses are needed. Also in accordance with previous studies (McFadyen & Winter, 1988; Nadeau et al., 2003; Riener et al., 2002), when compared with level walking, stair walking required the production of higher knee joint moments. In particular, the elderly subjects produced a higher knee rotational impulse during the pull up phase in the SA task, as well as throughout stance in the SD task, especially during the controlled lowering phase. Still in agreement with the literature (McFadyen & Winter, 1988; Nadeau et al., 2003; Riener et al., 2002), a higher hip extensor impulse was required during the first half of the stance to perform the SA task, higher hip flexion moments were produced during the second half of the stance while walking, and hip moments produced during the SD task were very small.

In the frontal plane, joint moment demands were higher for the stair tasks, especially for SD, when compared to walking. There are not many studies reporting frontal plane joint moments and the curve patterns presented are somewhat different between studies (Kowalk et al., 1996; Nadeau et al., 2003; Novak & Brouwer, 2011). In general, joint moment curve patterns in the frontal plane for SA and SD presented in this study have more agreement with the study of Novak & Brouwer (2011), although our results show larger ankle adduction moments in both tasks.

This study also revealed that the strategies adopted by the elderly during these different locomotor tasks varied according to their functional fitness level. Namely, the LFFL group consistently applied a higher hip extensor impulse and a lower plantarflexor joint moment in all the locomotor tasks performed. A similar redistribution of joint moments has been reported by DeVita & Hortobagyi (2000), when comparing old with young subjects while walking. These authors also reported that older adults, when compared to their younger counterparts, applied a lower knee extensor moment peak. Interestingly, in this study, although this difference was not found for walking, the LFFL group demonstrated a reduced knee extensor moment peak during the phases of higher demand in both SA and SD tasks. Furthermore, this redistribution of joint moments was in accordance with the posture adopted by the LFFL group subjects, who consistently walked with a more flexed hip, a higher pelvis anteversion and with a more forward trunk lean, in all tasks.

Regarding the frontal plane the LFFL group applied lower hip abductor moments, especially during walking and SA, which contrasts with what was found by Novak & Brouwer (2011), when comparing young and old subjects. The authors found that, when compared with their younger counterparts, older adults apply higher hip abductor moments at the end of the stance during both SA and SD tasks, a fact that they interpreted as a way to enhance perceived stability. In our study, the LFFL group applied lower hip abductor moment than the HFFL group. The higher abductor hip angle that the LFFL group showed during the same time period suggests that they were probably looking for a safe clearance of the contralateral limb.

To conclude, this study showed that the strategies adopted by older persons when performing locomotor tasks depend on their functional fitness level. In general, during these activities, older subjects with a lower functional fitness level score produce higher hip extensor moments and lower ankle plantaflexor moments. Further, in more demanding tasks (SA and SD) knee extensor moments also seem to be reduced. This redistribution of joint moments is in accordance with the more flexed posture that this group seems to adopt, probably looking for more stability (to compensate their poorer lower limb strength and balance). In the frontal plane, the LFFL group applied lower hip abductor moments, especially while walking and SA, which together with the more abducted hip shown by these subjects during this time period, seem to disclose a strategy to guarantee a safe clearance of the contralateral limb. As the performance of locomotor activities is determinant to preserve mobility and quality of life in the elderly, these gait patterns changes yield important information for the development of rehabilitation programs by the health and exercise professionals working with this population.

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Conflict of interest statement

The authors declare that they have no conflict of interests associated with this paper.

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6

Using induced accelerations to analyze gait in the elderly

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CHAPTER

Abstract

The purpose of this study was to use induced acceleration analysis to quantify the contributions of the lower extremity joint moments to the center of mass forward progression and support during gait in the elderly. Three healthy and active subjects (72.7±4.0y), with no gait pathology and no history of falls in the previous year, were tested. A seven segments model (two feet, two shanks, two thighs and a single head-arms-trunk) was built and optimized through inverse kinematics. Variables computed included spatial-temporal gait variables, lower limb joint angular displacements, lower limb joint moments and induced accelerations generated by lower limb joint moments on the center of mass forward and vertical accelerations. Although the tested older adults showed the typical kinematic and kinetic changes in pattern reported for this population, their strategy to accelerate the center of mass forward and vertically seems to be similar to the one reported for young adults. Specifically: (1) ankle plantarflexors joint moments are the largest contributors for both forward and vertical induced CoM acceleration; (2) the magnitude of the induced accelerations generated for both horizontal and vertical directions was somewhat lower compared to those reported for young adults; (3) forward progression seems to be generated by active push-off mainly due to plantar flexors action; and (4) neither the swing limb joint moments nor gravity seem to significantly contribute to the forward center of mass acceleration.

Keywords: Elderly, Gait, Joint moments, Forward and vertical accelerations.

6.1 Introduction

With the increase of life expectancy in the industrialized World and, as a consequence, the increase of the percentage of elderly within the total population in these countries, public health concerns have been changing and adapting to this new reality. It is reported in the Health Evidence Network Report (Todd & Skelton, 2004) that approximately 30% of people over 65 fall each year, and for those over 75 the rates are even higher.

Several risk factors have been related to falling (Todd & Skelton, 2004) and, among these, lower limb muscle weakness and gait and balance deficit seem to have a preponderant role (Rubenstein, 2006).

Biomechanical changes in elderly gait pattern have been reported since the 90s (Prince, Corriveau, Hébert, & Winter, 1997; Winter, 1991). However, an inverse dynamics analysis on its own gives a qualitative description of the strategies used to compensate for neuromuscular losses that occur with aging. On the other hand, induced acceleration analysis (IAA) allows the direct quantification of a joint moment contribution (or muscle force) on the acceleration of each body segment and has proven to be a powerful clinical assessment tool (Kepple, Siegel, & Stanhope, 1997; Siegel, Kepple, & Stanhope, 2006). This technique is based on the principles outlined by Zajac & Gordon (1989), who have proven that the joint moments produced by muscles that span a certain joint will generate acceleration in all body joints.

Until now, IAA has not been used to analyze elderly gait pattern. Therefore, the purpose of this study was to use IAA to quantify the contributions of the lower extremity joint moments to the center of mass progression (forward centre of mass (CoM) acceleration) and support (vertical CoM acceleration) during gait in the elderly.

6.2 Methods

Three healthy and active subjects, two women and one man, with more than 65y (72.7 ± 4.0y), no neurologic or other condition that would affect their gait pattern and without any history of falls in the previous year, accepted to participate in this study. Immediately prior to data collection, all participants were informed about the study, accepted to participate and signed the informed consent. The Ethics Committee of the Faculty of Human Kinetics approved the study protocol.

Data collection included the following assessments:

(1) Health perception and falls questionnaire: subjects were asked about their demographic data, general health, medication intake and fall history.

(2) Physical Activity questionnaire: quantification of daily physical activity duration and intensity was done through the Yale Physical Activity Questionnaire (YPAS) created by Dipietro, Caspersen, Ostfeld, & Nadel (1993).

(3) Functional Fitness tests: lower limb strength, power and coordination were assessed through the 8 feet Up & Go (UG) test and the Chair Stand (CS) test from Senior Fitness Test (SFT) battery (Rikli & Jones, 1999); and balance was assessed through items 4 – step up and over, 5 – tandem walk, 6 – stand on one leg and 7 – stand on foam eyes closed, of FAB Scale (Rose, Lucchese, & Wiersma, 2006).

(4) Anthropometric measures: subjects body mass, stature and trochanteric height were obtained according to ISAK (Marfell-Jones, Olds, Stewart, & Carter, 2006).

(5) Gait kinematics and kinetics: collected with a Qualisys Track Manager system (Qualisys AB, Gothenburg, Sweden) with 12 infrared, high speed cameras (Qualisys Oqus 300, Qualisys AB, Gothenburg, Sweden) working at a frequency of 200 Hz and synchronized with two Kistler force plates (9281B and 9283U014 Kistler Instruments Ltd, Winterthur, Switzerland). Subjects were asked to walk naturally, at a self selected speed. Prior to data collection training trials were done so that the subjects would become comfortable with the task.

All the described procedures were standardized and trained following authors' recommendations. Two trials from each subject, in which both feet contacted the force plates (starting with the left foot), were selected to be analyzed.

A fourth order Butterworth filter was used for both kinematic and kinetic data. Filter cut-off frequencies were determined by analysing the *Fast Fourier Transform* of each marker position/time curve. Marker's trajectories and force plate signals were filtered with a cut-off frequency of 10Hz (the same value was applied based on the work done by Van Den Bogert & Koning (1996)).

Data processing was performed through a continuous pipeline developed under Visual 3D software (Professional Version v4.80.00, C-Motion, Inc, Rockville, USA). An 7 segments model (two feet, two shanks, two thighs and a single head-arms-trunk) was built and optimized through inverse kinematics (Lu & O'Connor, 1999). Computed gait variables included spatial-temporal variables, lower limb joint angular displacements and joint moments. IAA was processed based on the method stated by Kepple et al. (1997), being the forward acceleration data only evaluated when the combined ground reaction force obtained from the two force platforms was anteriorly directed (~35-55% of the gait cycle (GC)), i.e. when the centre of mass was being accelerated forward. The support data evaluated from right toe off until the end of the GC, when it was possible to have force data from both platforms. For IAA the foot was fixed to the floor during foot flat and allowed to rotate about the centre of pressure for the rest of the time in accordance with Kepple, Siegel, & Steven J. Stanhope (2002). The accuracy of the model was measured for each subject by computing the absolute differences between the CoM acceleration derived from the force platform and the one induced through the model. The mean anterior-posterior error ranged from 0.06 to 0.07 m/s^2 and the mean vertical errors from 0.124 to 0.256 m/s^2. For all the subjects the mean errors were less than 5% of the total range of accelerations.

6.3 Results and Discussion

Study participants had a Body Mass Index of 28.1±5.0 Kg/m^2 (body mass: 63.2±4.1Kg and body height: 1.58±0.6m). Following steps 1 to 3 from data collection it was possible to verify that all the subjects were active (completing more than 30 minutes of moderate daily physical activity in all week days) had a good functional fitness level

(UG average test results: 4.71±0.47sec; CS average test results: 17.00±1.00 times in 30sec; Total Balance Test Score: 15.00 ± 1.00) and no history of falls.

Typically analyzed gait variables can be seen on table 6.1. Except for the duration of the support and double support phases, which values were similar to those reported for young adults (Prince et al., 1997; Winter, 1991), the results obtained for the gait variables are in accordance with the ones reported for old people by the mentioned authors. This means a reduction in stride length, stride velocity and horizontal reaction force peak at push-off, changes that are normally associated with a safer gait pattern (looking for more stability with a less vigorous push-off).

Table 6.1: Kinematic and kinetic gait variables

	$\bar{X}$	sd	$\tilde{X}$
Support Duration (% GC)‡	60.3	1.3	60.5
Double Support Duration (% GC) ‡	20.7	2.5	21.0
Stride Length (m)	1.23	0.04	1.25
Normalized Stride Length (m)*	0.78	0.01	0.78
Stride Velocity (m/s)	1.27	0.09	1.32
Normalized Stride Velocity (stature/s)*	0.80	0.03	0.81
Left GRF push-off peak Y (N/Kg)¥	1.76	0.06	1.79
Right GRF push-off peak Y (N/Kg) ¥	1.71	0.13	1.66

* Normalized to stature ¥ Normalized to body mass ‡ Normalized to CG duration
GC – Gait Cycle; ROM – Range of Motion; GRF – Ground Reaction Force

Joint moment data from lower limb in the sagittal plane (figure 6.1) also agrees with the reported elderly data (Winter, 1991): the shape of the curves is similar but plantar flexor moment peak is somewhat inferior in the elderly, probably related to a less vigorous push-off.

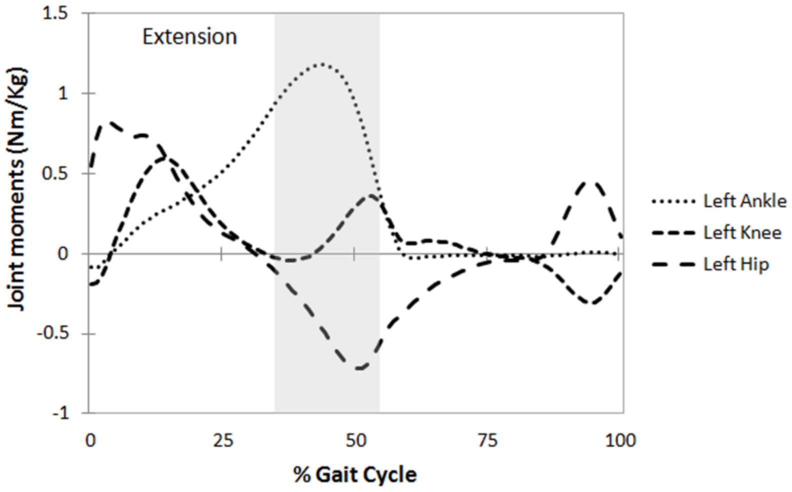

Figure 6.1: Mean (n=3) lower limb joint moments in sagittal plane as a % of gait cycle (GC) time. Forward acceleration interval is in grey

As was previously mentioned, reporting the observed gait pattern changes allow us to infer some of the functional consequences but with induced acceleration analysis we can actually quantify the contribution of each joint moment to the acceleration of a body segment and/or to the body CoM. Figure 6.2 shows the CoM induced accelerations (A – horizontal acceleration; B – vertical acceleration) for the tested elderly.

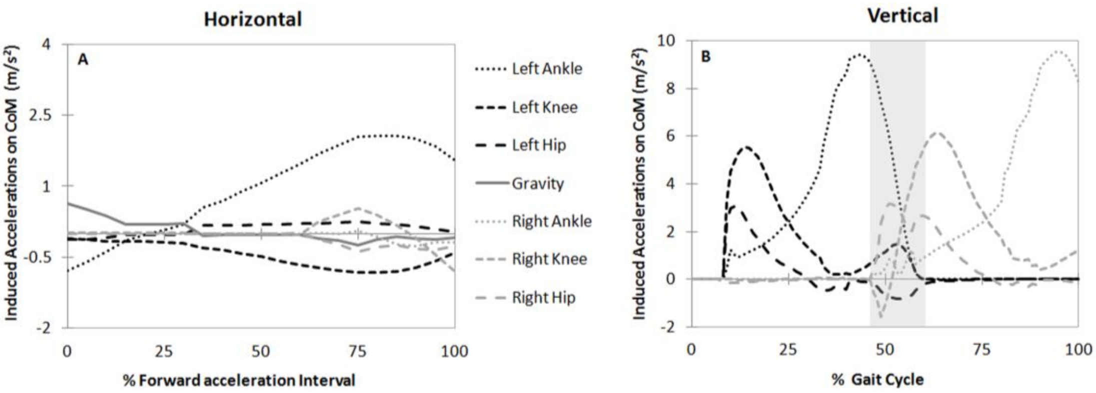

Figure 6.2: (A) Mean (n=3) induced horizontal acceleration on CoM during forward acceleration interval (~35-55% of total GC); (B) Mean (n=3) induced vertical acceleration on CoM during gait cycle (data computed only after right toe off ~10% GC; double support phase is in grey)

As can be observed in figure 6.2 (A), the left ankle moment was the largest contributor for forward acceleration and this contribution starts before the *push-off* phase (~45-65% GC, thus starting on ~50% of forward acceleration interval), when the plantarflexors are acting eccentrically. This fact was also reported by Kepple et al. (1997) when testing adults, who explained that the reaction force produced by a joint moment is transmitted through the segments chain and is independent of the velocity, i.e. independent of the contraction type. Thus, even though the moment is eccentric, it is able to accelerate other joints and/or the centre of mass. The same author also concluded that knee joint moment would also contribute to forward acceleration during the push-off and, in our study, this contribution is not observed. In fact, the knee joint moment produced a negative CoM acceleration, indicating that the knee joint moment has a different role, other than the generation of forward progression. This difference was probably due to the fact that, in the mentioned study (Kepple et al., 1997), the authors have quantified the lower limb joint moments' contributions to the acceleration of the head-arms-trunk segment, rather than the CoM acceleration.

In accordance with the results obtained from the aforementioned authors, we can also see for horizontal IAA results of our study that the combined right knee and right hip moments generated only a small amount of forward acceleration (the accelerations produced negate each other) and gravity is not the primary source of forward acceleration.

On figure 6.2(B) it is possible to observe that ankle joint moments are also the largest contributors to support, especially during mid and late stance, while the contribution of knee and hip moments is higher at the beginning of the stance. These results are also in accordance to Kepple et al. (1997) although the magnitudes of the induced accelerations are clearly smaller.

Conclusion

The purpose of this study was to use IAA to quantify the contributions of the lower extremity joint moments to the center of mass progression (forward centre of mass (CoM) acceleration) and support (vertical CoM acceleration) during gait in the elderly. The IAA approach may be of great value for fall prevention exercise programs in this population, as it allows to measure directly the effect of lower limb function on the attainment of the main functions of gait.

Although the tested older adults showed the typical kinematic and kinetic changes in pattern reported for this population, their strategy to accelerate the center of mass forward and vertically seems to be similar to the one reported for young adults (Kepple et al., 1997). Specifically: (1) ankle plantarflexors joint moments are the largest contributors for both forward and vertical induced CoM acceleration; (2) the magnitude of the induced accelerations generated for both horizontal and vertical directions was somewhat lower compared to those reported for young adults (Kepple et al. (1997)); (3) forward progression seems to be generated by active push-off mainly due to plantar flexors action, like it was suggested by Winter (1991); (4) neither the swing limb joint moments nor gravity seem to significantly contribute to the forward CoM acceleration.

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7

General Discussion

CHAPTER

This thesis aimed to provide a better understanding on the determinant factors for falling in Portuguese older adults, with a special emphasis on the biomechanical changes in gait patterns associated with the functional fitness decline in this population. Our methodological approach to this problem encompassed two different levels of analysis: in the first part two epidemiological studies were conducted in order to establish the determinant factors for falling within the Portuguese older adults (1); in the second part three laboratory-based studies were performed in order to determine the influence of functional fitness levels on elderly gait patterns (2). In this chapter, the main findings of each thesis study are summarized and discussed, though without the detail of the previous presented discussions (chapters 2 to 6). General methodological issues concerning the presented studies are also discussed and recommendations for future research are provided.

7.1 Summary of the main findings

The first part of this thesis focused on the determination of risk factors for falling (episodically and recurrently) in Portuguese older adults. To our knowledge, the epidemiological studies presented in this thesis (chapters 2 and 3) were the first population-based studies which characterized a cohort of Portuguese older adults and identified fall risk factors in this population.

The accomplishment of this goal would not have been possible without having a team of examiners collecting data. Consequently, one of the goals of the first study (chapter 2) was to describe all protocols and procedures followed and to assess the reproducibility and the convergent validity of the physical activity and functional fitness tests used. Repeatability results ranged from good to excellent for both functional fitness and physical activity parameters, while the convergent validity of these tools showed satisfactory to good results for field application. Further validation and cultural adaptation details regarding the field measurements were not the primary aim of this thesis and may be consulted elsewhere (Tavares, 2011; Valente, 2012).

In what concerns fall determinant factors in Portuguese older adults, these two initial studies (chapters 2 and 3) showed consistent results. Agreeing with the literature (Lord, Sherrington, Menz, & Close, 2007; Todd & Skelton, 2004; World Health Organization, 2007), falls were shown to result from the interaction of many risk factors. Within these, gender, functional fitness level and health parameters (especially fear of falling) were found to be the strongest fall determinants, even after adjusting for possible confounders by using multifactorial models. Medication intake and health perceptions (general and visual) were shown to be the factors that distinguished episodic from recurrent falls, which implies that the latest are more associated with comorbidities and less likely to occur due to extrinsic causes. Physical activity parameters were only determinant for falling episodically, after adjusting for possible confounders. Even though, the importance of these parameters in fall risk assessment and prevention programs should not be underestimated, given the role of physical activity on preventing functional fitness decline, clinical diseases and fear of falling (Cress et al., 1999; Rubenstein et al., 2000; U.S. Department of Health and Human Services, 1996; Zijlstra et al., 2007).

Other two important results of these studies (chapter 2 and 3) were that falls occurred mostly while performing locomotor tasks (walking, dealing with stairs or obstacles) and that age was not a determinant factor for falling, even when the cut-off values used represented very old individuals (≥75 years or ≥80 years). These results reinforced the need of characterizing elderly gait patterns according with their functional fitness levels, rather than age alone. In order to have a better insight about elderly gait patterns and the influence of functional fitness in those patterns, a laboratory study was conducted in which three different functional tasks (walking, stair ascent and stair descent) were assessed throughout instrumented gait analysis.

Instrumented gait analysis is particularly challenging when testing older adults due to the changes in body height and lean mass which occur with ageing (Sorkin, Muller, & Andres, 1999). These body composition changes, not only make the anatomical landmark palpation more difficult, but also introduce more soft tissue artifact when capturing the movement, two main sources of error related with this type of analysis (Leardini, Chiari, Della Croce, & Cappozzo, 2005). The study presented on chapter 4 intended to provide a better foundation on the decision making process related to the kinematic model to study elderly gait patterns, so that the mentioned artifacts are minimized. To accomplish this goal, three different models were built and the RMS differences in joint angles and moments between those models were computed. In one of the models, each segment was considered independent and with six degrees of freedom (segment optimization, SO) (Cappozzo, Cappello, Della Croce, & Pensalfini, 1997; Spoor & Veldpaus, 1980). In the other two models, global optimization was used, following Lu and O'Connor's method (Lu & O'Connor, 1999), with different joint constraints: 1) allowing all joint rotations (X, flexion/extension; Y, abduction/adduction; and Z, internal/external rotation), but restraining all joints' translations (GO); 2) allowing three rotations at the hip, one at the knee (flexion/extension) and two at the ankle (dorsi/plantar flexion, and external/internal rotation), while also restraining all joints' translations (GOR). The results showed that joint angles are more sensitive to the model's constraints than joint moments and that the more restrictive the model, the higher the differences between models, especially for the frontal and transverse planes. Additionally, with the exception of knee abduction/adduction angle, differences between SO and GO models were relatively small. Given the good accordance found between SO and GO, the recognized need of substantial effort in the frontal plane to successfully perform stairs tasks (Kowalk, Duncan, & Vaughan, 1996; Nadeau, McFadyen, & Malouin, 2003), and the GO model's ability to avoid the non-anatomical dislocations sometimes observed for SO due to soft tissue artifact, the GO model was chosen to perform the study presented on chapter 5.

The mentioned study (chapter 5) aimed to contribute to the characterization of sagittal and frontal lower limb joint moment patterns in three different functional tasks (level walking, stair ascent and stair descent) within a group of older adults; and to verify the influence of subjects' functional fitness level in those task patterns. To achieve this goal, two functional fitness levels were defined, within this group, according to the median of a total functional fitness score (22 scale points). This score was computed following the population-based functional fitness results obtained in the epidemiological study of chapter 3. Interestingly, the older adults able to perform all the laboratory tests (able to walk without stepping on the same force platform with both feet and able to ascend and descend the stairs, without using the handrail, in a step over step pattern) had a total functional fitness score of 17 points or higher, which was the cut-off value distinguishing good and bad functional fitness levels in chapter 3. This means that our laboratory sample was formed by older adults who scored above the population median (within Portuguese community dwelling older adults) in terms of functional fitness level.

Therefore it is not surprising that the elderly participants tested on the laboratory studies (namely on chapter 5) were very homogenous and that the defined functional fitness level subgroups did not differed in terms of age, body mass index, medication intake, falls, total physical activity time and tasks performance velocity.

One of the most consistent findings when testing elderly walking patterns is that older adults walk slower than younger adults (Prince, Corriveau, Hébert, & Winter, 1997). Because of this, scientists have been trying to determine if the detected changes in gait patterns result from the slower speed or from specific impairments (Kerrigan, Todd, Della Croce, Lipsitz, & Collins, 1998). Thus, the fact that our sample was very homogenous and that the tested elderly performed the tasks at a similar velocity, allowed us to point out specific gait patterns changes associated with different functional fitness levels.

The results showed that older subjects with a lower functional fitness level score consistently produced higher hip extensor moments and lower ankle plantaflexor moments when performing the tested locomotor tasks. Further, in more demanding tasks (stair ascent and stair descent) knee extensor moments were also reduced. This redistribution of joint moments is in accordance with the more flexed posture that this group seems to adopt, probably looking for more stability (to compensate their poorer lower limb strength and balance). In the frontal plane, this group also applied lower hip abductor moments, especially while walking and ascending stairs, which together with the more abducted hip shown by these subjects during this time period, seems to disclose a strategy to guarantee a safe clearance of the contralateral limb. These results were corroborated and complemented with an exploratory study in which we have used unsupervised learning techniques to determine the most relevant features to distinguish functional fitness levels (appendix 2).

These biomechanical gait pattern changes may yield important information for the development of rehabilitation and exercise programs by the health and exercise professionals working with older adults, not only because there is no *one-size-fits-all* intervention in what concerns fall prevention within this population (Rose, 2008), but also because the success of physical activity interventions is dependent on subgroup characterization (King, Rejeski, & Buchner, 1998).

Using an inverse dynamics approach on chapter 5 we were able to infer the strategies adopted by a group of elderly subjects while performing different locomotor tasks and to associate some differences in those strategies with functional fitness level. Although this study yielded valuable information for our problem, with the mentioned approach it is not possible to directly quantify the influence of those joint moment changes on the attainment of gait main functions like the generation of forward velocity (forward acceleration) and the vertical support of the body (vertical acceleration).

In chapter 6 we have performed an exploratory study to directly quantify each joint moment contribution for the forward and vertical center of mass accelerations during walking, thus complementing our analysis. The 3 older adults tested in this study had high functional fitness level, were physically active and seemed to demonstrate the typical changes in the walking pattern referred for older adults in the literature (Prince et al., 1997; Kerrigan et al., 1998; Winter, Patla, Frank, & Walt, 1990; DeVita & Hortobagyi, 2000). This means that, comparing with younger adults, these subjects showed a reduction in stride length, stride velocity, horizontal reaction force peak at push-off and plantarflexor joint moment peak. Despite of this fact, the induced acceleration patterns determined for these elders were similar (although differing in magnitude) with the ones reported for younger adults (Kepple, Siegel, & Stanhope, 1997). Specifically, ankle plantarflexor moments were still the main contributors for both forward and vertical center of mass acceleration and the knee and hip extensor moments also showed to contribute to antigravity support, especially at the beginning of the stance. Furthermore, the estimated contributions to forward progression from all the other joint moments of the support limb, swing limb and gravity, were relatively small.

In summary, although the tested elderly participants showed the typical kinematic and kinetic changes in pattern reported for this population, their strategy to accelerate the center of mass vertically and forward seems to be similar to the one reported for young adults. Therefore, induced acceleration analysis may be a promising tool for complementing the inverse dynamics approach to study elderly lower limb function and joint coordination when performing locomotor tasks, but more thorough studies are needed in order to reinforce these preliminary results.

7.2 Methodological considerations

Although the materials and methods used to perform the studies included in this thesis are described with detail in each of the studies (chapter 2 to 6) there are still some noteworthy methodological considerations which will be addressed in the following paragraphs.

Falls ascertainment

The epidemiological studies of this thesis are referred to the baseline period of the research project “Biomechanics of Locomotion in Elderly People. Relevant Variables for Risk of Fracture Reduction” (PTDC/DES/72946/2006) and, therefore, had a retrospective design. As a consequence, in order to measure falls frequency, older adults were asked how many times they had fallen in the previous year. This type of design is not ideal to ascertain falls frequency, as the ability to recall falls is a concern within community dwelling older adults (Ganz, Higashi, & Rubenstein, 2005). In order to overcome this limitation, we tested a large sample (n = 1416) at baseline, which represented 0.7% of the Portuguese elderly population.

Moreover, this initial research program was followed by the “More Active Ageing Program” funded by The European Union-Qren-Inalentejo (Alent-07-0262-Feder-001883). In this new project older adults tested at baseline continued to be tested quarterly over a period of 1 year follow-up. The preliminary results show a similar fall frequency (38.5%; n = 93), as well as similar risk factors for falling, to the ones reported in our initial studies, giving us confidence about the strength of our previous conclusions (chapters 2 and 3).

Physical performance tests

Due to the many different tools (from self-reported to performance tests) available to measure older adult’s physical function, the choice of the performance tests used to assess physical capacity in this thesis studies may be questioned.

The lack of non laboratory tests able to detect the physical capacity decline experienced by older adults lead to the development of the Senior Fitness Test (SFT) battery (Rikli & Jones, 1999a). Since then, population normative standards (for American (Rikli & Jones, 1999b) and recently for Portuguese older adults (Marques et al., 2014), as well as criterion reference standards in order to predict the loss of physical independence, have been proposed regarding SFT (Rikli & Jones, 2013). This battery of tests is more focused on fitness measures of strength, flexibility, aerobic endurance and agility (Rikli & Jones, 1999a).

The role of balance impairments on falls and the fact that balance activities became a regular fitness component of elderly exercise programs lead to the development of the Fullerton Advanced Balance (FAB) scale (Rose, Lucchese, & Wiersma, 2006). The FAB scale is mainly focused on the detection of balance impairments within community dwelling older adults and intended to complement other fitness measures developed for older adults (Rose et al., 2006).

In order to minimize the burden related to a large assessment duration, and as the main outcome of the epidemiological studies of this thesis was fall prevalence, within the tests included in these batteries we have chosen the ones with better reported ability to discriminate fallers (Chair Stand test and 8 foot Up-and-Go from SFT and FAB4 to FAB7 form the FAB scale) (Hernandez & Rose, 2008; Rose, Jones, & Lucchese, 2002; Toraman & Yildirim, 2010).

Marker set choice

There are several marker sets used to perform movement analysis (Richards, 2008). The choice of the marker set is determinant for estimating the pose of body segments and thus for assuring the quality of the movement data.

The marker set chosen for the movement analysis studies of this thesis was based on the calibrated anatomical system technique (CAST) proposed by Cappozzo, Catani, Della Croce, & Leardini (1995). Thirty passive markers and four marker clusters were used. Specifically, six markers were placed on the trunk, one on top of each acromion, one on the C7 spinous process and three on the sternum area (placed so that soft tissue artifact and collinearity was avoided). At the pelvis, two markers were placed on each posterior superior iliac spines and two along each iliac crest. A virtual marker was created in each anterior superior iliac spine, using a digitizing pointer, to avoid soft tissue artifact. Markers were also placed on the lateral and medial femur epicondyles, the lateral and medial ankle malleoli and on the top of the first and fifth metatarsal heads. Each foot had also one marker on the heel, another laterally in the middle of the foot and a third one between the two metatarsal heads. Finally, the mentioned marker clusters were attached to both thighs and shanks (Figure 7.1).

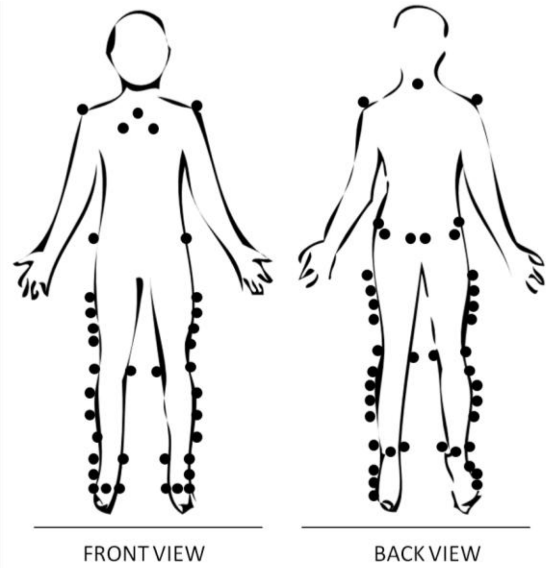

Figure 7.1: Marker set

The choice of this marker set may be questioned since some authors strongly recommend the use of the conventional gait model (also called Helen Hayes model), as it is the most widely used and studied marker set (Baker, 2013).

Simpler marker sets, like the conventional gait model, may have advantages because they require a lower number of markers and cameras for movement tracking (Richards, 2008). Nevertheless, they require the use of *direct pose* estimation algorithms, which are reported to offer the following disadvantages (Robertson, 2014):

- Body segments are defined by 3 markers and no redundancy is allowed. Therefore, if one of the markers is occluded, the segments' pose cannot be estimated.
- These methods do not use the rigid body assumption, being therefore more susceptible to soft tissue artifact.
- Segments pose rely on the joint center of the previous segment of the chain, which starts at the pelvis. This means that an error on pelvis tracking will affect all the other segments.
- As a joint center location is defined, joint translations cannot be measured.

On the other hand, in the CAST each segment may be modeled as independent (6 degrees of freedom) and, although soft tissue artifact is still a concern when using these type of pose estimation algorithms (segment optimization), they were shown to have high repeatability and to overcome the theoretical limitations of the conventional gait model (Collins, Ghoussayni, Ewins, & Kent, 2009). Further, using this technique does not restrain the use of other pose estimation algorithms, like global optimization methods. This allowed us to compare different pose algorithms and to choose the best suited for the study design and sample characteristics of this thesis (chapter 4).

Filter cut-off frequency

The choice of using a cut off frequency of 10 Hz for filtering the data signals could be questioned, since the slower motion velocity warrant a lower cut off frequency and the typically cut off frequency used for walking is 6 Hz (Payton & Barlett, 2008, pp 40; Winter, 2005, pp 47).

Commonly in biomechanical analysis, movement data is filtered with a lower cut-off frequency than force data. This is justified by the fact that force data is considered to be more accurate and, on the contrary of movement data, will not experience noise amplification, as force signals are not differentiated during the inverse dynamics computations. However, recent studies have shown that using different cut off frequencies can generate inconsistencies between the kinematic and the force data and thus, the use of the same cut-off frequency when combining kinematic and force data (e.g. in inverse dynamics computations) is recommended (Bisseling & Hof, 2006; Kristianslund, Krosshaug, & van den Bogert, 2012; Van Den Bogert & Koning, 1996).

In a preliminary analysis using the data from 3 participants, we have compared joint angles, joint velocities, ground reaction forces and joint moment curves, filtered with four different cut-off frequencies (4 Hz, 6 Hz, 10 Hz and 15 Hz) and verified that the best compromise, in order not to over smooth (verified through curve distortion) nor to under smooth (verified by the presence of non physiological peaks) the data, was the 10 Hz cut-off frequency. Furthermore, we have also analyzed, in these subjects, the power spectrum density using a Fast Fourier Transform of each marker position/time curves, and verified that, especially for the foot markers, the curve will flatten closer to the 10 Hz frequency than to the 6Hz frequency.

Following the literature recommendations for data filtering when performing an inverse dynamics analysis (Bisseling & Hof, 2006; Kristianslund et al., 2012; Van Den Bogert & Koning, 1996), and our preliminary tests, we chose to use a cut off frequency of 10 Hz.

Staircase design

A wooden staircase with three steps was built to perform the stair trials. Each step was 15 cm high and 27 cm deep. The last step was extended (80 cm depth) to avoid deceleration during stair climbing. The first force platform was embedded on the floor in front of the staircase while the second was covered by the first step. This step was securely fixed to the second force platform and was built ensuring the rigidity of the structure. Each force platform was independent of the surrounding wooden pieces (Figure 7.2).

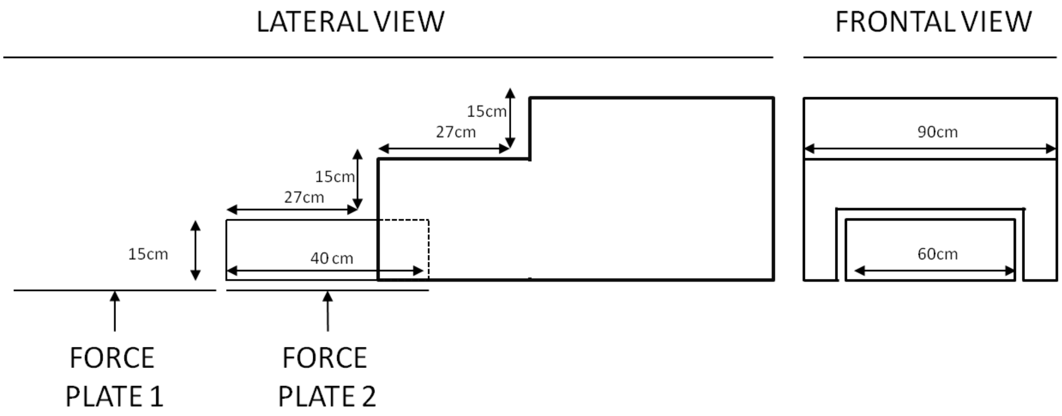

Figure 7.2: Diagram showing the custom-built staircase

Induced acceleration analysis

Induced acceleration analysis is an interpretative method based on the mathematical principles outlined by Zajac & Gordon (1989) which allows the direct quantification of the relative contribution of each joint moment to the acceleration of all body joints and to the body center of mass. This is done by solving the generalized equations of motion in the following form:

$$\ddot{\theta} = M_{joint}\, I^{-1}(\theta) + I^{-1}C\left(\theta, \dot{\theta}\right) + I^{-1}G(\theta)$$

In this equation, $\theta, \dot{\theta}$ and $\ddot{\theta}$ are the vector generalized coordinates, velocities and accelerations, M_{joint} is the matrix containing the joint moments, I^{-1} is the inverse of the inertia matrix, C is the matrix of the Coriolis terms and G is the matrix of the gravitational terms. Each individual joint moment contribution to the angular acceleration of each joint is obtained by setting all the other terms of the equation to zero (C, G and all the joint moments with the exception of the one which contribution is being computed) and solving for $\ddot{\theta}$. For example, the angular accelerations induced by gravity on each joint can be calculated by setting the all joint moments and Coriolis terms to zero. By doing this, we are assuming that each individual joint moment contribution to the joint acceleration may be computed by applying that moment while considering all the other joints to be frictionless, with no moments or stiffness (Kepple et al., 1997). Further, this equation also shows that, as stated by Zajac and Gordon (1989), the magnitude of the acceleration is not only dependent on the joint moment magnitude, but also on the configuration of body segments (I^{-1} (θ)).

Induced acceleration analysis has been criticized by Chen, (2004, 2006), who questioned the capability of this technique to present meaningful descriptions of task function, since its results depend on the model used, namely on the models' degrees-of-freedom.

The influence of the model's degrees-of-freedom on the results is not an exclusive problem of induced acceleration analysis. On chapter 4 of this thesis we have showed how joint angles and moments are sensitive to the model constraints and how the more restrained the model is, the larger the differences found. Some authors like Chen, defend the use of simpler models to perform movement analysis. However, though this type of models may provide useful insight on the basic mechanics of a motor task, they cannot explain muscle coordination and muscle synergies (Felix E Zajac, Neptune, & Kautz, 2003, 2004). Thus the choice of the model will depend on the goal of the study and the complexity of the task.

Induced acceleration analysis, both driven by joint moments (Kepple et al., 1997; Siegel, Kepple, & Stanhope, 2006) or by muscle forces (Anderson & Pandy, 2003; Neptune, Kautz, & Zajac, 2001), has shown to provide a great insight about lower limb function and coordination while walking and therefore its contribution for a better understanding on the factors affecting mobility in older age should not be underestimated.

7.3 Future research

Concerning the first part of this thesis, in which an epidemiological approach was conducted to establish the determinant factors for falling within the Portuguese older adults, future studies should be done in order to establish a cause-effect relationship between falls and respective risk factors, using a prospective cohort study design. Having this foundation, the validation of a falls screening tool able, not only to identify older adults at risk and to distinguish different risk profiles among them, but also feasible in a clinical/exercise setting, seems to be another important future step for the development of successful fall prevention programs within Portuguese older adults.

As the success of the intervention is also dependent on specific subgroup characteristics, namely functional limitations (King et al., 1998), more studies are needed in order to have a better insight about the specific physical capacity limitations leading to gait pattern changes and mobility decline. Induced acceleration analysis, especially muscle induced acceleration analysis, may yield an important contribution to this matter, through the identification of specific muscle coordination changes associated with different functional fitness levels. This will help the development of exercise interventions targeting specific muscle impairments affecting mobility within the elderly population.

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Conferences

Title	ECTs	Grade
Validation of methods and instruments in the assessment of human movement	2.5	N/A
Exercise is Medicine	2.5	N/A
Biomechanics of the neuromuscular system: empirical and modeling approaches and Neuromechanics of locomotion in human and animal models	2.5	N/A
Art, Culture and Society	2.5	N/A

N/A – Not Applicable

Advanced Studies

Title	ECTs	Grade
Validation of methods and instruments in the assessment of human movement	2.5	20/20
Advanced Topics In Skill Acquisition: An Ecological Dynamics Framework	2.5	18/20
Machine Learning: Base Concepts And Applications	2.5	19/20
O_2 Kinetics in Sports Performance	2.5	17/20

Research Methods

Title	ECTs	Grade
Validation of methods and instruments in the assessment of human movement	2.5	20/20
EMG in neuromuscular function	2.5	18/20
Nonlinear methods for studying perception and action	2.5	19/20
In search of the curve: modeling human growth using anthropometric data and Measuring and estimating height and maturation	2.5	17/20

1

Sensitivity of joint kinematics and kinetics to different pose estimation algorithms and joint constraints in the elderly (appendix data)

Vera Moniz-Pereira, Silvia Cabral, Filomena
Carnide and António P. Veloso

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APPENDIX

Stair Ascent

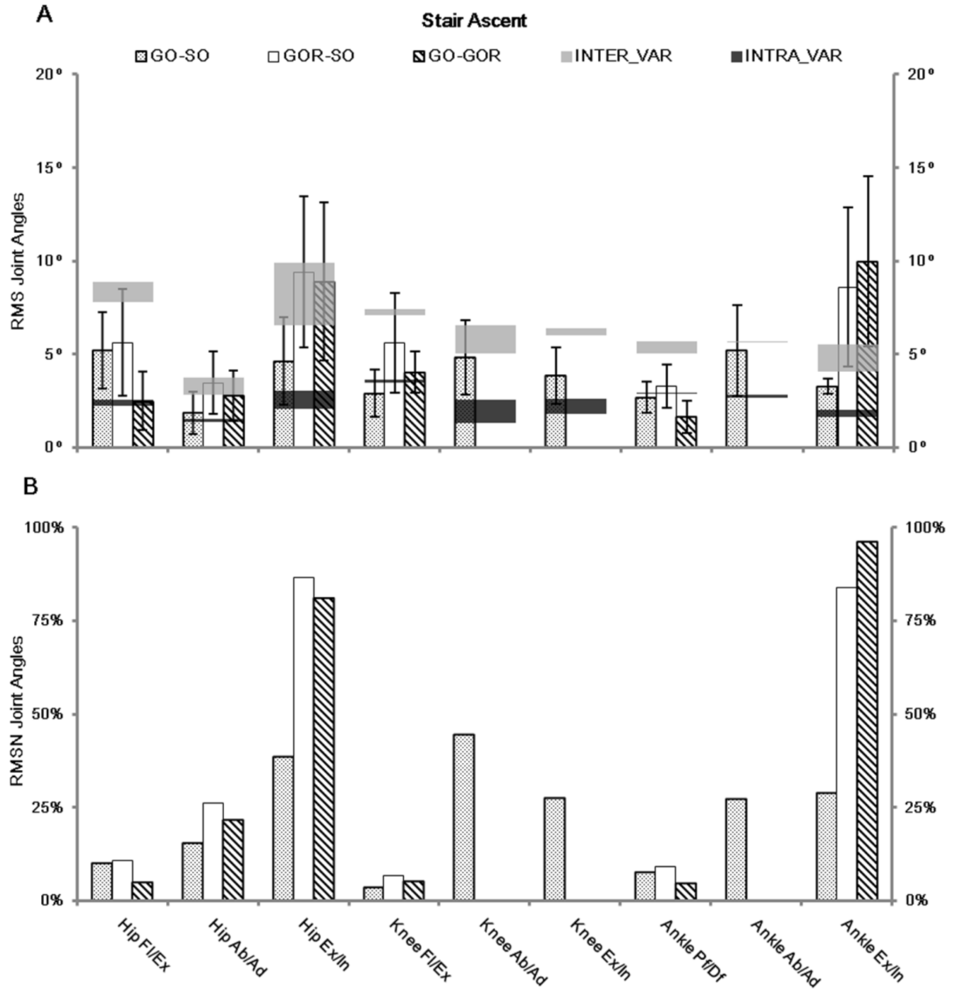

Figure 9.1: Joint angles root mean square (RMS) (A) and normalized RMS (RMSN) (B) differences between methods for the stair ascent task (Fl/Ex, Ab/Ad, Ex/In and Pf/Df stand for flexion/extension, abduction/adduction, external/internal rotations and plantar/dorsiflexion). Maximum and minimum intersubject variability (INTER_VAR) is represented by the gray shadow, while maximum and minimum intrasubject variability (INTRA_VAR) is represented by the black shadow.

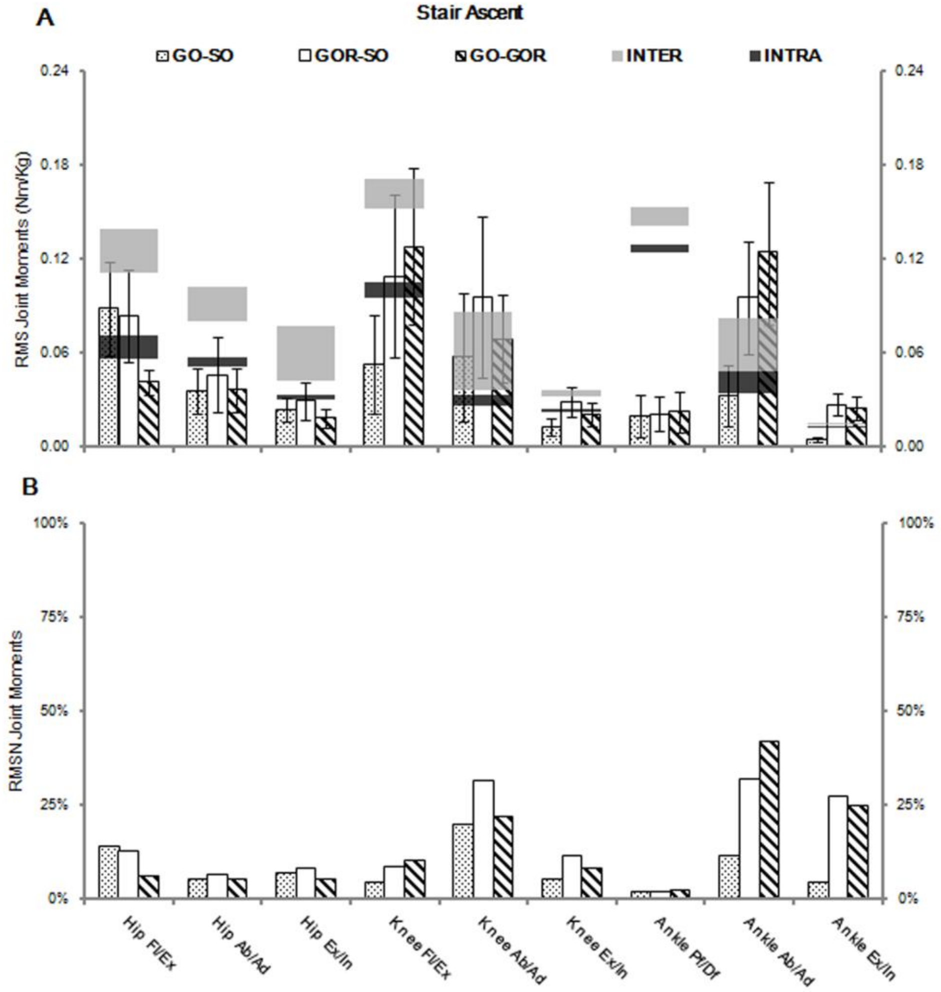

Figure 9.2: Joint moments root mean square (RMS) (A) and normalized RMS (RMSN) (B) differences between methods for the stair ascent task (Fl/Ex, Ab/Ad, Ex/In and Pf/Df stand for flexion/extension, abduction/adduction, external/internal rotations and plantar/dorsiflexion). Maximum and minimum intersubject variability (INTER_VAR) is represented by the gray shadow, while maximum and minimum intrasubject variability (INTRA_VAR) is represented by the black shadow.

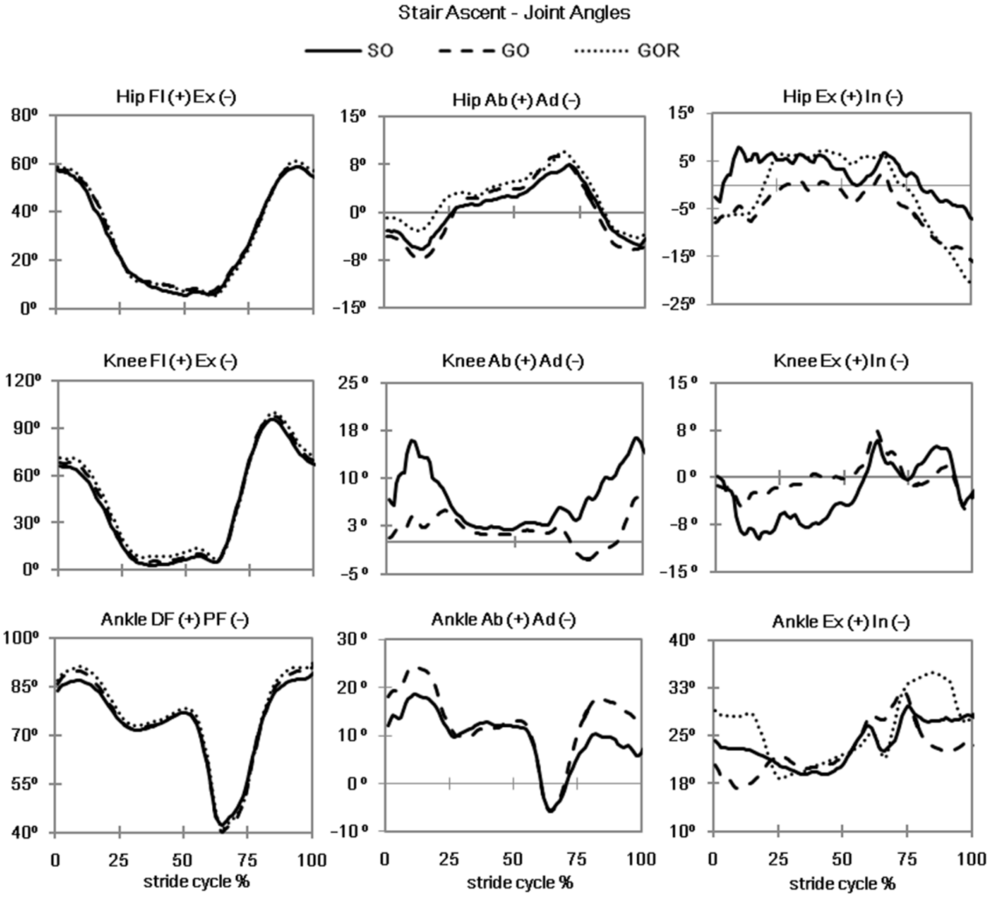

Figure 9.3: Joint angular displacements, of one of the subjects, for the 3 different methods during a stair ascent stride cycle (from right foot contact to right foot contact). Fl/Ex, Ab/Ad, Ex/In and Pf/Df stand for flexion/extension, abduction/adduction, external/internal rotations and plantar/dorsiflexion.

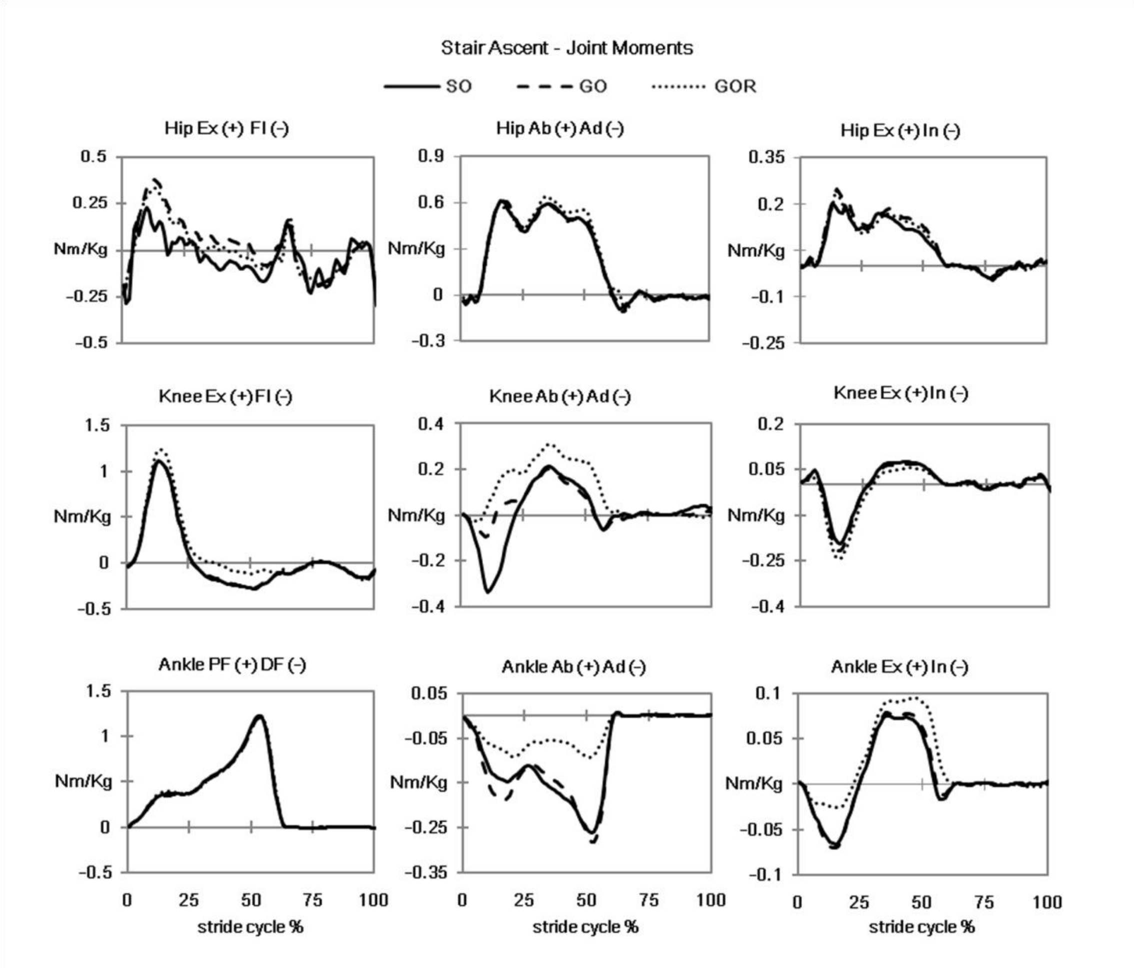

Figure 9.4: Joint moments, of one of the subjects, for the 3 different methods during a stair ascent stride cycle (from right foot contact to right foot contact). Fl/Ex, Ab/Ad, Ex/In and Pf/Df stand for flexion/extension, abduction/adduction, external/internal rotations and plantar/dorsiflexion.

Stair Descent

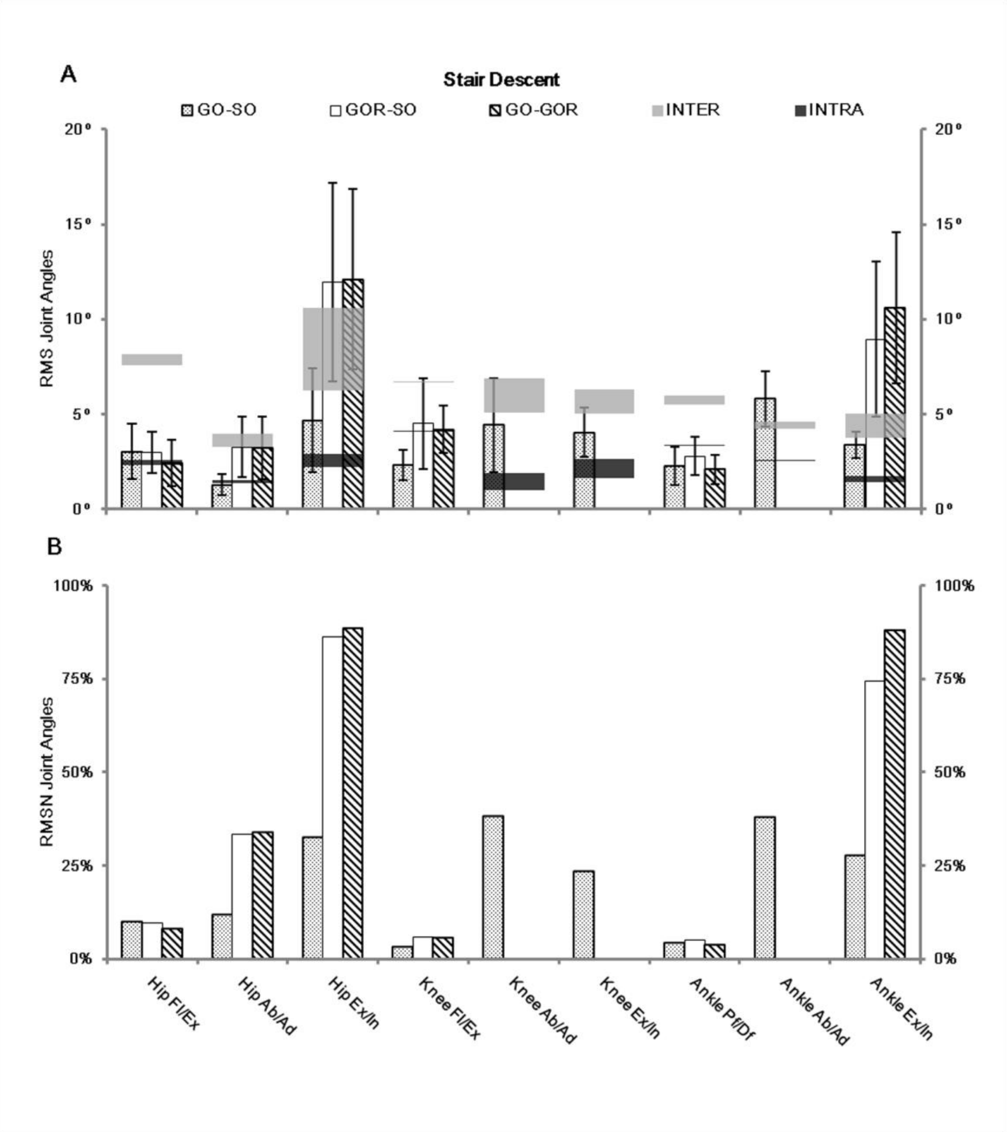

Figure 9.5: Joint angles root mean square (RMS) (A) and normalized RMS (RMSN) (B) differences between methods for the stair descent task (Fl/Ex, Ab/Ad, Ex/In and Pf/Df stand for flexion/extension, abduction/adduction, external/internal rotations and plantar/dorsiflexion). Maximum and minimum intersubject variability (INTER_VAR) is represented by the gray shadow, while maximum and minimum intrasubject variability (INTRA_VAR) is represented by the black shadow.

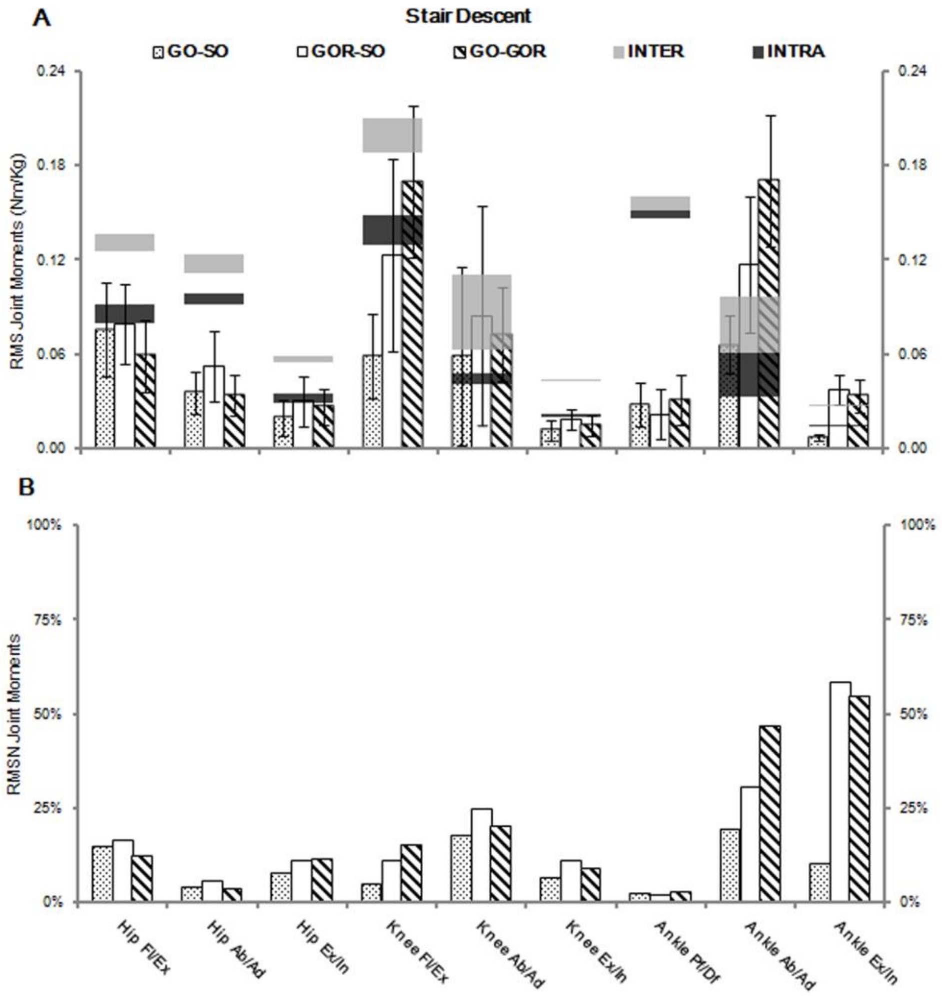

Figure 9.6: Joint moments root mean square (RMS) (A) and normalized RMS (RMSN) (B) differences between methods for the stair descent task (Fl/Ex, Ab/Ad, Ex/In and Pf/Df stand for flexion/extension, abduction/adduction, external/internal rotations and plantar/dorsiflexion). Maximum and minimum intersubject variability (INTER_VAR) is represented by the gray shadow, while maximum and minimum intrasubject variability (INTRA_VAR) is represented by the black shadow.

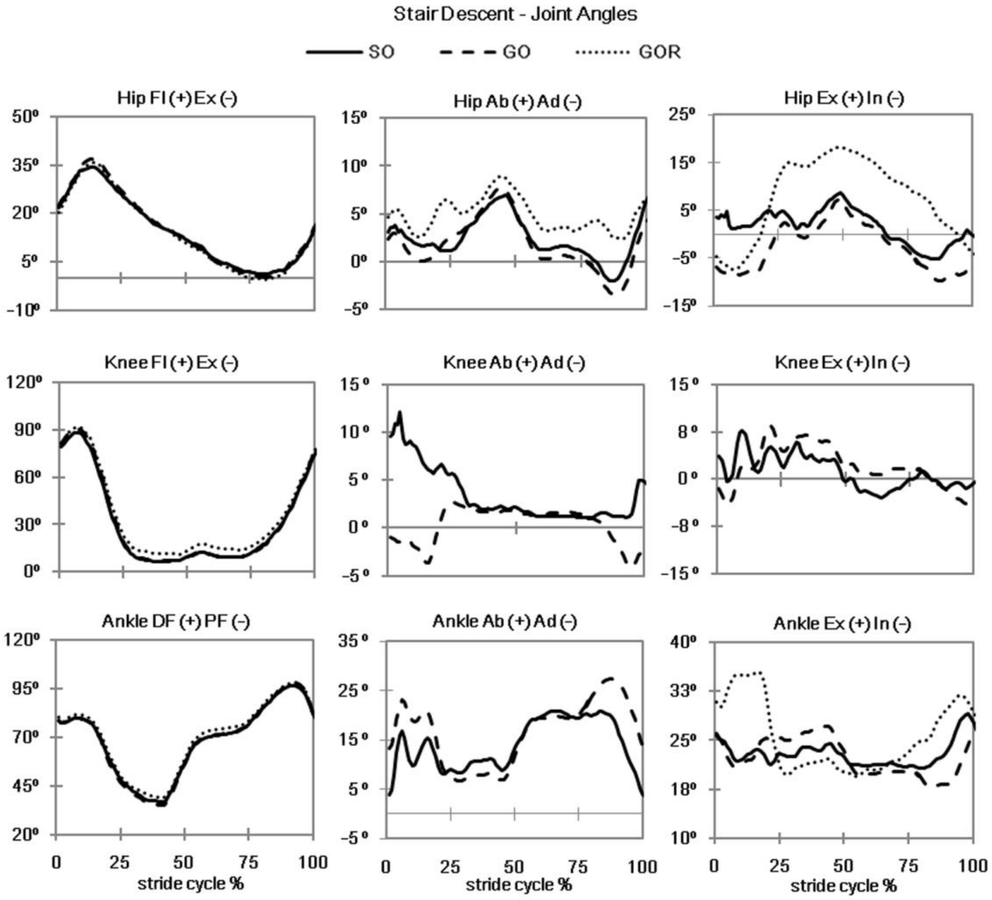

Figure 9.7: Joint angular displacements, of one of the subjects, for the 3 different methods during a stair descent stride cycle (from right foot off to right foot off). Fl/Ex, Ab/Ad, Ex/In and Pf/Df stand for flexion/extension, abduction/adduction, external/internal rotations and plantar/dorsiflexion.

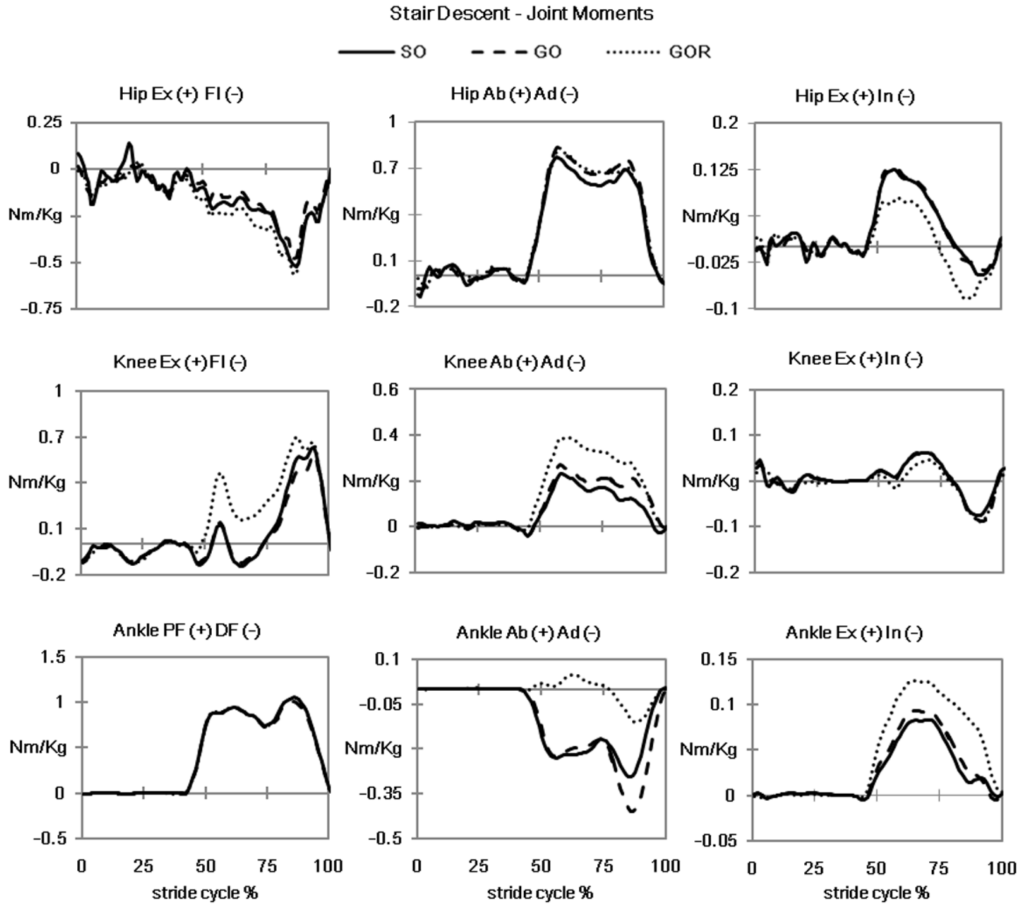

Figure 9.8: Joint moments, of one of the subjects, for the 3 different methods during a stair descent stride cycle (from right foot off to right foot off). Fl/Ex, Ab/Ad, Ex/In and Pf/Df stand for flexion/extension, abduction/adduction, external/internal rotations and plantar/dorsiflexion.

2

Relevant Elderly Gait Features for Functional Fitness Level Grouping

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Relevant Elderly Gait Features for Functional Fitness Level Grouping

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Keywords: Functional Fitness Level, Elderly Population, Clustering, Kinematic and Kinetic Parameters, Feature Selection.

Abstract: Locomotor tasks characterization plays an important role in trying to improve the quality of life of a growing elderly population. This paper focuses on this matter by trying to characterize the locomotion of two population groups with different functional fitness levels (high or low) while executing three different tasks - gait, stair ascent and stair descent. Features were extracted from gait data, and feature selection methods were used in order to get the set of features that allow differentiation between functional fitness level. Unsupervised learning was used to validate the sets obtained and, ultimately, indicated that it is possible to distinguish the two population groups. The sets of best discriminate features for each task are identified and thoroughly analysed.

1 INTRODUCTION

Fall-related morbidity and mortality rates are referred to as one of the most common and serious problems faced by the elderly, affecting around 30% of the population above 65 years (Todd and Skelton, 2004). Several risk factors have been associated with falls, of which lower limb muscle weakness and gait and balance deficit seem to have a preponderant role (Rubenstein, 2006). Accordingly, we have found, in a cohort of 647 Portuguese older adults, that falls might not be an inevitable consequence of ageing and that health, functional fitness and physical activity parameters were the most determinant factors for both episodic and recurrent falls (Moniz-Pereira et al., 2012). Further, we also verified that the majority of the falls occurred in an outdoor setting, and mainly while walking or climbing stairs. Thus, the biomechanical characterization of locomotor tasks in older people with different levels of functional fitness may have an important contribution for the prevention of falls and the improvement of quality of life in this population.

The particular case of locomotion data analysis presents several inherent difficulties (Chau, 2001a), such a: high-dimensionality (several kinetic and kinematic variables acquired through a period of time); temporal dependence (there's a quasi-periodic temporal dependence, being difficult to model); high variability (intrasubject and intersubject); data is typically composed by curves which are hard to correlate, and the relationships between variables are nonlinear.

Usually, gait data analysis is done through statistical studies (Horváth et al., 2001), (Prince et al., 1997) leading to a series of means and standard deviations of the parameters measured for pre-determined population groups, which can be hard to analyse and do not reflect the relative importance of the measures in the problem studied.

Pattern recognition systems have been explored as an alternative way of looking into gait data. Through the analysis of gait patterns it has been possible to detect gait pathologies (Kohle et al., Jun; Hausdorff et al., 1997), fatigue (Janssen et al., 2011), to evaluate the effects of medical procedures on gait (Ishii et al., 1996), or to detect subject's features (age group, fitness level) (Reid et al., 2010). These systems usually require the following sequence of steps: (1) sensing, (2) segmentation and data cleaning, (3) feature extraction, and (4) learning. Learning can be supervised (where training is required and performed using labelled samples) or unsupervised (where the system finds natural groups in data).

One of the steps required in pattern recognition systems is feature extraction. Most of the times, features are empirically defined by visualization of the

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signal, which can lead to a big amount of extracted features. Due to the ”curse of dimensionality” problem (Raudys and Jain, 1991), classification error increases with the increase of the number of features for datasets with few observations. Feature selection is an optional step performed before (or during) learning, that eliminates irrelevant features and overcomes this problem, leading to improvements in the performance. As an example, (Begg and Kamruzzaman, 2005) used feature selection in gait data causing an increase on it's SVM classifier's accuracy; and (Chan et al., 2002) performed this as a pre-step of several classifiers, resulting in an increase of the classification rate.

In this work, we will use several kinetic and kinematic variables acquired from a group of elderly, to verify the possibility to distinguish between high and low functional fitness (FF) levels groups (Rikli and Jones, 1999; Rose et al., 2006) and which locomotion features are more relevant for the distinction of these two groups. Due to the small sample available and since we meant to approach the data in an exploring perspective, unsupervised learning techniques are used.

The rest of the paper is organized as follows: section 2 gives a quick overview of related work; section 3 thoroughly explains the general methodology used in this work, from data collection, passing by feature extraction and selection and finally clustering and validation methods used; section 4 shows the results of applying the proposed methodology to our dataset; on section 5 the biomechanical meaning of the selected features is discussed; and section 6 draws the final conclusions.

2 RELATED WORK

Even though most of the gait pattern recognition investigation has been focused on supervised learning (Chau, 2001a) and (Chau, 2001b), some papers have reported the use of unsupervised learning techniques to investigate several gait characteristics. In (Xu et al., 2006), the authors tried to find underlying gait patterns among pathological and healthy gaits by applying k-means and hierarchical clustering algorithms (Jain and Dubes, 1988) to a series of features previously extracted. Cluster evaluation was done in terms of silhouette and mean square error (Halkidi et al., 2002).

In (Vaughan and O'Malley, 2005) fuzzy clustering is used to identity different walking strategies in children and young adults with cerebral palsy. In (Toro et al., 2007) hierarchical cluster analysis is used on sagittal kinematic gait data derived from children with and without cerebral palsy. Different walking strategies were distinguished by (Su et al., 2001) in patients with ankle arthrodesis using a fuzzy clustering technique. Non-hierarchical cluster analysis was used by (Mulroy et al., 2003) to classify the gait patterns of patients recovering from a stroke based on the temporal-spatial and kinematic parameters of walking. In (Jiang et al., 2010), affinity propagation clustering is used to better grouping of gait data based on the person's characteristics, and help to explain its relationship with human gait.

As shown there are several different clustering algorithms used for gait pattern recognition. In this study we apply the classical hierarchical clustering algorithms due to its simplicity and interpretability.

3 METHODOLOGY

Having as goal the separation of two populations (with high or low functional fitness level), the main focus of this work was to determine which features, from the acquired data, would be more relevant.

Several kinematic and kinetic variables were acquired from 3 different locomotor tasks, further described. The analysis is performed separately for each of the tasks, to systematically analyse the features involved, and because the tasks induce a different morphology in some variables.

The features were empirically determined by inspection of the signals, and selected using feature selection techniques. For the latter, we used a Wrapper method (Alelyani et al., 2013) combined with clustering. Finally, the obtained subsets of features were evaluated against the true label in order to verify the relevance of the features selected to our problem.

The methodology followed in this paper is systematized in figure 1.

3.1 Experimental Sets and Data Acquisition

A convenience sample of 27 participants over 65 years was selected from (Moniz-Pereira et al., 2012). None of them had any neurologic or orthopedic condition that would affect their gait pattern. Immediately prior to data collection, all participants were informed

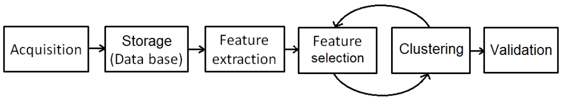


Figure 1: Methodology followed in this work.

about the study, accepted to participate and signed an informed consent. The Ethics Committee of Faculty of Human Kinetics approved the study protocol.

Functional fitness level was established according to a total score (TFFs) of 6 functional fitness tests (the 8 foot up and go, and the 30 second Chair Stand, from Senior Fitness Test battery (Rikli and Jones, 1999), and items 4 [step up and over] , 5 [tandem walk], 6 [stand on one leg] and 7 [stand on foam eyes closed] from the Fullerton Advanced Balance Scale (Rose et al., 2006)).

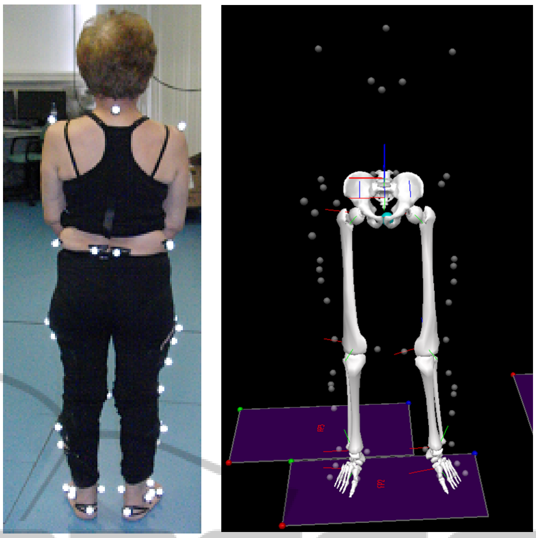
Three locomotor tasks were performed by each subject: gait (G), stair ascent (SA) and stair descent (SD). Several kinetic and kinematic variables were acquired relative to one gait cycle while performing each task. When performing the locomotor tasks, participants were barefoot and wore tight black shorts and t-shirts. Anthropometric measures (subjects body mass, stature and trochanteric height) were taken and the marker set used was based on the calibrated anatomical system technique (CAST) (Cappozzo et al., 1995), using a digitizing pointer for the ASIS markers 2(a).

Kinematic and kinetic data was collected with a Qualisys Track Manager system (Qualisys AB, Gothenburg, Sweden) with 8 infrared, high speed cameras (Qualisys Oqus 300, Qualisys AB, Gothenburg, Sweden) working at a frequency of 200 Hz and synchronized with two Kistler force plates (9281B e 9283U014 Kistler Instruments Ltd, Winterthur, Switzerland). For the stairs trials, a wooden staircase with three steps was built. Each step had 15 cm of height and 27 cm of depth. The last step was extended (80 cm depth) in order to avoid deceleration during stair climbing.

Two force platforms were used. The first was embedded on the floor in front of the staircase, while the second was covering and securely fixed on the first step. This step was built ensuring an extreme rigidity of the structure. Each force platform was independent of the surrounding wooden pieces to ensure adequate measures.

Participants were asked to walk at their comfortable pace. Prior to data collection, training trials were allowed so that the subjects would become comfortable with each task. Three trials from each task were collected, and the order of the tasks (walking and stairs) was randomized.

A seven segments (feet, shanks, thighs and pelvis) model was built for each subject 2(b) and optimized through inverse kinematics (Lu and O'Connor, 1999) to minimize the effect of soft tissue artefact. The joints were modelled as spherical joints, i.e. rotational motion was allowed in the 3 axis, but translations were restricted.



(a) Instrumented suject.

(b) Subject based 7 segment 3D model.

Figure 2: Aquisition set.

A fourth order Butterworth low pass filter at 10Hz was used for both kinematic and kinetic data. Gait variables included: (1) foot and pelvis absolute angles, (2) lower limb joint angles (using a XYZ Cardan sequence), (3) ground reaction forces, (4) lower limb joint moments and powers (determined through inverse dynamics). Kinetic data was normalized to subjects body mass. As all variables were computed for the 3 planes of motion (X sagital plane, Y frontal plane and Z transverse plane), a total of 34 variables were analysed

All the aforementioned data processing was performed through a continuous pipeline developed under Visual 3D software (Professional Version v4.80.00, C-Motion, Inc, Rockville, USA).

3.2 Feature Extraction

Each *acquisition* comprises a total of 34 kinetic and kinematic variables acquired during one gait cycle performing a certain task. The data set contained 3 acquisitions of the same task per individual (from a total of 27 individuals). The individuals were divided in two groups according to their total functional fitness score (TFFs) - High FF level (HFFl) and Low FF level (LFFl). The median of the TFFs was 21 and the subjects were classified as having a Low FF score (TFFs range from 17 to 21 in a total of 14 subjects) and High FF score (TFFs range from 22 to 24 in a total of 13 subjects).

Due to limitation of the acquisition setup, in gait and stair descent tasks, a gait cycle (GC) is consid-

Table 1: Total functional fitness score of the population of this study. Low TFFs range: 17-21; High TFFs range: 22-24.

TFFs	17	18	19	20	21	22	23	24
Freq.	1	1	1	4	7	2	3	8

ered from toe off to toe off, and in stair ascent from heel strike to hell strike. Also, the signal morphology varied considerably for some variables from task to task. So, it is not possible to simply compare the variables when acquired during different tasks, and, therefore, the acquisitions are further separated by task performed.

The features extracted included the signals' mean, standard deviations, maxima, minima, area under the curve and skewness. Through visual analysis of each variable, a set of characteristics was extracted resulting in a total of 33, 31 and 37 features extracted for the G, SA and SD tasks, respectively. The features were then normalized in amplitude per task.

3.3 Feature Selection

One of the main problems in machine learning is the selection of relevant features from a set of extracted features. The feature selection can be divided in two main tasks: subset selection and subset evaluation.

In this work we used three techniques for subset selection (Molina et al., 2002): forward, backward and floating forward feature selection.

Forward feature selection (FS) is a bottom up method, i. e., it begins with an empty set and the best features are added at each step. The best features are the ones that, together with the rest of the subset of features already selected, will result in a better score according to some evaluation criteria.

Backward feature selection (BS) is similar to FS only it uses a top-down perspective, i. e., it begins with a full set and deletes the less relevant features. The less relevant features are the ones which exclusion will lead to a set of features with the highest score, according to some evaluation criteria.

The main disadvantage of the forward and backward feature selection methods is that they converge to local maxima of the evaluation function. To avoid this, and since we have a small number of features and samples, we have evaluated all the of possible cardinalities of the feature subset. This means that we have studied/evaluated the subsets resulting from setting all the possible values of *Min. no. of features* as a stopping criterion. This will return the full behaviour of the evaluation function allowing us to choose its global maximum.

Sequential floating forward feature selection (FFS) (Pudil et al., 1994) starts with an empty subset of features as in FS. However, the number of features does not increase monotonously. The algorithm involves both adding and deleting features. In this way nesting of feature sets is avoided.

In this study the application of the feature selection step is evaluated a clustering validity index over the clusters obtained using the subset of features under evaluation. We used the Ward's hierarchical method in combination with two clustering validity indexes: Adjusted Mutual Information score (AMI) (Vinh et al., 2010);Consistency Index (CI) (Fred, 2001).

3.4 Clustering

Unsupervised learning refers to the problem of finding hidden structure on the data. In this study Ward clustering (Murtagh and Legendre, 2011) (Jain and Dubes, 1988) is used and is, therefore, described in the next subsection. The last subsection, explains the validation methods used.

Other clustering methodologies, such as k-means, where used. However their results were worse than the ones obtained with Ward clustering therefore, and due to space constrains, these results are not presented nor this methodology is detailed.

3.4.1 Ward Method

Ward minimum variance method is an hierarchical clustering method that aims to minimize the sum of squared differences within the clusters (Murtagh and Legendre, 2011). It starts by considering each sample as a single cluster (singleton). Then, it will find the two clusters that, after merging, will lead to the minimum increase in the total within cluster variance. At each step, the clusters obeying this condition will be merged until a pre-defined total number of clusters is reached.

3.4.2 Subset Evaluation and Clustering Validation

After obtaining the natural clustering partitions of the data, we need to check if the partitions revealed are correlated with the parameter we want to investigate,the functional fitness level. This is done by comparing the partitions obtained with the data's true label using a validation method. The validation method will return a score that is a measure of the similarity between the partitions obtained and the true label.

We used two external criteria: Adjusted Mutual Information score (AMI)(Vinh et al., 2010) and Consistency Index (CI) (Fred, 2001) to compare the obtained results with the ground truth information.

As a Mutual Information function, AMI measures the agreement of the two assignments, ignoring permutations. Furthermore, it is normalized against chance. It is bounded between 0 and 1. Values close to 0 indicate random or largely independent labels, while values close to one indicate significant agreement. Also, it is invariant to cluster shape so it can be used with any clustering algorithm.

Let U and V be two clusters, $H(U)$ (eq. 1) and $H(V)$ (analogous to eq. 1) the entropy of the clusters, $I(U,V)$ the mutual information between the two clusters (eq. 2), and $E[I(U,V)]$ the expected mutual information between the two clusters. The AMI score is given by equation 3.

$$H(U) = \sum_{i=1}^{|U|} P(i)log(P(i)) \tag{1}$$

$$I(U,V) = \sum_{i=1}^{|U|}\sum_{j=1}^{|V|} P(i,j)log(\frac{P(i,j)}{P(i)P(j)}) \tag{2}$$

$$AMI(U,V) = \frac{I(U,V)-E[I(U,V)]}{maxH(U),H(V)-E[I(U,V)]} \tag{3}$$

The consistency index (CI) reflects the fraction of shared samples in matching clusters in two data partitions, over the total number of samples. It is an iterative procedure that, in each step, determines the pair of clusters having the highest matching score, given by the fraction of shared samples. As AMI, it ignores permutations, is bounded between 0 and 1 (0 means no matching at all, 1 means perfect match). CI can be generally expressed by:

$$CI = \frac{1}{n}\sum_{i=1}^{min\{nc_1,nc_2\}} n\_shared_i \tag{4}$$

where nc_i the number of clusters in partition i and n_shared_i is the number of samples shared for the i^{th} clusters. One can say that the CI score is the clustering equivalent to an accuracy measure since it reflects the fraction of well classified samples.

4 RESULTS

As a baseline approach, we applied the clustering algorithm directly to the extracted features, without performing feature selection. A total of 33, 31 and 37 features were used for clustering in the gait (G), stair ascent (SA) and stair descent (SD) tasks, respectively. As a result, we obtained a CI score of 0.667 for the G and SD tasks, and 0.556 for the SA task, indicating that the features selected, as a group, did not allow a good differentiation between the locomotion of the subjects belonging to the two functional fitness levels.

Table 2: CI score and number of features of the subsets obtained with the different feature selection configurations. The results were obtained with the classical feature selection algorithms, column "Typical", and our adapted version to find the global maximum of the subset evaluation function, column "Global max". Best results are highlighted.

		AMI		CI	
		Typical	Global max	Typical	Global max
BS	G	**0.827** **(13)**	**0.827** **(13)**	0.741 (22)	0.741 (22)
	SA	0.827 (23)	0.79 (4)	0.852 (14)	0.859 (11)
	SD	0.778 (21)	0.815 (16)	0.704 (15)	0.778 (3)
FS	G	0.679 (1)	0.802 (5)	0.802 (5)	0.802 (5)
	SA	0.79 (2)	0.889 (17)	**0.889** **(4)**	**0.889** **(4)**
	SD	0.802 (6)	0.815 (16)	0.802 (3)	0.815 (10)
FFS	G	0.679 (1)	-	0.802 (5)	-
	SA	0.78 (2)	-	0.889 (6)	-
	SD	**0.852** **(7)**	-	0.802 (3)	-

In order to investigate which features would be relevant for this purpose, we experimented several feature selection configurations. As referred in the previous sections, three subset search methods where used (forward, backward and floating forward feature selection), combined with two subset evaluation measures (AMI and CI scores), resulting in 6 different feature selection configurations. Also, we tried the typical BS and FS approach in which the only stopping criteria is "no improvement in the evaluation criteria" versus a search for the global maximum of the evaluation function. We present these results in table 2.

Results improved with feature selection. Also, as expected, results were generally better with the global max method; there are few situations where the first maximum coincided with the global maximum of the evaluation function.

The best CI scores obtained were of 0.827, 0.889 and 0.852 for the G, SA and SD tasks. These results indicate that the the features identified by the feature selection algorithms allow to distinguish the subjects of each group with a reasonable degree of confidence and it is worth to analyse the subsets in detail, which will be done in the next section.

5 SELECTED FEATURES DISCUSSION

For the results presented in the table 2 we defined *best result* as a higher CI score or a lower number of selected features. However, in a biomechanical context, fewer variables can mean results that are very difficult to interpret. Indeed, other configurations presented subsets with the same score but with a higher number of features. For the G and SA tasks 3 and 14 configurations, respectively, presented a score equal to the one selected as best. For the SA task, the best subset only contained 4 features, which is not enough for the biomechanical analysis, so we were forced to look into other frequently selected features present in the subsets with the same score as the best one. The maximum score for the SD task corresponded to a selection of features with small locomotor relevance, so we investigated the features frequently chosen by subsets with the second higher score for this task - 0.815.

In the next subsections we describe and discuss the features that are both frequently chosen by high score subsets and relevant to the locomotor task.

5.1 Gait Task

The group of elderly subjects with lower functional fitness level (LFFl) walked with the hip more flexed throughout the stance (figure 3(a)). (DeVita and Hortobagyi, 2000) have detected the same difference when comparing young with elderly subjects. In their work, the authors suggested that the increased hip flexion in elderly gait pattern was probably a postural adjustment in order to be able to produce larger extensor hip joint moment during stance and to compensate for the lower plantarflexor joint moment exerted. Although in this study we have not found differences in the hip extensor joint moment, the ankle plantaflexor joint moment peak showed to be lower in the LFFl group, meaning that these subjects have a significant less vigorous push off. Other authors (Prince et al., 1997); (Winter, 1991) have also reported a reduction in peak plantarflexor moment when comparing elderly with young subjects. These differences are also in accordance with the lower ground reaction force vertical peak showed by the LFFl peak during the push-off phase.

In contrast with the previously referred studies, however, we have found that subjects with a LFFl had a higher knee extensor joint moment peak at the beginning of the stance, during the weight acceptance phase. As the LFFl subjects also presented a higher degree of knee flexion (figure 3(b)) during this phase, a larger knee extensor moment may be necessary to control knee flexion and thus to properly support the body.

Data concerning the other planes of motion is scarce in the literature for this population. Nevertheless, the higher external rotation of the hip, ankle adduction joint moment (figure 3(c)) and knee abductor angular impulse seem to suggest a higher effort to control medio-lateral body stability in the LFFl group.

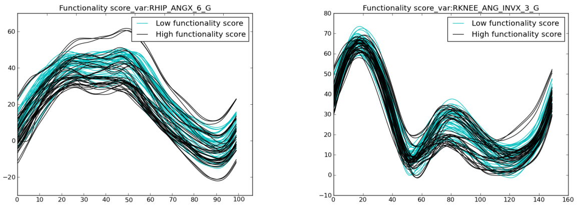
5.2 Stair Ascent Task

When compared to the HFFl group, the LFFl group also showed to adopt a different strategy to deal with the SA task. The higher hip and pelvis flexion angles (figures 3(d) and 3(e)) and a higher abduction hip angle may be a strategy of the subjects with low functional fitness level in order to guarantee a safe clearance of the swing leg through the intermediate step. Also, as mention before for the walking task, a more flexed hip during the stance may also be a postural adjustment in order to produce a larger extensor moment of the hip during the stance (DeVita and Hortobagyi, 2000). In fact, the subjects from the LFFl group seem to compensate their lack of plantarflexor joint moment during the stance, with a higher extensor hip moment. This was also verified by (Novak and Brouwer, 2011), when comparing young and older subjects. Furthermore, subjects higher functionality showed, not only to use more their plantarflexors, but also to produce more knee extension power during the weight acceptance phase.

On the contrary of what has been reported when comparing young with older subjects (Novak and Brouwer, 2011), the LFFl group showed a lower hip abductor joint moment (figure 3(f)) when compared to the HFFl group. It could be hypothesize that due to the higher task demand, the subjects with a lower functional fitness level were not able to rely as much as the HFFl subjects on the hip abductor muscles to control the body lateral stability.

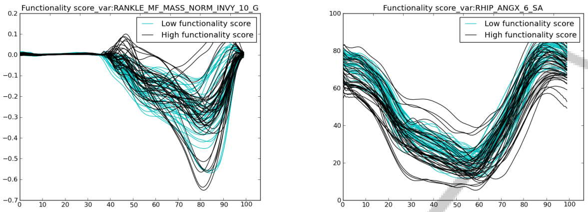
5.3 Stair Descent Task

Finally, for the SD task the more significant features obtained to distinguish the LFFl group from the HFFl group were difficult to interpret in a biomechanical point of view. However, if we consider the features belonging to the second highest score subsets, it is interesting to verify that in accordance to what was verified in the previous tasks, the LFFl group had a more flexed hip (figure 3(g)) during the SD task and produce a higher hip extensor joint moment. Further, similar to what we have found for the SA task, the subjects with lower functionality produced a lower



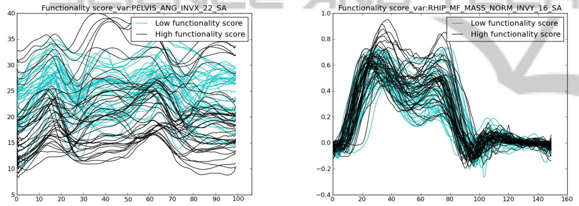
(a) Hip's angle in X (G). Feature: mean.

(b) Knee's angle in X (G). Feature: 2nd max



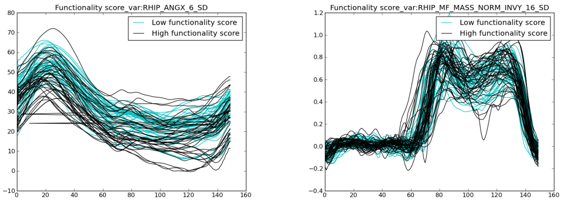
(c) Ankle's joint moment in Y (G). Feature: maximum (40% to 60% of GC), minimum and mean on the second third of the signal

(d) Hip's angle in X (SA). Features: mean (till 20% of the GC)



(e) Pelvis' angle in X (SA). Feature: mean.

(f) Hip's joint moment in Y (SA). Features: mean.



(g) Hip's angle in X (SD). Features: mean.

(h) Knee's momentum force in Y (SD). Feature: mean.

Figure 3: Plot of some of the gait cycle variables from which features where selected as most distinctive. Individuals with low functionality score are plotted in blue, and high functionality scores in black.

hip abduction joint moment (figure 3(h)) during this task showing therefore not to rely, as much as the HFFl group, on hip abductors to control the medial lateral stability of the body.

6 CONCLUSIONS

This paper summarizes the potential of different kinetic and kinematic features, acquired using an 7 segments model (feet, shanks, thighs and pelvis), to distinguish different functional fitness levels in an sample of elderly population. Unsupervised learning methodologies were used, and evidence was found favouring the natural separation of elderly population groups according to this parameter. Feature selection has proven to be an effective tool in revealing interesting variables increasing the discriminative capacity.

A set of best distinguishing features for each task is presented along with an analysis of the features selected and their meaning for the elderly locomotion. The results showed that some of the differences observed between groups are similar to the ones reported in the literature when studying differences between young and old subjects. In general, LFFl subjects adopted a more flexed hip posture during the analysed taskstasks. Additionally, they seem, not only to redistribute joint moments and compensate their lack of plantarflexor moment with a higher hip extensor moment, but also not to rely on the hip abductors, as much as the HFFL group, to control medio-lateral stability in more challenging tasks (SA and SD). These changes may increase the predisposition to fall in the LFFl group. Further, this could mean that changes in gait pattern may not be only a consequence of ageing, but also be caused by losses in functionality. The further investigation of these different gait patterns is therefore important for the establishment of exercise programs, aiming to improve functionality and therefore to prevent falls, for this population.

Future work includes trying different learning methods and feature selection methods and an extensive evaluation of the approach for larger data sets.

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