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Impact of muscle fatigue on mechanics and motor control of walking

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Impact of muscle fatigue on mechanics and motor control of walking

Thesis submitted in partial fulfillment of the requirements of the Instituto de Biociências do Campus de Rio Claro, Universidade Estadual Paulista Júlio de Mesquita Filho, for the degree of Ph.D. in Ciências da Motricidade.

Supervisor: Lilian Teresa Bucken Gobbi, Ph.D.

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Rio Claro, 28 de Novembro de 2012.

“Always overcoming challenges and goals”

I dedicate this thesis to my family
and the special friends of my life.

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ABSTRACT

The aim of the study is to analyze the effects of muscle fatigue on mechanics and motor control of walking in different environments. A series of walking experiments addressedmuscle fatigue impact in different gait tasks, age-related changes in control of gait with muscle fatigue, and effects of fatigue in different muscular group on mechanics and control of gait during stepping down. The present thesis showed that quadriceps muscle fatigue modifies gait fairly independent of the environment. In walking on a level surface, during obstacle crossing and during stepping down quadriceps fatigue caused with a wider basis of support and reduced stride duration, but without modulation of placement of the feet in crossing an obstacle and stepping down a curb. This strategyimproves the balance to avoid falling. Furthermore, the mechanics and control during the last stride before stepping down and in landing phase were dependent on whether ankle muscles or knee muscles were fatigued. It should be noted that the joint used to absorb kinetic energy in stepping down with ankle muscle fatigue was dependent on whether a heel or toe landing strategy was used. However, the variability of trailing and leading foot-step horizontal distance was higher after both fatigue protocols, which indicates a reduced control of foot placement. Moreover, the effects of knee muscle fatigue on even and uneven walking of young adults were independent of physical activity level but age-related. The spatial-temporal and kinetic modulations in both tasks after knee muscle fatigue started over 40 years old with a risky strategy for older individuals (over 60 years old). In conclusion: a) knee muscle fatigue affects medio-lateral balance control independently of type of gait, which were compensated by modulation of the spatial-temporal and kinetic parameters, angular movement, muscle activity and energy absorption to maintain stability; b) compensatory muscle strategies were used according to the muscle groups that were fatigued, recruiting unfatigued muscle groups to adjust the gait pattern and to enhance balance control. In addition, the variability of trailing and leading foot-step horizontal distances increased with fatigue, suggesting a loss of control; c) physical activity level did not mediate the effects of knee muscle fatigue on walking on even and uneven surfaces in young adults. On the other hand, the aging process impacts the walking over even and uneven terrains after knee muscles fatigue.

Key-words: Muscle fatigue; Walking; Obstacle; Stepping down; Aging; Physical activity level; Biomechanics; Motor control.

RESUMO

O objetivo do estudo é analisar os efeitos da fadiga muscular na mecânica e controle motor do andar em diferentes ambientes. Uma série de estudos envolvendo fadiga e andar analisaram o impacto da fadiga no andar em diferentes ambientes, as mudanças no controle do andar relacionado com a fadiga muscular, e os efeitos da fadiga em diferentes grupos musculares na mecânica e controle do andar durante descida de degrau. A presente tese mostrou que a fadiga no quadríceps modifica substancialmente o padrão do andar independentemente do ambiente. No andar em ambiente regular, durante a ultrapassagem de obstáculo e durante a descida de obstáculo, a fadiga do quadríceps aumentou a base de suporte e reduziu a duração da passada, mas não modificou o posicionamento dos pés em relação ao obstáculo e ao degrau, melhorando o equilíbrio para evitar quedas. Ainda, a mecânica e o controle durante a última passada antes de descer o degrau e a aterrissagemforam dependenteda fadiga nos músculos do tornozelo ou joelho. Foi encontrado que a articulação usada para absorver a energia cinética na descida do degrau após fadiga dos músculos do tornozelo foi dependente da estratégia de descida usada, contato com o calcanhar ou com o metatarso. No entanto, a variabilidade da distancia horizontal pé-obstáculo da perna de abordagem e de suporte foi maior após ambos os protocolos de fadiga, indicando redução no controle do posicionamento do pé. Além disso, os efeitos da fadiga nos músculos do joelho no andar em ambiente regular e irregular de adultos jovens foram independentes do nível de atividade física, mas com efeito do envelhecimento. As modulações espaço-temporal e cinética nas duas tarefas depois da fadiga dos músculos do joelho iniciaram após a idade de 40 anos com estratégia mais arriscada para indivíduos mais velhos (acima de 60 anos). Em conclusão: a) fadiga do quadrícepsafetou negativamente o controle da estabilidade médio-lateral independentemente do tipo de andar, sendo compensado pelas modulações nos parâmetros espaço-temporais e cinéticos, movimento angular, atividade muscular e absorção da energia; b) estratégias musculares compensatórias foram usadas de acordo com o grupo muscular fadigado, recrutando grupos musculares não fadigados para ajustar o padrão de andar e aumentar o equilíbrio. Ainda, a variabilidade da distancia horizontal do pé-degrau dos membros de abordagem e de suporte aumentaram após a fadiga, sugerindo perda de controle; c) o nível de atividade física não interferiu nos efeitos da fadiga dos músculos do joelho do andar em ambiente regular e irregular em adultos jovens. Por outro lado, o envelhecimento teve impacto depois da fadiga dos músculos do joelho.

Palavras-chave: Fadiga muscular; Andar; Obstáculo; Descida de degrau; Envelhecimento; Nível de atividade física; Biomecânica; Controle motor.

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Chapter 1

General introduction

1.1. Introduction

Fatigue is generally considered a safety hazard, and may for example increase the risk of falling (Parijat and Lockhart, 2008a,b). The increasing prevalence of fatigue and its conception as a safety hazard has lead to increased regulation of fatigue by governments (Dawson and McCulloch, 2005). Although fatigue can be considered a negative consequence of physical activity, it also functions as a safety mechanism, as it limits exertion and as such may prevent injury due to overexertion (Ratel et al., 2006; Abbiss and Laursen, 2005;). Fatigue involves a feeling of tiredness, reduced energy and muscle weakness (Kroenke et al., 1988). The latter aspect of fatigue, indicated by a decreased force producing capacity is defined as muscle fatigue, and forms the main interest of this thesis in which the mechanics and motor control of walking with muscle fatigue are studied. The main aim was to understand the mechanics and control adjustments with muscle fatigue during walking in different environments. This might help to identify the impact of fatigue on walking, and contribute to the prevention of falls.

In this general introduction, fatigue was defined and then an overview was given of prevalence of fatigue in society to illustrate the importance of studying fatigue in daily activities. Next, the relation between muscle fatigue and aging and subsequently the effects of fatigue on walking were described, indicating the lack of data on fatigue effects on walking in complex environments. Finally, the aims and the outline of this thesis were specified.

1.1.1. Fatigue definition

Diverse definitions on fatigue have been formulated, which vary considerably in theirdescription causes, defining attributes, related factors and how the condition might best be alleviated (Trendall, 2000; Ream and Richardson, 1996). The multidimensional characteristic of fatigue complicates a clear definition.Fatigue may be a conceptwhose subjective experience alters rapidly (Hangelin et al., 2007). Normally, fatigue is scaled and defined according to general fatigue, physical fatigue, reduced motivation, reduced activity, and mental fatigue (Smets et al., 1995).

However, muscle fatigue can more clearly be defined. Traditionally, muscle fatigue has been defined as the failure to maintain a required or expected force (Edwards, 1981), or the failure to continue working at a given exercise intensity (Booth and Thomason, 1991) or as a loss of muscle performance during repeated or continuous activation (Stackhouse et al., 2001). Closely related to this is the concept ofendurance, whichdescribes the time to failure in

maintaining a target muscle force or power output (Kent-Braun, 2009; Hocks et al., 2001). However, as fatigue develops from the onset of activity, a more useful definition of muscle fatigue is given in terms of the capacity to produce muscle force or power (Bigland-Ritchie and Woods, 1984), which can thus be operationalized as a decline in the force generation capacity of muscle over or after a series of repeated contractions or sustained contractions (Kent-Braun, 2009; Gandevia, 2001). Due to thesis context, the definition related to endurance (Kent-Braun, 2009; Hocks et al., 2001) was used for this thesis.

1.1.2. Fatigue prevalence and its effects in daily life

Fatigue is recognized as a serious social problem, and an important prerequisite in its prevention is the ability to evaluate fatigue development during daily activities living (Hancock and Desmond, 2000; Cohen et al., 1995). Due to the use of different definitions, reports on the prevalence rate of fatigue in daily activities are inconsistent. The fatigue prevalence is measured according to a general fatigue, which is subjective and causes difficult in the interpretation.Nevertheless, demography studies are indicated that prevalence rates vary from 7 to 42% in the general population (Loge et al., 1998; Pawlikowska et al., 1994; Chalder et al., 1993; Chen, 1986) and depend on gender, age, and physical activity level. There is no specific data on the prevalence of muscle fatigue in society.

Muscle fatigue, however, appears to be an important factor in performance of daily activities. For example, many workers are affected by muscle fatigue (Swaen et al., 2003; Tralongo et al., 2003) and studies have shown that between 25% and 33% of falls in the work place occur due to the fatigue (Swaen et al., 2003; Bentley and Haslam, 1998). Muscle fatigue decreases some aspects of motor control and efficiency of performance in daily activities (Ribeiro et al., 2007), which may have functional consequences. For example, increased muscle fatigue may limit the number of stairs that a person can descend or ascend, or cause problems in crossing or circumventing an obstacle, leading to functional limitations and hazards in activities of daily living. Liao et al. (2000) indicated that muscle fatigue influenced functional ability as reflected in walking, cleaning the house, general household chores, getting exercise, and lifting things. In addition, adequate muscle strength in the lower limb muscles has been shown to be required to maintain functional independence in ambulatory activities (Petrella et al., 2005). Therefore, muscle fatigue can contribute to disability, regarding occupational activities and activities of daily living and as such be the cause of a deterioration in quality of life.

1.1.3. Muscle fatigue and aging

With aging the musculoskeletal and neuromotor systems deteriorate (Kang and Dingwell, 2008; Norris et al., 2007), which might be related to muscle fatigue. Ninety percent of older people show one or more impairments that negatively affect their mobility (Theou et al., 2008). The main impairments are related with dysfunction of muscle (Ross et al., 1997) and proprioception (Shaffer and Harrison, 2007). Importantly age-related alterations include substantial loss of muscle strength and slowed contractile characteristics (Allman and Rice, 2002; Hunter et al., 1998).

Despite the high prevalence in the general population, fatigue appears to vary according to the population's age. In one study 83% of young adults reported moderate or severe fatigue (Amaducci et al., 2010), while in another study more than 50% of adults between 50 and 65 years old reported to be fatigued (Santos-Eggimann et al., 2009) and in another study, 98% of respondents above 70 years old reported fatigue symptoms, with 40% reporting moderate fatigue and 7% severe fatigue (Liao and Ferrell, 2000). However, it is questionable whether these studies can be compared directly, given differences in methods and population characteristics.

Overall, age effects on muscle fatigue also remain unclear (Yassierli and Nussbaum, 2007), with several studies showing less fatigue in elderly (Lanza et al., 2004; Tralongo et al., 2003; Watt et al., 2000) and some an increase of fatigue with age (Kent-Braun, 2009; Baudry et al., 2007; McNeil and Rice, 2007; Mens-Verhulst and Bensing, 1998; Lawrie et al., 1997). These inconsistencies may be due to differences in contraction modes, protocol, muscle group or subject characteristics (Kent-Braun, 2009; Katsiaras et al., 2005). Nevertheless, the age of the subjects may be important in fatigue response (McNeil and Rice, 2007). Therefore, age is an important consideration in studies of fatigue and its effects on motor performance (Allman and Rice, 2002).

1.1.4. Muscle fatigue and walking

The negotiation of obstacles and uneven surfaces form an important aspect of walking in daily life (Berard and Vallis, 2006). In real life, individuals frequently step up or down level change, and cross or circumvent obstacles in ongoing gait, such as when stepping on or off the sidewalk to cross a street and when crossings a hole or an object on the street or in the home.These tasks require gait adjustment, which may threaten stability. Stability during locomotion is maintained through reactive, predictive, and anticipatory strategies and mainly involves moving the base of support relative to the body mass (Patla, 2003). However, while

gait on even surfaces has been extensively studied, negotiation of obstacles and uneven surfaces is comparatively uncharted, especially when other aspects are involved, such as fatigue, aging, and physical activity level. Obstacle crossing causes adjustments during walking, in which the individual modulates the foot-obstacle distance and toe-clearance to safely cross the obstacle (Silva et al., 2011; Gobbi et al., 2009; Siu et al., 2008; Di Fabio et al., 2004;Hedel et al., 2002). In addition, while crossing over an obstacle, gait velocity is reduced by reducing step length and cadence (Lowrey et al., 2007). With respect to uneven surfaces, while stepping down a height difference, step size is adjusted to allow the last step on the high level to land close to the height difference (Begg and Sparrow, 2000; Crosbie and Ko, 2000), and the forward and linear angular momentum gained during stepping down are reduced by making a larger step with the leading leg (Dieën et al., 2008). Failure to do so can cause a loss of balance (Dieën et al., 2008).

Various factors can affect walking in a more complex environment. For example; a) with aging, cadence and stride duration are increased and walking velocity and stride length are decreased (Owings and Grabiner, 2004; Shkuratova et al., 2004); b) low physical activity level is associated with poor balance and propulsion (Petrella et al., 2005; Sadeghi et al., 2004; Merletti et al., 2002). On the other hand, motor control literature has emphasized the ability to adapt motor behavior to destabilizing conditions to reduce error probability (Diëen and Pijnappels, 2009), such as when fatigue destabilizes motor performance and decreases muscle strength (Gates and Dingwell, 2008; Selen et al., 2007). Adequate muscle strength in lower limb muscles is required for safely crossing an obstacle and stepping down a curb (Petrella el al., 2005). Muscle fatigue can impair motor control by increasing muscle co-contraction and limiting fast corrective movements (Izawa et al., 2008; Franklin et al., 2007; Dieën et al., 2003), and by adversely affecting proprioception, movement coordination and muscle reaction times (Lin et al., 2009; Parijat and Lockhart, 2008a), which are important components of balance control (Parijat and Lockhart, 2008a,b; Helbostad et al., 2007; Lord et al., 1993).A new segmental organization in the presence of muscle fatigue is required to maintain motor performance, as observed by changes in time and spatial gait parameters (Murdock and Hubley-kozey, 2011; Olson, 2010; Granacher et al., 2010; Lin et al., 2008; Parijat and Lockhart, 2008a,b; Helbostad et al., 2007; Kavanagh et al., 2006; Yoshino et al., 2004). Thus, a relationship between muscle fatigue in the lower extremities and deficits in the control of gait is likely.

However, to our knowledge, there is no study available that investigated the impact of muscle fatigue on walking in complex environments, such as in obstacle crossing and

stepping down a curb. The understanding of muscle fatigue effects could help to avoid falls, slip, trips and injuries during walking in complex environments. Furthermore, fatigue may be a useful model to study the effects of disease as it impairs muscle torque-generating capacity, yet does not have confounding factors like pain or swelling (Murdock and Hubley-Kozey, 2011).

1.1.5. Aims and outline of this thesis

The aim of the study is to analyze the effects of muscle fatigue on mechanics and motor control of walking in different environments. A series of walking experiments addressed muscle fatigue impact have been conducted, in order to obtain the required information. The chapters arising from these studies address the following topics: the effects of muscle fatigue on walking, muscle fatigue impact on walking in different environments, age-related changes in control of gait with muscle fatigue, and effects of fatigue in different muscular group on mechanics and control of gait during stepping down.

First, we analyzed the effects of fatigue on gait by means of a systematic review (Chapter 2). In this chapter, we tried to determine the effects of fatigue on gait on even ground and the gaps in our knowledge in this context. The specific question addressed was: What are the effects of fatigue on the spatiotemporal characteristics of gait?

Second, we investigated whether the fatigue impact is similar in walking in different environments. For this, we analyzed the effect of muscle fatigue in young adults on the kinematic and kinetic parameters of even walking and obstacle crossing (Chapter 3). The complexity of obstacle crossing could change the strategy and the stability of walking with muscle fatigue. In the Chapter 4, a similar study was performed but age-related effects were included. We expected that the effects of muscle fatigue on gait would be increased with aging.

Thirdly, we examined the changes in the mechanics and control of gait in negotiating level changes when quadriceps or triceps surae muscles were fatigued. In Chapter 5, the aim was to evaluate the effects of muscle fatigue on mechanics and stability of stepping down in ongoing gait. The participants performed a fatigue protocol on two different days (one day for the quadriceps muscles and another day for the triceps surae muscles). The hypotheses were: a) a shift of negative work from the fatigued muscles to non-fatigued muscles; b) increased negative work at landing and a conservative gait pattern with fatigue. Chapter 6 reports the effects of quadriceps and triceps surae muscle fatigue during the approach phase before

stepping down. We specifically address the variability of foot placement and other kinematic parameters as well as electromyography parameters.

Finally, in Chapter 7, the main findings and conclusions of this thesis are summarized and a number of recommendations for further research are provided.

Chapter 2

Systematic review of the effects of fatigue on spatiotemporal gait parameters

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2.1. Abstract

This systematic review aimed to assess changes in spatiotemporal gait parameters due to fatigue. A search was carried out in literature published from 1950 to December 2010 and retrieved 771 articles using terms referring to walking and fatigue in the title, abstract or keywords. Two researchers assessed the selection and quality of each article independently. Seven studies were selected for this systematic review, two of which reported on the same data set. Several biomechanical parameters were reported to change with fatigue, but the few variables studied in multiple studies, gait speed and stride or step length and stride time were affected only in single studies. Fatigue appears to modulate spatiotemporal gait parameters, but the effects of fatigue appear to be dependent on the muscles that are fatigued and age appears to be a moderator of the effects of fatigue on gait.

2.2. Introduction

Fatigue is used to describe a number of phenomena with a variety of causes (Ergenton et al., 2009), but may be more strictly defined as any exercise-induced reduction in the ability of a muscle to generate force or power (Edwards, 1981), or failure tocontinue working at a given exercise intensity (Booth and Thomason, 1991). Fatigue development is mediatedbya range of individual factors such as the presence of pathology, age (older adults fatigue faster than young adults), physical activity level (inactive individuals fatigue faster than active individuals), and the type of activity performed.Fatigue not only affects elderly and diseased populations, as 5-56% of employees in 15 European countries reported fatigue at work (Benavides et al., 2000)and one-third of the US workforce experienced fatigue in the workplace (Swaen et al., 2003).

Fatigue is considered as a safety mechanism to prevent injury (Ratel et al., 2006; Abbiss and Laursen, 2005), but it may have negative effects on activities of daily living (ADL) (Liao and Ferrell, 2000). For example, walking distance, cleaning the house, general household chores and getting exercise are limited by fatigue (Tralongo et al., 2003). Therefore, fatigue can contribute to disability, regarding occupational activities and ADL and as such be the cause of a deterioration in independence and quality of life. Furthermore fatigue adversely affects proprioception, movement coordination and reaction times (Lin et al., 2009), and consequently has negative effects on motor control (Ribeiro et al., 2007). For example, fatigue may compromise balance control and predispose to falls (Helbostad et al., 2010; Lin et al., 2009; Parijat and Lockhart, 2008a,b; Helbostad et al., 2007). In an investigation of slip and fall accidents among postal delivery workers in the UK (Bentley and Haslam, 1998), fatigue was found to be a precursor of 25% of all fall incidents.

The literature provides some evidence of fatigue-related changes of the biomechanical characteristics of gait, indicating that a new segmental organization occurs in the presence of muscle fatigue, as observed by changes of spatiotemporal gait parameters (Murdock and Hubley-Kozey, 2012; Olson, 2010; Granacher et al., 2010; Lin et al., 2009; Parijat and Lockhart, 2008a,b; Helbostad et al., 2007; Kavanagh et al., 2006; Yoshino et al., 2004). However, a comprehensive overview of which gait parameters and how these parameters are changed by fatigue is lacking. Therefore, a systematic review was performed with the aim to assess changes of spatiotemporal gait parameters due to fatigue. An understanding of fatigue effects on walking could help to avoid falls, slip, trips and injuries (Murdock and Hubley-Kozey, 2012), and as such improve quality of life.

2.3. Methods

2.3.1. Search strategy

The initial search strategy was performed to identify all articles on the effect of fatigue on spatiotemporal gait parameters. An electronic search was conducted in 6 databases: Cochrane Library, Embase, Medline – ISI, PsycInfo, PubMed, and Web of Science – ISI. We searched articles from 1950 to December 2010. Targeted searching of frequently cited journals, authors and article reference lists ensured that all relevant articles were located. To be deemed relevant for review, an article had to contain terms referring to walking and fatigue in the title, abstract or keywords. The word gait was used together walking due to the similarity in the terminology. Key terms within the search strategy were also matched using medical subject headings (MeSH) in databases such as Medline. Articles on animal studies, robotics, children and reviews, methodological or descriptive papers were excluded using another set of key terms. As an example, the following search strategy was used in the PubMed: "gait OR walking AND fatigue" searched in the title/abstract, with following limits: language – English; type of article – clinical trial, randomized controlled trial and journal article; species: humans.

2.3.2. Section criteria and quality assessment

The initial yield was obtained by combining all original articles from electronic databases and targeted searches. Articles not relating to walking were excluded during an initial screening of titles and abstracts. The remaining abstracts were checked against the inclusion/exclusion criteria. The full text was examined if the abstract contained insufficient information to decide on inclusion.

Two reviewers screened all articles for inclusion. A set of guidelines and examples for completing article reviews was provided to both reviewers to improve inter-reviewer reliability. The two researchers independently assessed the selection and quality of each article. Only English language articles were considered for analysis. Studies that investigated effects of fatigue on gait in health young, middle-aged and older adults, but not pathological individuals were initially selected. If a study investigated both walking freely on flat ground and another form of locomotion or walking with concurrent task, only details pertaining to effects of fatigue in the walking freely on flat ground were considered. Articles were included in the systematic review if they investigated the effects of fatigue in walking freely on flat ground on spatiotemporal parameters. As differences in terminology and writing style exist

between researchers, a list of synonyms for spatiotemporal (step or stride length and width, stride time, speed, velocity, acceleration, spatiotemporal and spatial-temporal) was used for each key term to identify all relevant articles. Studies on treadmill walking were excluded because gait adaptations on a treadmill may be different from those in over ground walking.

The quality of a study was defined as its capacity to avoid potential bias and to generate results that can be generalized. We used a quality appraisal tool developed by Galna et al. (2009), which is specific for this type of systematic review. A scoring system was used to quantify the quality of each study and to assess its methodological strengths and weaknesses. Each question on the quality appraisal tool was scored with a maximum of one, indicating high quality research, with a 0.5 score indicating lack of detail or unclear information and a zero score indicating low quality. Study quality was used to weigh the evidence in case of conflicting outcomes.

2.4. Results

2.4.1. Yield and Quality Assessment

The search in the databases revealed 771 articles (Figure 2.1). Following abstract review, 81 articles were related to effect of fatigue in gait on spatiotemporal parameters. The final yield included seven articles that analyzed effects of fatigue on spatiotemporal parameters of gait. Two papers reported data collected in the same experiment (Parijat and Lockhart, 2008a,b), leaving six papers for review.

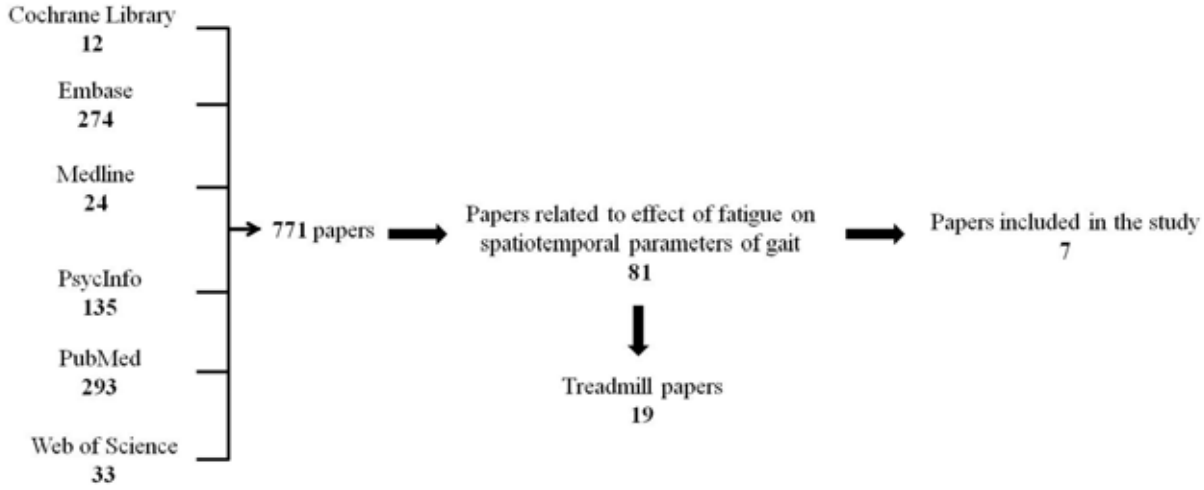

Figure 2.1. Flowchart of articles included for review. The number under the text indicates the number of original articles (i.e. not duplicated) at each stage of the search.

Table 2.1 summarizes the quality assessment for these papers. Overall, quality was satisfactory, the articles stated the aims with sufficient clarity, gave an appropriate description of the participants, detailed the key outcomes clearly, employed a suitable methodology, discussed the results appropriately and indicated implications. One important shortcoming in the statistical analysis was noted for the study by Yoshino et al. (2004). In this study, subjects were sub-grouped based on the kinematic changes that occurred due to fatigue (duration of stride time). This makes it impossible to judge whether changes in spatiotemporal parameters were significant at the group level. Nevertheless the results of the largest subgroup (8 vs 4 subjects) were included in the review. Most investigations controlled for age and gender, but typically did not control for height, limb asymmetries and strength differences between groups. Details provided were adequate to replicate the studies, although methods for inclusion/exclusion criteria were often not reported. No study completely described the recruitment and sampling methods. The reliability of key outcome measures and the internal validity of the key outcome measures were reported in only one study.

2.4.2. Sample Characteristics

Both male and female participants were recruited in the studies analyzed (Table 2.2), except for three studies in which participants of one sex were recruited: one study included only females (Olson, 2010) and two studies included only males (Kavanagh et al., 2006; Yoshino et al., 2004). Four studies (Parijat and Lockhart, 2008b; Kavanagh et al., 2006; Yoshino et al., 2004; Olson et al., 2010) analyzed the influence of muscle fatigue in young adults, while one paper (Helbostad et al., 2007) evaluated the effect of fatigue on gait in elderly. A single study (Granacher et al., 2010) compared the effects of fatigue on gait between age groups (young vs older adults). In the seven papers, the mean age of the young adults ranged from 20 to 34 years and of the older adults it ranged from 71 to 81 years.

Table 2.1. Methodological quality appraisal results. Y – yes; YL - yes, lacking detail or clarity; N – No; AV – average. A score of one indicated high quality research, with a 0.5 score indicating lack of detail or unclear information and zero indicated lower quality.

Question	Scoring criteria	Yoshino et al. (2004)	Kavanagh et al. (2006)	Helbostad et al. (2007)	Parijat et al. (2008a,b)	Granacher et al. (2010)	Olson (2010)
1. Research aims or questions stated clearly	1 – Y; 0.5 – YL; 0 - N	1	1	1	1	1	1
2. Participants detailed	Number	1	1	1	1	1	1
	Age	1	1	1	1	1	1
	Sex	1	1	1	1	1	1
	Height	0	1	0	1	1	1
	Sub Total	0.75	1	0.75	1	1	1
3. Recruitment and sampling methods described	1 – Y; 0.5 – YL; 0 - N,	0	0.5	0.5	0	0.5	0
4. Inclusion and exclusion criteria detailed	1 – Y; 0.5 – YL; 0 - N	0	0.5	1	0.5	1	0.5
5. Controlled covariates	Height	0	0	0	0	0	0
	Walking Speed	1	0	1	0	1	1
	Age	1	1	1	1	1	1
	Gender	1	1	0	1	1	1
	Limb Asymmetries	0	0	0	0	1	0
	Strength	0	1	0	1	1	0
	Sub Total	0.5	0.5	0.33	0.5	0.83	0.5
6. Key outcome variables clearly described	1 – Y; 0.5 – YL; 0 - N	1	1	1	1	1	1
7. Adequate methodology able to repeat study	Participant sampling	0	1	1	1	1	1
	Equipment	1	1	1	1	1	1
	Procedure	1	1	1	1	1	1
	Data processing	1	1	1	1	1	1
	Statistical analysis	1	1	1	1	1	1
	Sub total	0.8	1	1	1	1	1
8. Methodology able to answer research question	Participant sampling	1	1	1	1	1	1
	Equipment	1	1	1	1	1	1
	Procedure	1	1	1	1	1	1
	Data processing	1	1	1	1	1	1
	Statistical analysis	0	1	1	1	1	1
	Sub total	1	1	1	1	1	1
9. Reliability of the methodology stated	1 – Y; 0 – N	0	0	0	0	0	0
10. Internal validity of the methodology stated	1 – Y; 0 – N	0	0	0	0	0	0
11 Research questions answered adequately in the discussion	1 – Y; 0 – N	1	1	1	1	1	1
12. Key findings supported by the results	1 – Y; 0 – N	1	1	1	1	1	1
13. Key findings interpreted in a logical manner which is supported by references	1 – Y; 0 – N	1	1	1	1	1	1
14. Clinical implications stated	1 – Y; 0.5 – YL; 0 - N	0.5	1	1	1	1	1

2.4.3. Methods to Induce Muscle Fatigue

Protocols used to induce fatigue differed between the studies analyzed including isometric contractions at different percentages of maximal voluntary contraction (Olson, 2010; Kavanagh et al., 2006), isokinetic exercise (Granacher et al., 2010; Parijat and Lockhart, 2008a,b), repeated sit-to-stand transfers (Helbostad et al., 2007) and walking itself (Yoshino et al., 2004). When isometric and isokinetic contraction were used, the loads ranged from 50% to 70% of the maximum. Regarding the time to execute the fatigue protocol, studies used a fixed time period (Kavanagh et al., 2006; Yoshino et al., 2004), or the time that participant could maintain performance at a given contraction level (Granacher et al., 2010; Olson, 2010; Parijat and Lockhart, 2008a,b), or the time until the participant felt too exhausted to do more repetitions (Helbostad et al., 2007). Moreover, different muscles were fatigued. In three studies the knee extensor muscles were fatigued (Granacher et al., 2010; Parijat and Lockhart, 2008a,b; Helbostad et al., 2007), in two studies the trunk muscles [19,20], and in one study the lower limb muscles (Yoshino et al., 2004). Fatigue as defined by a decrease in force producing capacity of the muscles exercised was confirmed to be present at the end of or after the fatigue protocol in all studies but two (Helbostad et al., 2007; Yoshino et al., 2004). The latter studies did report subjective indications of fatigue and Yoshino et al. (2004) did show indications of muscle fatigue in the EMG of the tibialis anterior muscle in the largest sub-group of subjects in their study.

2.4.4. Spatiotemporal Parameters

The spatiotemporal parameters analyzed in the included studies were gait speed, stride and step length, stride time, step width, cadence, trunk accelerations, transitional acceleration and heel contact velocity. In addition, some studies addressed the variability of selected spatial and/or temporal parameters, i.e. of stride time, stride length, step width and trunk accelerations. The results are summarized per study in Table 2.2 and per parameter studied in Table 2.3.

Table 2.2. Description articles examined fatigue in walking. YA - young adults; OA - older adults; MVC - maximal voluntary contraction; ST - stride time; SL - stride length; SPL - step length; GS - gait speed; SPW - step width; HCV - heel contact velocity; TA - transitional acceleration.

AUTHORS	OBJECTIVES	GROUP	FATIGUE PROTOCOL	GAIT PARAMETERS	FATIGUE EFFECTS*
Yoshino et al. (2004)	to examine whether gait patterns and physiological rhythms are affected by fatigue	12 males (19-26yrs): Group A (long gait cycle time in the 2° half of protocol) and Group B (short gait cycle time)	to walk 3h continuously at preferred pace on ground level	ST, variability of ST, trunk acceleration	YES**
Kavanagh et al. (2006)	to examine how fatigue affects the ability to maintain head stability during walking	8 males (23±4yrs)	isometric contraction of lumbar and cervical erector spinal muscles: 60% MVC (30 s contraction, 30 s rest)	GS, ST, SPL, cadence	NO
Helbostad et al. (2007)	to investigate the effect of fatigue on trunk and foot level gait characteristics	17 females and 10 males (fatigue group: 78.2±5yrs; control group: 80.4±4.9yrs)	sit-to-stand repeatedly from a chair at a fast speed until felt too exhausted	trunk acceleration amplitudes and variability, SPW, variability of SPL SPL, GS, variability of SPW	YES NO
Parijat et al. (2008a,b)	to investigate the effects of lower muscle fatigue on gait characteristics	6 females and 10 males (24.6±3.5yrs)	isokinetic knee extension at 70% MVC until force drops below 60% MVC	HCV, TA, GS	YES NO
Granacher et al. (2010)	to examine the effects of fatigue on gait under single and dual-task conditions	16 females and 16 males (YA: 24.3±1.4yrs; OA: 71.9±5.5yrs)	max. isokinetic knee extension until force drops below 50%MVC	YA: GS, SL OA: GS, SL; YA and OA: SL variability	YES NO
Olson (2010)	to study changes in muscle activation and gait parameters with fatigue	14 females (27.5±12yrs)	isometric trunk extension at 50% or 70% MVC until force drops below 20% MVC	GS, ST, SL	NO

* We indicated only statistics effects of fatigue for free gait.

** In largest sub-group defined post-hoc based on increase in average stride time.

2.5. Discussion

The following question was addressed in this systematic review: What are the effects of fatigue on the spatiotemporal gait parameters? The literature retrieved was limited in numbers and used widely different protocols to induce fatigue and a range of different dependent variables. Strikingly the most commonly studied variables, gait speed, step or stride length and stride time did not appear to be affected in a majority of studies. Nevertheless, several other gait parameters appear to change due to fatigue, although many were reported in only one or two studies.

The effects of muscle fatigue on the spatiotemporal gait parameters appear dependent on the muscles that were fatigued, with changes being more evident when leg muscles were fatigued than when postural (trunk) muscles were fatigued. However, the studies addressing trunk muscle fatigue did not report variables related to trunk movement (e.g. medial-lateral trunk acceleration or angular displacement). Thus, when trunk muscles are fatigued, individuals appear not to modulate lower limb gait kinematics. The knee extensor muscles, which obviously have a more specific role in gait, were fatigued in most of the studies, and although lower limb kinematics appear to be affected the diversity of dependent variables studied precludes definitive conclusions.

As for exercise type, the diversity of fatigue protocols used does not allow definitive conclusions. Although isometric protocols may offer a safe, selective and standardized way of fatigue muscles (Ratel et al., 2006), the strategy of neuromuscular recruitment varies according to the task (isometric or isotonic task) (Olson, 2010) and hence results may be influenced by the task used(Ergenton et al., 2009). Therefore, inducing fatigue under dynamic conditions may be more relevant to physical performance during daily living activities (McNeil and Rice, 2007). Induction of fatigue through a functional task like walking or repeated sit-to-stand transfers as used in some of the studies likely has the advantage that results are more representative for daily life conditions. In addition to the type of exercise, the duration of the fatigue protocol may affect the results, specifically because the fatigue effects are measured over a period of walking after the protocol during which recovery may occur. Recovery after short, high-intensity exercise may be relatively fast (Lattier et al., 2004). To reflect daily activity,it has been recommended that the duration of the exercise should be controlled rather than the task intensity or workload(Ergenton et al., 2009).

Table 2.3. Description of articles results per parameter. ↑ - increase after fatigue; ↓ - decrease after fatigue; ~ - similar after fatigue; YA - young adults; OA - older adults; GS - gait speed; SL - stride length; SPL - step length; SPW - step width; ST - stride time; HC - hell contact; HCV - heel contact velocity; ang vel - angular velocity; TA - transitional acceleration; trunk accel - trunk acceleration.

	MEAN VALUES								VARIABILITY			
	Gait speed	Stride/Step length	Step width	Cadence	Stride time	Heel contact velocity	Transitional acceleration	Trunk acceleration	Stride/Step length	Step width	Stride time	Trunk acceleration
Yoshino et al. (2004)*					↑			↓			↑	
Kavanagh et al. (2006)	~	~		~	~							
Helbostad et al. (2007)	~	~	↑					↑**	↑	~		↑
Parijat et al. (2008a,b)	~					↑	↓					
Granacher et al. – YA (2010)	↓	↓							~			
Granacher et al. – OA (2010)	~	~							~			
Olson (2010)	~	~			~							

* In largest sub-group defined post-hoc based on increase in average stride time

** In frail elderly only

Only one study directly compared young and old adults, hence no definitive conclusion on the moderating effect of age can be made. The results of this study (Granacher et al., 2010), with reductions in gait speed and stride length in young adults only, suggest that young adults use a more conservative strategy (Gobbi et al., 2011; Patla, 2003) with muscle fatigue. Also other studies with young adult participants only showed indications of a more conservative strategy possibly to prevent slips, although heel contact velocity increased with fatigue, which would increase slip risk (Lockhart et al., 2005). Overall, young adults seem to modulate gait performance to increase safety. In older adults the gait pattern appears less robust with fatigue, as indicated by increased trunk accelerations and increased variability of stride length and trunk acceleration, possibly as direct effects of fatigue and concomitant loss of control (Mbourou et al., 2003; Brach et al., 2001). As possible adaptations, older adults did show an increase of step width (Helbostad et al., 2007; Helbostad and Moe-Nilssen, 2003), which would increase medio-lateral stability of gait (Hof et al., 2007). Remarkably, no evidence was found for reductions in gait speed and stride length in older adults. An increase in gait speed may decrease the mediolateral displacement of the center of mass, further contributing to medio-lateral balance control (Staszkiewicz et al., 2010; Lee and Chou, 2006; Orendurff et al., 2004). There may be a U-shaped relation between fall risk and gait speed(Helbostad and Moe-Nilssen, 2003). Possibly young adults normally walk above the speed at which their fall risk is minimal, making a decrease in speed useful for them to decrease their risk in case of fatigue. A similar decrease might not be effective in older adults who already prefer lower walking speeds than young adults (Lockhart et al., 2005).

With fatigue spatiotemporal gait parameters appear to be modulated. However, the adjustments appear to be dependent of the muscles that are fatigued, the type and duration of exercise and on the subjects' age. Fatigue coincides with a decrease in muscle strength (Ergenton et al., 2009; Petrella et al., 2005), reduced proprioceptive acuity, and delayed neuromuscular responses (Taimela et al., 1999). These changes are likely to increase fall risk during gait. Some of the changes in biomechanical gait parameters (increased heel contact velocity, increased trunk acceleration and increased variability of stride length) appear to reflect this increased risk of falling. However, simultaneously others changes (increased step width, reduced gait speed and stride length) may reflect adaptations to counteract the increase of the risk of falling.

Several limitations from this review are evident. Despite of importance the fatigue in the daily activities and gait, few studies have addressed this issue. More studies are required to understand the effects of fatigue on gait with careful consideration of subjects' age and the

muscle that are fatigued as well as the type of exercise used to do so. From the literature reviewed, we conclude that: a) fatigue appears to modulate the spatiotemporal parameters of gait b) the effects of fatigue on the spatiotemporal gait parameters appear dependent on the muscles that are fatigued; c) age appears to be a moderator of the effects of fatigue on gait.

Chapter 3

Effect of muscle fatigue and physical activity level in motor control of the gait of young adults

Submitted to Gait and Posture

3.1. Abstract

The aim of this study was to analyze the effect of muscle fatigue in active and inactive young adults on the kinematic and kinetic parameters of normal gait and obstacle crossing. Twenty male subjects were divided into active (10) and inactive (10), based on self-reported physical activity. Participants performed three trials of two tasks (normal gait and obstacle crossing) before and after a fatigue protocol, consisting of repeated sit-to-stand transfers until the instructed pace could no longer be maintained. MANOVAs were used to compare dependent variables with the following factors: physical activity level, fatigue and task. The endurance time in the fatigue protocol was lower for the inactive group. Changes of gait parameters with fatigue, among which increased step width and increased stride speed were the most consistent, were independent of task and physical activity level. These findings indicate that the kinematic and kinetic parameters of gait are affected by muscle fatigue irrespective of the physical activity level of the subjects and type of gait. Inactive individuals used a slightly different strategy than active individuals when crossing an obstacle, independently of muscle fatigue.

3.2. Introduction

Fatigue affected the performance of daily activities, such as walking. To maintain motor performance in the presence of fatigue, adjustments in temporal and spatial parameters of gait are required (Parijat and Lockhart, 2008a,b; Helbostad et al., 2007). Fatigue effects are task-dependent (Brujin et al., 2009; Enoka and Duchateau, 2008) and may thus be different for gait in environments of different complexity. While fatigue effects on gait characteristics have been studied to some extent in an unobstructed environment allowing free gait, characteristics of adaptive gait for example to cross or circumvent obstacles, as is commonly required in daily locomotion (Vitório et al., 2010), has to our knowledge not been studied previously.

Gait characteristics appear to be influenced by physical activity levels, with inactive individuals showing differences from active individuals in free gait reflective of a poor neuromuscular condition affecting both balance control and propulsion (Gotshalk et al., 2008; Katsiaras et al., 2005). In adaptive gait, inactive individuals showed a lower walking speed and increased foot-obstacle horizontal distance of the leading limb compared to active individuals (Niang and McFadyen, 2005). Physical activity levels also mediate fatigue development (Katsiaras et al., 2005), with inactive individuals being more fatigable than active individuals (Viner et al., 2008), and may alter fatigue effects on motor performance.

The aim of this study, therefore, was to analyze the effects of muscle fatigue in active and inactive young adults on the kinematic and kinetic parameters of free and adaptive gait. We expected that the motor control of free and adaptive gait would be dependent on the physical activity level before and after fatigue induction and hypothesized interaction effects between physical activity level and fatigue. Furthermore, we expected that muscular fatigue affect free and adaptive gait differently. We analyzed spatial-temporal gait characteristics, which have been related to fall risk or have been shown adapted to decrease fall risk (e.g. gait speed, step duration, step width). In addition, we looked at the spatial relations between the feet and the obstacle, which determine the probability of tripping over or stepping on the obstacle. Finally, we analyzed vertical ground reaction forces to characterize weight acceptance and horizontal forces to provide insight into how speed is modulated.

3.3. Material and Methods

3.3.1. Participants

Thirty young male adults participated of this study. The exclusion criteria of the study were factors that could interfere with gait and other experimental procedures, such as medication use, presence of osteomyoarticular, neuromuscular or cardio-respiratory diseases and balance and vision disorders. Ten recruited subjects did not fit the criteria of the study. So, twenty individuals were included in the study sample. Theywere distributed into active and inactive (Table 3.1).

The study was approved by the local Ethics Committee (2055/2008). The active group was composed of individuals who performed physical activity for more than three months for at least three times a week and at least one hour per day and the inactive group was composed of individuals who had not performed regular physical activity in at least the last three months (Greaves et al., 2011; Florindo et al., 2009). In addition, participants filled out the Questionnaire of Habitual Physical Activity (Baecke et al., 1982). In this questionnaire the responses are scored on a five-point scale and result in three different indices reflecting physical activity during work, leisure time excluding sport and sport activities. The summation of the three indices was defined as the overall physical activity index. The values for the active group were ≥ 9 and the inactive group scored ≤ 7 (Cocker et al., 2009).

3.3.2. Experimental design

Participants were instructed not to perform any strenuous physical activity 48h before evaluation. The experiment was divided into two days. On the first day, participants filled out a questionnaire on medical history, the Questionnaire of Habitual Physical Activity and the Multidimensional Fatigue Inventory (Smets et al., 1995). The latter was used to determine the presence of fatigue prior to study, and no fatigue was found for both groups (Table 3.1). In addition, the anthropometric measurements were performed.

At the beginning of the second day, there was a warm-up period of 5min, with walking, stretching and movements in the Leg Press. After that, participants performed the trials of free and adaptive gait following the maximum voluntary isometric contractions. Immediately after the he maximum voluntary isometric contractions, the fatigue protocol was performed. Subsequently, the gait tests and the maximal voluntary contractions were performed once again.

3.3.3. Gait task

Three trials for each experimental condition, free and adaptive gait, with the order randomly defined were performed before and after the fatigue protocol. The starting point of each gait trial was adjusted to ensure that the obstacle was crossed with the right leg and that at least two strides were completed prior to obstacle crossing. The instruction given to the participant was to walk over an 8m pathway, at self-selected speed. For the adaptive gait trials, the participant was instructed to avoid contact with the obstacle (15 cm high, 80 cm wide and 2 cm thick), which was positioned between two force platforms. For free gait we analyzed the stride (period between two consecutives heel contacts of the left limb) in the middle of the pathway, which was compared to the stride preceding the obstacle crossing for adaptive gait (approach phase). For adaptive gait, we additionally analyzed the crossing step (from heel contact of the left limb in front of the obstacle to heel contact of right limb behind the obstacle) and the step (from heel contact of the right limb behind the obstacle to heel contact of left limb behind the obstacle) after crossing the obstacle (N+1).

3.3.4. Data collection

Ground reaction forces were measured using two force plates (AccuGait, Advanced Mechanical Technologies) at a sample rate of 200 samples/s, positioned across the central area of the pathway (20 cm away from each other). Acquisition of kinematic gait parameters was accomplished with a three-dimensional optoelectronic system (OPTOTRAK Certus), positioned in the sagittal right plane, using a sample rate of 100 samples/s. Four infrared emitters were placed over the following anatomical points: lateral face of calcaneus and head of the fifth metatarsus of the right limb, and medial face of calcaneus and head of the first metatarsus of the left limb. To determine the heel contact and toe-off of the limbs during gait, only the markers on the calcaneus and toe were used (O'Çonnor et al., 2007). The data acquisition systems were electronically synchronized.

3.3.5. Isometric force measurements

After the free and adaptive gait trials, maximum voluntary isometric contractions were performed in a Leg Press device (Gotshalk et al., 2008). A load cell with precision of 0.98N was used in combination with a signal amplifier (EMG System do Brasil Ltda.). The participant performed the test with both legs, with the instruction to produce maximum force as fast as possible. Total contraction duration was 5 s. The participants were seated in a backward inclined chair, with the hip joint at 90° (180° is full extension) and knee joint at

110° (180° is full extension). Participants performed two attempts before and after the fatigue protocol, with 2 min rest between attempts. The means of the two attempts before and after muscle fatigue were calculated for each participant.

3.3.6. Fatigue protocol

To induce fatigue, the participant performed the sit-to-stand task, with arms across the chest region from a chair (Helbostad et al., 2007), with the speed controlled by a metronome (30 beats/min). So, the cycle of sitting to standing and back to sitting was performed in 2 s. A standard chair (43 cm in height, 41 cm in width, 42 cm in depth) without arm rests was used for all participants. The instruction given to the participants was: stand up to an upright position with your knees fully extended, then sit back down and repeat this at the beat of the metronome until you can no longer perform the task.

The fatigue protocol was stopped and it was assumed that the leg muscles were fatigued when the subject indicated not to be able to continue the task, or when the subject no longer performed at the desired movement frequency, or after 30 min. The time between the fatigue protocol and the gait trials (< 3 min) was expected not to allow full recovery (Parijat et al., 2008b).

3.3.7. Data analysis

All the data were digitally filtered using zero-lag Butterworth filter. Kinematic data were filtered with a 5th order low-pass filter with cutoff frequency of 6Hz. Kinetic data were filtered with 4th order filter with cutoff frequency of 16Hz, and the magnitude of the ground reaction force was normalized by body weight. For free and adaptive gait (approach phase), the stride length, step width, stride duration, single and double support duration, speed in the stride (stride length divided by stride duration), maximum braking and propulsive vertical and anterior-posterior forces, and braking latency time (time between the foot contact with the ground and the maximum braking force) of the vertical forces were measured. For adaptive gait trials, step length, step width, step duration, single and double support duration and speed for the obstacle crossing and N+1 steps, the foot-obstacle distance before and after obstacle crossing, and toe-clearance for the leading and trailing limbs were calculated. Moreover, the maximum force in the maximum voluntary contractions and the endurance time in the fatigue protocol were measured.

3.3.8. Statistical analysis

The dependent variables of interest were statistically analyzed with SPSS 15.0 for Windows® (α <0.05). The data were normally distributed, verified by the Shapiro-Wilk test. To verify the similarity between groups, the anthropometric characteristics, age, Multidimensional Fatigue Inventory values, maximum force and kinematic and kinetic variables before fatigue induction were compared through the Student t test for independent groups. The same statistical test was used to compare the endurance times between groups. To verify the development of fatigue, the Student t test for paired samples was applied on the maximum force values before and after the fatigue protocol for each group. The dependent variables of free and adaptive gait were compared using MANOVAs. One MANOVA was used for kinematic data of free gait and the approach phase of adaptive gait, with as independent variables level of physical activity (active and inactive), fatigue (before and after) and task (free and adaptive gait), with repeated measures over the last two factors. A similar MANOVA was used for kinetic data of the first force platform. The third MANOVA was for the kinetic data of the second force plate in adaptive gait and had level of physical activity and fatigue as independent variables, with repeated measures over fatigue. Similarly two MANOVAs were performed for kinematics of obstacle crossing and step N+1. When MANOVA revealed a main effect, univariate analyses were used to locate the differences.

3.4. Results

The active and inactive groups were similar for age, anthropometric characteristics, muscle strength, fatigue level (Table 3.1) and different only with respect to body fat percentage ($t_{1,8}$=-3.3, p<0.01). The fatigue protocol did induce fatigue in both groups as demonstrated by the lower maximum voluntary forces (active individuals: $t_{1,9}$=4.1, p<0.01; inactive individuals: $t_{1,9}$=2.6, p<0.01). Among the active participants, four individuals performed for the full 30 min; among the inactive participants none completed the full 30 min. Mean endurance time was shorter in the inactive individuals (Table 1; $t_{1,8}$=2.4, p<0.02).

Table 3.1. Mean and standard deviation of the general characteristics, anthropometric measure, scores on the Multidimensional Fatigue Inventory and Habitual Physical Activity, maximal isometric force before (pre) and after (post) induction to fatigue and endurance time to fatigue for each group. * pre ≠ post; + active group ≠ inactive group.

Variables		Group	
		Active (n=10)	Inactive (n=10)
Age (months)		296.5 ± 34.2	296.9 ± 35.4
Weight (kg)		73.2 ± 4.4	82.7 ± 17.6
Height (cm)		178.7 ± 10.1	178.8 ± 5.6
Percentage of body fat		9.6 ± 4.1+	20.1 ± 8.9
Multidimensional Fatigue Inventory (points)		47.5 ± 5.6	46.9 ± 10.3
Habitual Physical Activity (points)		10.4 ± 1.49+	5.9 ± 1.2
Maximal isometric force (N)	**pre**	3346.7 ± 1002.3*	3099.1 ± 1351.9
	post	2923.2 ± 1132.4*	2730.8 ± 1302.1
Endurance time to fatigue (s)		1018.4 ± 697.4+	416.4 ± 381.7

Before fatigue, the groups were similar for all gait variables. Analysis of the kinematics of free gait and the approach phase in adaptive gait revealed main effects of task (Wilks' Lambda=0.58, $F_{7,12}$=27.70, p<0.01) and fatigue (Wilks' Lambda=0.33, $F_{7,12}$=3.40, p<0.03) only.

For task (Table 3.2), univariate analyses indicated that free gait coincided with shorter stride durations ($F_{1,18}$=9.95, p<0.01) and double support duration ($F_{1,18}$=107.08, p<0.01), larger stride length ($F_{1,18}$=23.58, p<0.01), higher speed ($F_{1,18}$=23.56, p<0.01) and longer single support duration ($F_{1,18}$=5.83, p<0.02). With respect to fatigue (Table 3.3), univariate analyses showed that fatigue coincided with increased step width ($F_{1,18}$=18.11, p<0.01) and speed ($F_{1,18}$=10.09, p<0.01), and decreased single support ($F_{1,18}$=6.58, p<0.01) and stride durations ($F_{1,18}$=10.89, p<0.01).

For the kinetic data of free gait and adaptive gait, the MANOVA indicated an effect of task (Wilks' Lambda=0.09, $F_{7,12}$=16.114, p<0.01) and fatigue (Wilks' Lambda=0.29, $F_{7,12}$=4.17, p<0.01). Specifically for task (Table 3.2), the univariate analyses showed that adaptive gait coincided with greater maximum braking and propulsive vertical forces ($F_{1,18}$=114.70, p<0.01 and $F_{1,18}$=22.07, p<0.01) as well as greater maximum braking and propulsive anterior-posterior forces ($F_{1,18}$=89.31, p<0.01 and $F_{1,18}$=24.29, p<0.01). For fatigue (Table 3.4), the analysis indicated that fatigue coincided with a lower vertical maximum braking force ($F_{1,18}$=5.55, p<0.03).

Table 3.2. Mean and standard deviation of the free and adaptive gait variables. Kinematics variable of approach phase and kinetic variables. BW – body weight. # free gait ≠ adaptive gait.

Dependent variables	Free gait	Adaptive gait
stride length (cm)	135.91±11.74#	131.30±10.50
step width (cm)	12.10±2.70	12.57±2.91
single support duration (s)	0.77±0.05#	0.75±0.07
double support duration (s)	0.29±0.4#	0.35±0.04
stride duration (s)	1.07±0.08#	1.11±0.10
stride speed (cm/s)	127.21±17.17#	119.22±14.27
maximum braking vertical force (BW)	1.08±0.07#	1.20±0.08
maximum propulsive vertical force (BW)	1.11±0.05#	1.17±0.05
braking latency time of vertical force (ms)	0.18±0.02#	0.16±0.02
maximum braking anterior-posterior force (BW)	0.15±0.03#	0.20±0.04
maximum propulsive anterior-posterior force(BW)	0.19±0.03#	0.24±0.04

Concerning obstacle crossing and N+1 variables (Table 3), the MANOVAs showed an effect of fatigue (Wilks' Lambda=0.14, $F_{10,9}$=5.38 p<0,01 and Wilks' Lambda=0.31, $F_{6,13}$=4.64, p<0,01). For obstacle crossing and N+1, univariate analyses revealed that fatigue coincided with a larger step width ($F_{1,18}$=6.37, p<0.01 and $F_{1,18}$=27.33, p<0.01), shorter double support time ($F_{1,18}$=7.51, p<0.01 and $F_{1,18}$=16.33, p<0.01), and higher speed ($F_{1,18}$=5.35, p<0.03 and $F_{1,18}$=8.34, p<0.01). In addition, for N+1 only we found a shorter step duration ($F_{1,18}$=6.55, p<0.02) after fatigue.

In the kinetic data of the force platform after the obstacle (Table 3.4), the MANOVAs showed an effect of physical activity level (Wilks' Lambda=0.35, $F_{7,12}$=3.09 p<0,04). The univariate analyses showed that inactive individuals produced a higher maximum braking anterior-posterior force ($F_{1,18}$=7.1, p<0.01) and maximum propulsive vertical force ($F_{1,18}$=6.42, p<0.02).

Table 3.3. Mean and standard deviation of spatial and temporal parameters according to fatigue (independently task and physical activity level) and physical activity level (independently task and fatigue). Kinematic variables of free gait/approach phase, crossing obstacle (N) and step after crossing (N+1). LL – leading limb; TL – trailing limb. * pre (before fatigue) ≠ post (after fatigue).

Dependent variables	Moments	Pre	Post	Active	Inactive
stride/step length (cm)	free/approach	135.66±11.71	130.82±10.57	132.65±8.72	134.55±13.77
	N	71.67±8.01	72.79±7.17	73.55±7.28	70.94±8.49
	N+1	65.22±6.27	66.52±7.08	63.70±7.48	68.04±6.63
step width (cm)	free/approach	11.48±2.51*	11.80±2.70	11.97±3.09	12.70±2.94
	N	10.58±2.67*	12.80±3.06	11.96±3.18	11.41±4.08
	N+1	14.22±4.36*	16.11±6.02	14.32±5.47	16.01±5.46
single support duration (s)	free/approach	0.78±0.06*	0.76±0.07	0.78±0.04	0.74±0.07
	N	0.42±0.05	0.42±0.06	0.43±0.04	0.40±0.06
	N+1	0.50±0.06	0.50±0.06	0.50±0.05	0.50±0.08
double support duration (s)	free/approach	0.30±0.04	0.35±0.04	0.32±0.04	0.32±0.06
	N	0.20±0.04*	0.18±0.04	0.19±0.04	0.20±0.06
	N+1	0.16±0.02*	0.15±0.02	0.16±0.02	0.15±0.03
stride/step duration (s)	free/approach	1.08±0.09*	1.12±0.10	1.11±0.08	1.07±0.11
	N	0.62±0.09	0.61±0.07	0.63±0.07	0.60±0.11
	N+1	0.67±0.07*	0.65±0.07	0.66±0.07	0.66±0.09
stride/step speed (cm/s)	free/approach	121.60±15.81*	124.83±16.62	119.49±11.96	126.93±19.58
	N	117.66±28.37*	124.66±36.33	117.14±19.24	125.18±28.18
	N+1	98.88±15.62*	103.80±18.62	96.91±18.23	106.43±18.26
foot-obstacle distance before obstacle - LL (cm)	N	112.66±10.13	113.96±9.75	112.43±8.88	113.98±13.00
toe-clearance - LL (cm)	N	9.09±3.01	9.38±2.91	8.36±2.40	10.06±3.78
foot-obstacle distance after obstacle - LL (cm)	N	24.22±4.78	24.42±5.24	24.91±6.30	23.73±6.15
foot-obstacle distance before obstacle - TL (cm)	N	48.18±6.19	48.41±6.36	49.68±6.45	46.77±8.08
toe-clearance - TL (cm)	N	31.28±3.64	30.16±4.59	29.65±5.85	31.65±4.67
foot-obstacle distance after obstacle - TL (cm)	N	89.62±8.64	91.05±10.37	88.81±11.29	91.78±10.19

3.5. Discussion

The aim of this study was to analyze the effect of muscle fatigue in active and inactive young adults on the kinematic and kinetic parameters of free and adaptive gait. The expectations of the study were confirmed in part, by showing that muscle fatigue interferes with spatial-temporal and kinetic parameters of free and adaptive gait, but fatigue effects were not different between active and inactive individuals. Active young adults showed greater endurance in the fatigue induction protocol than inactive young adults. Furthermore, the changes in the spatial-temporal gait parameters with fatigue were independent of the type of gait.

The adjustments in adaptive gait compared to free gait consisted of increased stride and double support durations and decreased stride length, single support duration and stride speed. This speed modulation appears to be caused by a larger magnitude of the negative horizontal (braking) force in the last stride before crossing the obstacle. Locomotion in complex environments requires adaptive ability from the locomotor system (Krell and Patla, 2002) and more attention (Bradshaw and Sparrow, 2001), especially when crossing an obstacle (Gobbi et al., 2011; Silva et al., 2011). Reduced speed allows more exploration and collection of relevant information and more time for planning the action (Tresilian, 2004). The decreased step length, gait speed and stride duration appear to disclose the use of such proactive mechanisms for modulation of the effector system according to the perceived environmental characteristics (Gerin-Lajoie et al., 2005) and an anticipatory strategy to guarantee dynamic stability during obstacle crossing (Patla, 2003). From this perspective, we expected more pronounced changes with fatigue in adaptive gait than in free gait, which were, however, not observed.

Table 3.4. Mean and standard deviation of kinetic parameters according fatigue (independently task and physical activity level) and physical activity level (independently task and fatigue). Kinetic variables of free gait/approach phase and crossing obstacle (N). * pre (before fatigue) ≠ post (after fatigue); + active group ≠ inactive group.

Dependent variables	Moments	Pre	Post	Active	Inactive
maximum braking vertical force (BW)	free/approach	1.15±0.09*	1.12±0.10	1.13±0.10	1.14±0.10
	N	1.15±0.11	1.12±0.08	1.11±0.09	1.16±0.11
maximum propulsive vertical force (BW)	free/approach	1.15±0.06	1.14±0.06	1.13±0.06	1.16±0.07
	N	1.10±0.06	1.10±0.07	1.07±0.07+	1.13±0.12
braking latency time of vertical force (ms)	free/approach	0.17±0.02	0.17±0.03	0.17±0.02	0.17±0.03
	N	0.17±0.03	0.16±0.04	0.17±0.03	0.17±0.04
maximum braking anterior-posterior force (BW)	free/approach	-0.18±0.04	-0.17±0.04	-0.16±0.04	-0.19±0.04
	N	-0.26±0.09	-0.25±0.09	-0.22±0.03+	-0.26±0.02
maximum propulsive anterior-posterior force (BW)	free/approach	0.22±0.04	0.21±0.04	0.20±0.04	0.23±0.04
	N	0.13±0.10	0.15±0.10	0.12±0.03	0.14±0.03

The fatigue protocol used can be expected to mainly affect the quadriceps muscles. Indeed, knee extension strength was reduced after the fatigue protocol. Reduced strength after exercise is considered the indication of muscle fatigue in accordance with its definition as a loss of force generating capacity (Katsiaras et al., 2005; Bigland-Ritchie and Woods, 1984). The decrease of the maximum vertical force in the braking phase in both tasks may be a consequence of this loss of force producing capacity, through decreased knee stiffness during weight acceptance. Moreover, in the approach phase of stepping down, we found that quadriceps muscle fatigue coincided with a decreased muscle activity of the quadriceps muscle (Barbieri et al., 2012c). Quadriceps fatigue adversely affects knee proprioception (Bigland-Ritchie and Woods, 1984), postural control in single leg stance (Paillard et al., 2010), and has been associated with an increased risk of falling (Parijat and Lockhart, 2008a,b; Lattanzio et al., 1997). Modulations in performance with fatigue were not task-dependent. One possible explanation is that, despite that individuals did need to adjust their gait when the obstacle was present, this task is not very challenging for young adults. Possibly fatigue of another muscular group or a more challenging adaptive task could show different results.

The participants in this study appeared to seek more stability during gait after the fatigue protocol than before. They increased step widths in both free and adaptive gait as was previously demonstrated in elderly adults in free gait (Helbostad et al., 2007). Increased step width provides a larger margin of safety in controlling medio-lateral movements of the body's center of mass (Hof et al., 2007). Participants also reduced stride durations and related variables, such as durations of single and double support, as well as braking forces, irrespective of the type of task. Reduced step duration, facilitates control of the body center of mass in the fore-aft direction (Hof et al., 2007; Hof et al., 2005) and appears to be the preferred strategy to deal with balance threats (Hak et al., 2012) even if this coincides with an increased speed (Brujin et al., 2009) as was the case in the present study. In line with the present results, increased gait speed with fatigue was found in older people (Granacher et al., 2010). This may be a direct consequence of the reduction in step duration. On the other hand participants may have tried to perform the task as quickly as possible (Granacher et al., 2010) and the increase in speed could be a risky strategy that decreases the reaction and processing time required to cross the obstacle (Gobbi et al., 2011; Silva et al., 2011; Tresilian, 2004), which may be compensated for by larger step width (Helbostad and Moe-Nilssen, 2003). Previous authors have suggested that muscle fatigue increases fall risk (Parijat and Lockhart, 2008a,b), however this was based on an increased heel contact velocity, which mainly relates

to the risk of slipping. In the present study, we did not find a decrease in braking latency time, which would indicate a less safe weight transfer to the new stance leg. Furthermore, toe-clearance, the most obvious indicator of the risk of tripping in the adaptive gait task, did not change with fatigue in either leg.

Active and inactive young adults showed almost the same behavior before and after muscle fatigue. The active group had a better muscular capacity, as reflected by the longer endurance times. However, muscle strength before and after fatigue was not different between groups. A similar general locomotor strategy for active and inactive young adults was previously found in free gait and adaptive gait (Niang and McFadyen, 2005). However, gait speed and speed of the leading leg in crossing an obstacle were higher in the active participants (Niang and McFadyen, 2005). In the present study, the only difference between groups was found also for the leading leg in the crossing step, where inactive individuals produced a higher maximum braking anterior-posterior force. This suggests a somewhat more cautious strategy, reducing gait speed even further after the first step over the obstacle, to facilitate crossing of the trailing limb. The subsequent maximum propulsive vertical force was higher and there was tendency towards a similar effect in the horizontal force, probably to increase gait speed again after the obstacle is crossed.

Some limitations of this study are evident. The use of a standard chair for all participants may induce early fatigue in taller individuals. The fixed height of the obstacle can similarly have increased between-subject variance, in this case affecting smaller individuals. However, in everyday motor tasks, individuals of different stature use the same chairs and cross-similar height obstacles, with 15cm being comparable to the standard curb height. Furthermore, the groups had similar height, body weight and gait variables before fatigue, avoiding a possible interference of these limitations in the results. Finally, we used a relatively small sample of participants (ten young adults in each group). Considering these limitations, generalization of especially negative results should be done with care.

In the present study, kinematic and kinetic parameters of gait were affected by muscle fatigue irrespective of the physical activity level of the subjects. For free and adaptive gait, muscle fatigue did not have task-dependent effects. Inactive individuals used a slightly different strategy than active individuals when crossing an obstacle, independently of muscle fatigue.

Chapter 4

Interactions of age and knee muscle fatigue in walking and obstacle crossing

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4.1. Abstract

Older adults commonly report muscle fatigue that is associated with reduced walking ability. The aim of this study was to analyze the interaction effects of aging and knee muscle fatigue on gait parameters in walking and obstacle crossing. One hundred and twenty men, who were divided in six groups according to their age, participated in this study. Participants performed three trials of normal gait and obstacle crossing before and after knee muscle fatigue. Spatial-temporal gait parameters were analyzed, and compared by two-way ANOVA (group and fatigue). The results confirmed our hypothesis, showing age-related effects of knee muscles fatigue in both gait conditions. From 40 years on, participants modulated spatial-temporal in both tasks more in response to fatigue than younger participants, apparently to improve stability and safety. In conclusion, the knee muscle fatigue caused age-dependent changes in both level gait and obstacle crossing.

4.2. Introduction

Loss of functional ability occurs with ageing due to decreased muscle strength, and declined information processing (Helbostad et al., 2010; Norris et al., 2009; Kang and Dingwell, 2008; Kovacs, 2005). As a result, elderly show limitations in locomotion, and a higher incidence of stumbles and falls (Mitchell, 2011; Galna et al., 2009). The annual incidence of falls is 30% in people over 65 years and 50% in people over 80 years (Mitchell, 2011). As a compensation, elderly walk more cautiously, with increased cadence (Laufer, 2005; DeVita and Hortobagyi, 2000), increased double support time (Laufer, 2005; Petrofsky et al., 2004; Shkuratova et al., 2004) decreased gait speed (Laufer, 2005; Petrofsky et al., 2004; Riley et al., 2001) and decreased stride length (Lockhart et al., 2007; Riley et al., 2001; DeVita and Hortobagyi, 2001). Additionally, when crossing obstacles, older adults adopt a conservative strategy, which is characterized again by decreased speed (Lowrey et al., 2007; McFadyen and Prince, 2002) and step length (Yen et al., 2009; Lowrey et al., 2007; Lu et al., 2006; McFadyen and Prince, 2002) in the step crossing the obstacle.

Older adults commonly report fatigue (Vestergaard et al., 2009; Liao and Ferrell, 2000) and muscle fatigue is associated with restricted activity and reduced walking ability (Helbostad et al., 2010; Vestergaard et al., 2009). Experimentally, muscle fatigue has been shown to reduce gait stability (Parijat and Lockhart, 2008a,b; Helbostad et al., 2007), change gait spatial-temporal parameters (Barbieri et al., 2012a,b,c; Murdock and Hubley-Kozey, 2012; Granacher et al., 2010; Parijat and Lockhart, 2008a,b; Helbostad et al., 2007), and it may limit generation of fast corrective movements. Aging may affect the adjustments to muscle fatigue. To our knowledge, only Granacher et al. (2010) have investigated age-related effects of muscle fatigue on gait. They found that, in walking on a level surface, young adults decreased gait speed and stride length with muscle fatigue, while older adults increased both speed and stride length.

The aim of this study was to analyze the impact of age and knee muscle fatigue on gait parameters while walking over a level surface and in obstacle crossing. We hypothesized that interaction effects of age and fatigue would occur in walking over a level surface and in obstacle crossing.

4.3. Material and Methods

4.3.1. Participants

Over two hundred men were invited to participle in the study. One hundred and twenty individuals reached the inclusion criteria: factors that could interfere with gait, diabetes disease and other experimental procedures, such as medication use, presence of osteomyoarticular, neuromuscular or cardio-respiratory diseases and balance and vision disorders. The participants were distributed in six groups, 20 individuals in each group, according their age: G20 – from 20 years old to 29 years old; G30 – from 30 years old to 39 years old; G40 – from 40 years old to 49 years old; G50 – from 50 years old to 59 years old; G60 – from 60 years old to 69 years old; G70 – above 70 years old (Table 4.1). The study was approved by the local Ethics Committee (#2055/2008).

4.3.2. Procedures

After agree to be enrolled in this study, participants were instructed not to perform any strenuous physical activity 48 h before evaluation. The individuals filled out a questionnaire on medical history. In addition, the anthropometric measurements were performed. In sequence, the participants performed a warm-up period of 5 min, with walking, stretching and movements in the Leg Press.

The sequence of experiment was: a) maximum voluntary contraction protocol; b) gait trials; c) muscle fatigue protocol; d) gait trials; e) maximum voluntary contraction protocol.

4.3.3. Maximum voluntary contraction protocol

Maximum voluntary isometric contractions were performed in a Leg Press device (Barbieri et al., 2012c). A load cell with precision of 0.98 N was used in combination with a signal amplifier (EMG System do Brasil Ltda.). The participant performed the test with both legs, with the instruction to produce maximum force as fast as possible. Total contraction duration was 5 s. Two attempts were made with 2 min rest between attempts before and after muscle fatigue.

4.3.4. Gait trials

Participants performed three trials of both even and uneven gait. The order of trials was randomized for each participant. The instruction given to the participant was to walk over an 8 m pathway, at self-selected speed. For the uneven gait trials, the participant was

instructed to avoid contact with the obstacle (15 cm high, 80 cm wide and 2 cm thick), which was positioned between two force platforms in the midway down the pathway. The starting point of each gait trial was adjusted to ensure that the obstacle was crossed with the right leg and that at least two strides were completed prior to obstacle crossing.

Acquisition of kinematic gait parameters was accomplished with a three-dimensional optoelectronic system (OPTOTRAK Certus), positioned in the right sagittal plane, using a sample rate of 100 samples/s. Four infrared emitters were placed over the following anatomical points: lateral face of calcaneus and head of the fifth metatarsus of the right limb, and medial face of calcaneus and head of the first metatarsus of the left limb. The data acquisition systems were electronically synchronized.

4.3.5. Muscle fatigue protocol

To induce fatigue, each participant performed the sit-to-stand task, with arms across the chest region from a chair (Barbieri et al., 2012a,b,c), with the speed controlled by a metronome (30 beats/min). So, the cycle of sitting to standing and back to sitting was performed in 2 s. A standard chair (43 cm in height, 41 cm in width, 42 cm in depth) without arm rests was used for all participants. The instruction given to the participants was: stand up to an upright position with your knee joints fully extended, then sit back down and repeat this at the beat of the metronome until you can no longer perform the task. The fatigue protocol was stopped when the participant indicated that he or she was unable to continue, when the movement frequency fell below and remained below 0.5 Hz after encouragement, or after 30 min. Immediately after the fatigue protocol, the participant performed the gait trials and the maximal voluntary contractions once again. The time between the fatigue protocol and the gait trials (< 3 min) was expected not to allow full recovery (Parijat and Lockhart, 2008b). The rate of perceived exertion was measured by Borg Scale (Borg, 1982) at the beginning and the end of protocol. Finally, the endurance time during the fatigue protocol was recorded.

4.3.6. Data analysis

The mid-pathway stride was analyzed for level gait. In this stride, we determined stride length, duration, and speed (step length divided by step duration), and step width. For obstacle crossing trials, the crossing steps (the steps with which the individual crossed the obstacle) were analyzed. The step parameters (length, duration, speed and width), the trailing and leading foot-obstacle distance before and after obstacle crossing, and trailing and leading

toe-clearance were calculated. Finally, the maximum force in the maximum voluntary contractions was determined.

All the data were digitally filtered using zero-lag Butterworth filters. Kinematic data were filtered with a 5th order low-pass filter with cutoff frequency of 6 Hz. The dependent variables of interest were statistically analyzed with SPSS 15.0 for Windows® ($\alpha < 0.05$). The data were normally distributed, as verified by the Shapiro-Wilk test. To verify the similarity between groups before knee muscle fatigue, the anthropometric characteristics, age, endurance time and final rate of perceived exertion were compared through an ANOVA with age group as the only factor (G20, G30, G40, G50, G60 and G70). The spatial-temporal of level gait and obstacle crossing, and maximum isometric force were compared using a two-way ANOVA, with group and fatigue (without and with knee muscle fatigue), with repeated measures over the last factor. We performed three ANOVAs, one for level gait, one for obstacle crossing, and one for maximum isometric force.

4.4. Results

The characteristics of each group are presented in Table 4.1. The groups had similar body mass, but the G70 individuals were shorter than all other groups.

The fatigue protocol did induce fatigue in all groups as demonstrated by the lower values of maximum voluntary forces and almost maximum rate of perceived exertion at the end of the protocol (Table 4.1). For maximum isometric force, univariate analyses indicated a main effect of group ($p<0.001$) and fatigue ($p<0.001$), with a group*fatigue interaction ($p<0.001$). For group, the G60 and G70 groups had lower isometric force values than the G20, G30 and G40 groups. For fatigue, there was a decrease in maximum isometric force after the fatigue protocol. For the interaction group*fatigue, all groups decreased the isometric force after fatigue with G50 showing a larger reduction (25.7% versus 11.6% on average in the other groups). The final rate of perceived exertion was not different between groups. However, there was a difference in endurance times between groups. Values for the G20 group were higher than for the G70, and values for the G30 group were higher than for the G60 and G70 groups.

Table 4.1. Subject characteristics, endurance time, rating of perceived exertion (RPE) and maximum isometric force for each group. Pre – without muscle fatigue; post – with muscle fatigue. P-values indicate the effects of group. Only for maximal isometric force, p-value indicates interaction group*fatigue.

Variables		G20	G30	G40	G50	G60	G70	p-values
age (years)		24.00±2.88	32.5±2.74	44.00±2.98	54.5±3.25	64.00±2.68	74.50±4.50	**0.001**
weight (kg)		77.96±14.74	79.26±14.23	84.63±15.51	82.17±13.40	77.99±12.61	73.00±12.26	0.15
height (m)		1.78±0.04	1.74±0.06	1.75±0.06	1.71±0.07	1.71±0.06	1.65±0.06	**0.001**
endurance time (min)		12.00±10.50	12.90±11.00	8.60±9.80	6.50±7.00	4.8±3.43	3.00±2.49	**0.001**
RPE (maximum = 20)		19.15±1.14	18.70±1.42	18.60±1.31	18.65±3.08	18.60±1.60	17.39±1.61	0.07
maximal isometric force (N)	**pre**	3269.28±1170.72	4012.97±1014.06	3610.14±685.43	3009.34±1078.21	2420.07±929.41	2765.02±935.44	**0.001**
	post	2878.65±1194.63	3320.91±896.55	3293.85±532.45	2235.28±818.39	2223.84±633.16	2433.96±711.76	

4.4.1. Level gait

Univariate analyses indicated main effects of group and fatigue for all spatial-temporal and some kinetic variables (Table 4.2). Moreover, there were group*fatigue interactions for stride length, stride duration, double support duration, stride velocity, braking latency fatigue, braking vertical impulse and propulsive vertical impulse (Figure 4.1).

Regarding the group*fatigue interactions for the spatial-temporal variables, the older groups (G40, G50, G60 and G70, significantly so G40 and G70) increased stride length with knee muscle fatigue, while the younger groups (G20 and G30) did not show an effect of muscle fatigue. All groups reduced stride duration with muscle fatigue, but the oldest groups (G60 and G70) decreased stride duration more. Moreover, all groups increased stride speed with muscle fatigue, but the older (G40, G50, G60 and G70) groups showed a larger increase of stride speed in comparison to the youngest (G20 and G30) groups.

4.4.2. Obstacle crossing

For most spatial-temporal parameters (Table 4.3), univariate analyses indicated main effects of group and fatigue. Moreover, there were group*fatigue interactions for step duration, trailing foot-obstacle distance before obstacle, and trailing and leading toe-clearance (Figure 4.2).

Table 4.2. Means and standard deviations of spatial-temporal and kinetic variables in level gait by group without and with muscle fatigue. For each variable, the first line is without knee muscle fatigue and the second line is with knee muscle fatigue. The last three columns show the p-values for main effects of group and fatigue and for the group*fatigue interaction, respectively.

Variables	G20	G30	G40	G50	G60	G70	group	fatigue	group* fatigue
spatial-temporal variables									
stride length (cm)	135.67±11.71 136.15±12.05	134.25±10.19 134.62±12.25	131.00±8.20 133.97±7.70	137.07±13.93 138.97±14.57	135.35±13.10 139.55±12.70	124.18±13.49 128.62±15.41	**0.001**	**0.001**	**0.001**
step width (cm)	11.48±2.70 12.73±3.06	11.42±2.42 12.78±2.69	12.85±3.59 14.06±2.99	11.80±2.87 13.01±3.30	9.97±2.60 10.96±2.71	10.22±2.50 11.10±2.67	**0.001**	**0.001**	0.9
stride duration (s)	1.09±0.10 1.07±0.08	1.11±0.24 1.09±0.25	1.10±0.09 1.06±0.09	1.07±0.07 1.05±0.08	1.10±0.08 1.06±0.07	1.08±0.11 1.04±0.11	**0.03**	**0.001**	**0.001**
stride velocity (cm/s)	125.73±17.32 128.70±17.68	125.28±21.12 128.88±24.25	120.12±13.66 127.38±14.66	128.95±18.25 136.62±19.66	124.00±17.34 133.30±18.06	116.79±19.63 126.2±5.29	**0.002**	**0.001**	**0.001**

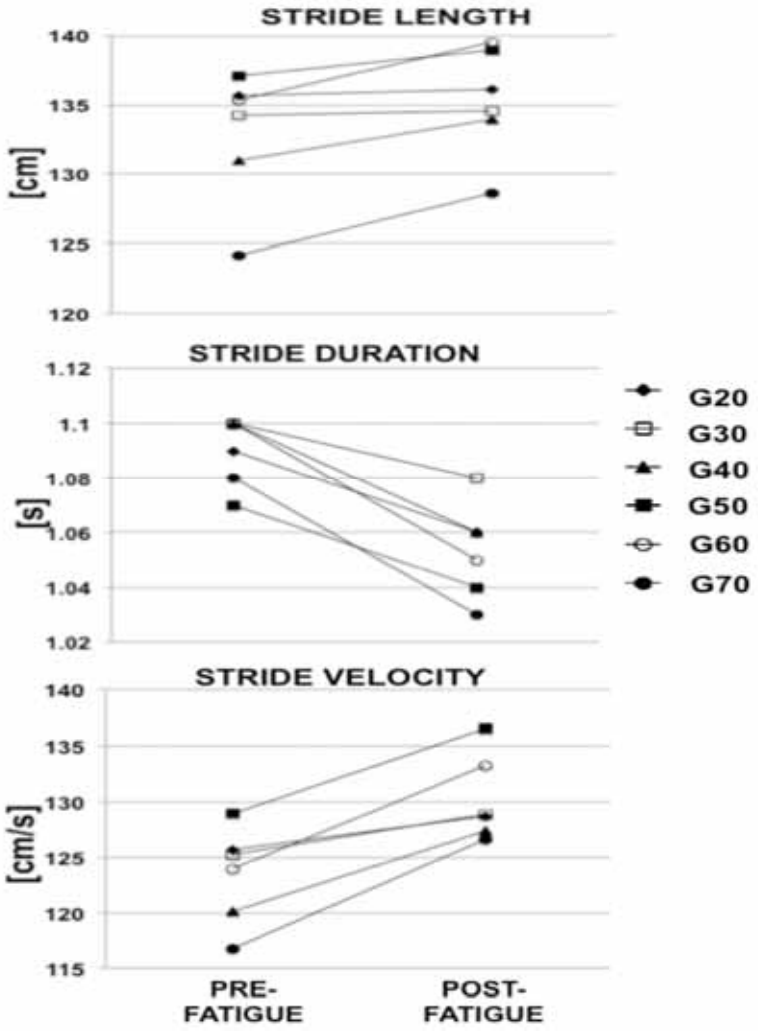

Figure 4.1. Group*fatigue interaction for spatial-temporal variables of level gait.

Group*fatigue interactions showed that older groups (G50, G60 and G70) increased the trailing limb obstacle-foot distance, the G20 and G40 groups did not change the distance to the obstacle with muscle fatigue, and the G30 group even decreased this distance. In addition, the G70 group showed lower obstacle-foot distances than the other groups without and with fatigue. All groups decreased the duration of the crossing step with fatigue, removing the differences among the groups shown before muscle fatigue due to a greater reduction in the older groups (G40, G60 and G70). For leading limb toe-clearance, no clear age-related pattern was observed: the G70 group did not change clearance with fatigue, the G30 group decreased clearance and the other groups increased clearance. For trailing limb toe-clearance, also no clear age-related pattern was observed: the G40 group did not show an effect of fatigue, while the G20, G30 and G60 groups decreased clearance and G50 and G70 groups increased it.

Table 4.3. Mean and standard deviations of spatial-temporal variables in obstacle crossing for each group without and with knee muscle fatigue. For each variable, the first line is without knee muscle fatigue and the second line is with knee muscle fatigue. The last three columns show the p-values for main effect of group, fatigue and group*fatigue interaction, respectively. Foot-obstacle distance - distance between foot and obstacle before crossing the obstacle; obstacle-foot distance - distance between foot and obstacle after crossing the obstacle.

Variables	G20	G30	G40	G50	G60	G70	group	fatigue	group* fatigue
step length (cm)	71.68±8.45 72.79±7.52	71.90±7.78 71.29±7.37	70.30±7.36 70.88±7.38	72.41±7.66 73.53±8.75	69.89±7.48 70.03±9.13	68.47±9.06 69.13±9.01	**0.03**	0.08	0.51
step width (cm)	10.58±3.30 12.81±3.69	10.39±3.77 12.34±4.03	12.52±4.13 13.95±4.82	10.35±4.05 12.01±4.32	9.61±5.09 10.88±5.07	12.33±5.09 13.02±5.27	**0.001**	**0.001**	0.41
step duration (s)	0.63±0.10 0.61±0.09	0.61±0.06 0.60±0.07	0.65±0.05 0.61±0.06	0.60±0.08 0.59±0.09	0.65±0.07 0.62±0.11	0.65±0.08 0.60±0.09	0.17	**0.001**	**0.006**
step velocity (cm/s)	117.66±29.78 124.66±54.92	120.52±21.33 121.11±20.23	110.00±15.38 118.13±18.47	121.97±21.50 123.90±21.69	109.85±17.97 115.94±23.51	108.73±24.34 116.93±25.36	**0.04**	**0.001**	0.33
trailing foot-obstacle distance (cm)	48.03±7.04 48.42±7.85	43.89±5.62 45.70±7.88	42.21±5.36 43.24±6.29	48.17±7.16 49.37±6.79	46.16±7.28 46.41±8.97	46.24±8.87 46.20±9.41	**0.001**	**0.02**	0.64
trailing obstacle-foot distance (cm)	89.55±10.11 91.06±11.52	96.77±11.93 93.26±13.36	94.24±13.26 94.69±12.27	91.65±11.72 96.66±16.87	90.59±14.39 93.17±13.83	82.70±13.05 88.26±15.04	**0.001**	**0.001**	**0.001**
trailing toe-clearance (cm)	31.15±5.62 30.16±5.11	30.51±6.97 29.93±6.66	29.32±7.65 29.62±7.21	28.06±4.73 29.64±5.45	29.34±6.59 28.57±7.39	26.93±7.16 27.82±7.29	**0.05**	0.78	**0.01**
leading foot-obstacle distance (cm)	112.46±11.61 113.97±10.63	106.79±9.15 109.45±13.80	104.76±9.73 105.24±9.09	113.38±14.05 116.55±14.96	111.50±10.61 113.26±13.41	104.94±15.87 106.56±14.00	**0.001**	**0.001**	0.79
leading obstacle-foot distance (cm)	24.22±6.38 24.43±6.13	27.83±7.25 26.74±11.38	28.09±6.07 27.42±6.75	24.42±6.07 24.44±7.26	23.95±7.55 23.35±8.44	21.58±5.90 22.24±6.39	**0.001**	0.49	0.74
leading toe-clearance (cm)	9.05±3.36 9.38±3.20	9.71±4.14 9.38±4.71	9.90±4.13 11.11±4.63	10.03±4.46 11.36±5.18	8.75±4.24 9.61±4.69	9.91±3.65 9.88±3.93	0.16	**0.001**	**0.005**

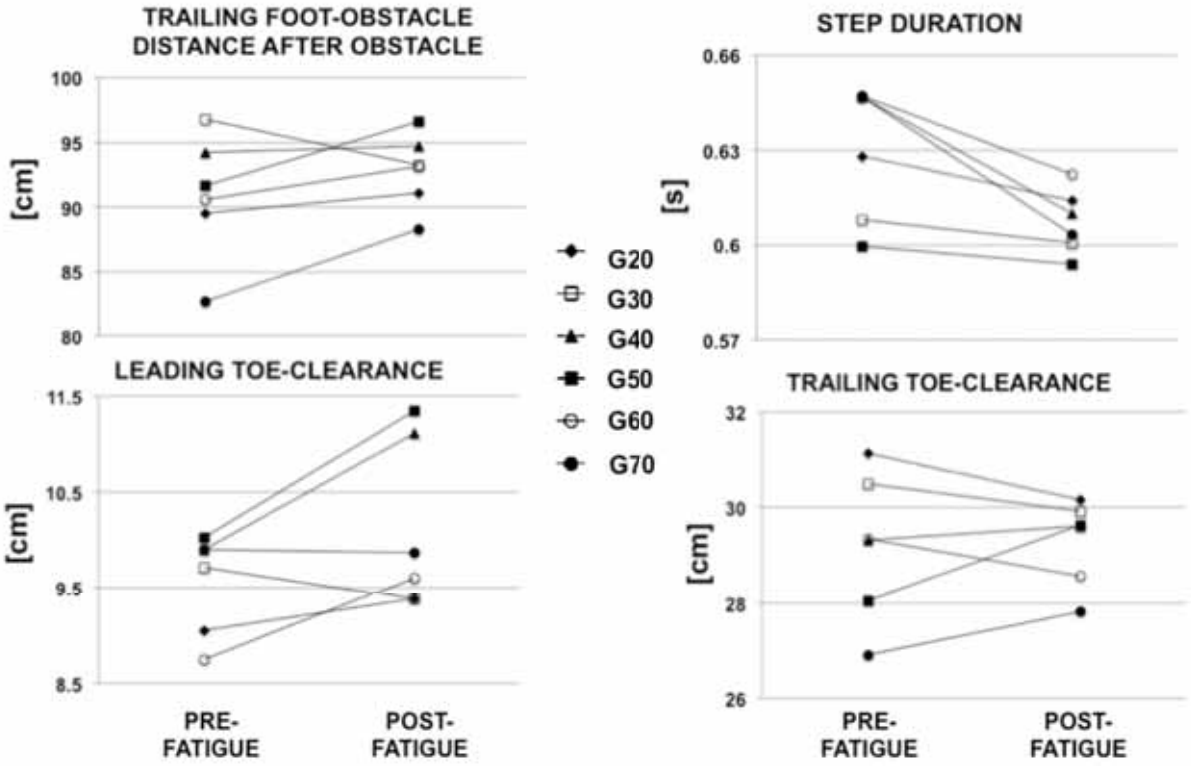

Figure 4.2. Group*fatigue interaction for spatial-temporal parameters in obstacle crossing.

4.5. Discussion

The main finding of this paper was that effects of knee muscles fatigue in walking and obstacle crossing are age dependent, confirming our hypothesis. For most of the variables studied, changes with fatigue were more pronounced in the older groups (above 40 years old). The main question then is whether these changes should be interpreted as adverse effects of muscle fatigue or rather as adaptations aimed at dealing with the fatigue. We will address this question in the following paragraphs.

4.5.1. Level walking

For all spatial-temporal gait variables, except step width, changes with fatigue were more pronounced in the elderly. Stride length increased with fatigue and more so among the older groups. An increase in stride length is unlikely to be a direct effect of fatigue, since probably more muscle force is required to take bigger strides. It could be that stride length is increased to enhance balance control in the sagittal plane. In walking, the anterior margin of safety is negative, implying that a next step is needed to maintain balance. Increasing step length may decrease the magnitude of the negative margin, making it easier to come to a stop

in a single step and in principle making it easier to avoid a forward fall (Hof et al., 2007,2005). However, in experiments in which balance was externally perturbed by means of lateral translations of a treadmill, subjects shortened steps presumably to increase the backward margin of safety at the expense of the forward margin of safety (Hak et al., 2012). Obviously, the perturbations of balance control are different between these experiments, but it is at present unclear why either the forward or backward margin of safety would be prioritized in these conditions.

Stride duration decreased with fatigue and again more so among the older groups. Again this is unlikely to be a direct effect of fatigue. A decrease in stride time has been observed under external perturbations of balance (Hak et al., 2012) and facilitates balance control in the medio-lateral direction as well as in the fore-aft direction (Hof et al., 2007,2005; Pai and Patton, 1997). Moreover, step width increased with fatigue in a similar manner across age groups. An increase in step width with fatigue has been reported previously (Helbostad et al., 2007) and is generally interpreted as facilitating balance control in the medio-lateral direction (Hak et al., 2012; Helbostad et al., 2007; Hof et al., 2007). Apparently older groups combined modulations of stride duration and step width to improve medio-lateral balance.

The increase stride length and decreased stride duration caused an increase in gait speed, which, as the changes in the underlying variables, was more pronounced in the older groups. Granacher et al. (2010) reported a similar increase in stride length and gait speed with fatigue in older adults. It is often assumed that increased gait speed is associated with an increased risk of falls (Granacher et al., 2010). However, it appears that changes in stride length and duration are more important in terms of balance control then the resulting gait speed (Hak et al., 2012) and stability of the gait pattern may actually be improved with higher gait speed (Brujin et al., 2009).

4.5.2. Obstacle crossing

As in level gait, with fatigue participants increased step width and decreased step duration in obstacle crossing. In line with the above, these changes might be interpreted as compensatory changes to facilitate balance control. Similar to level walking this coincided with an increased gait speed and a tendency towards an increase in step length. The latter findings appears to be in contrast with a pervious study on obstacle crossing in which sit was found that step length and gait speed decreased in the presence of a postural threat (McKenzie and Brown, 2004). This suggests that the present findings cannot simply be interpreted as the

consequence of an increase in postural threat experienced due to fatigue, but are more specific to the fatigue experienced.

In addition, with fatigue participants increased the distance of the trailing foot relative to the obstacle. Recently, a trend towards a similar change with fatigue was reported (Hatton et al., 2012). Again, the effect of postural threat has been reported to be opposite (McKenzie and Brown, 2004). This may facilitate crossing the obstacle, as it has been suggested to allow a posture-preserving strategy (Hatton et al., 2012). In the young this increased distance to the obstacle may have caused the decrease in trailing toe clearance observed. However, quiet strikingly trailing toe clearance increased in the older groups, suggesting a more cautious strategy. Similarly leading foot toe clearance increased in the older groups, but not in the younger groups. High toe-clearance maybe used to avoid obstacle contact (Silva et al., 2011; Lu et al., 2006; Patla and Rietdyk, 1993), in spite of a higher energy demand (Jansen et al., 2011). The exception here was the oldest group (over 70 years), which also showed no increase in clearance. It could be that strength decrements that occur from the fifth decade at a rate of approximately 12–15% per decade (Hurley, 1995; Wolfson et al., 1995), in combination with muscle fatigue limits task performance in this group directly.

4.6. Limitations and conclusion

Effects of aging were studied in a cross-sectional design. However, an alternative longitudinal study would need more than 50 years and appears not feasible. The participants over 70 years old were on average shorter than the other groups. However, an analysis on spatial parameters normalized by height yielded similar results. Finally, only men were analyzed and we did consider their habitual level of physical activity. Generalization of the results should therefore be done with care.

In conclusion, knee muscle fatigue caused age-dependent changes in both level gait and obstacle crossing. In general, spatial-temporal gait parameters were changed in such in a way that stability and safety are enhanced, probably to counteract adverse fatigue effects. The adjustments in gait with fatigue in both tasks were more pronounced in participants over 40 years old than in younger individuals.

Chapter 5

Effect of triceps surae and quadriceps muscle fatigue on the mechanics of landing in stepping down in ongoing gait

Submitted to Ergonomics

5.1. Abstract

The aim of this study was to evaluate the effects of muscle fatigue of triceps surae and quadriceps muscles in stepping down in ongoing gait. We expected that the subjects would compensate for muscle fatigue, to prevent potential loss of balance in stepping down. Ten young participants walked over a walkway at self-selected velocity to step down a height difference of 10-cm halfway. Five trials were performed before and after a muscle fatigue protocol. Participants performed two fatigue protocols: one for ankle muscle fatigue, and another for knee muscle fatigue. Kinematics of and ground reaction forces on the leading leg were recorded. Fatigue did not cause a change in the frequency of heel or toe landing. Our results indicate that in stepping down fatigue effects are compensated by redistributing work to unfatigued muscle groups and by gait changes aimed at enhancing balance control, which was however only partially successful.

5.2. Introduction

Stepping down an elevation in ongoing gait is a common task, such as when stepping off the sidewalk to cross a street. Problems with transitions between levels in gait, such as when stepping from a curb, are common causes of falls (Lord et al., 1993; Ivers et al., 1998; Tinetti et al., 1995). Misplaced steps formed the third cause of falls and accounted for 12% of all cases (Berg et al., 1997). To avoid a fall during landing a step, the leading leg must dissipate this kinetic energy at landing by means of eccentric contractions (Dieën et al., 2008). Failure to do so, as occurs in unexpected stepping down, can cause a loss of balance (Dieën et al., 2007).

Muscle fatigue, defined as a decrease in the force generating capacity of muscles (Edwards, 1981), is a common phenomenon in the general population (Hancock and Desmond, 2000) and is even more pronounced in aged and diseased populations (Vestergaard et al., 2009; Feasson et al., 2006). Muscle fatigue may impair motor control by increasing force variability and limiting generation of fast corrective torques (Ribeiro et al., 2007; Lin et al., 2009). Fatigue has been reported to reduce stability of gait on level ground and increase the risk of falls (Helbostad et al., 2007; Parijat and Lockhart, 2008a,b; Murdock and Hubley-Kozey, 2011). At the same time, muscle fatigue appears to coincide with compensatory gait changes that enhance gait stability, such as an increased step width (Helbostad, et al. 2007).

With respect to negotiating a curb, it was shown that fatigue increases the variability of placement of the trailing and leading limb relative to the curb, suggesting a loss of control and consequently an increased risk of making a misstep (Barbieri et al., 2012c). The effects of muscle fatigue on the step down are not known, but it can be surmised to affect the ability to dissipate energy gained during the step down. The strategy used to step down is dependent on characteristics of the environment such as the height of the step (Dieën and Pijnappels, 2009). In stepping down, the quadriceps muscle dissipates most of the energy at landing when a heel landing strategy is used, while the triceps surae muscle does so when a toe landing strategy is used (Dieën et al., 2008). In the last stride before stepping down, quadriceps muscle fatigue coincided with a decreased muscle activity of both triceps surae and quadriceps muscles (Barbieri et al., 2012c). On the other hand, triceps surae muscle fatigue coincided with an increased muscle activity of the biceps femoris in the stance phase and rectus femoris in the swing phase (Barbieri et al.,2012c). These findings indicate differential effects of quadriceps and triceps surae muscle fatigue on the approach phase and possible also on the landing phase in stepping down.

Therefore, the aim of this study was to evaluate the effects of muscle fatigue of quadriceps and triceps surae muscles at landing in stepping down in ongoing gait. We induced quadriceps and triceps surae muscle fatigue using a functional task, to guarantee ecological validity. While functional tasks do not cause isolated muscle fatigue in a single muscle group, tasks were selected to cause effects predominantly on either of these muscles. We expected that the subjects would compensate for muscle fatigue, to prevent a potential loss of balance at landing. We thus hypothesized an increase in the use of the heel landing strategy with ankle muscle fatigue and an increase in toe landing with knee muscle fatigue. Second, within the same strategy we hypothesized a shift of negative work from the fatigued muscles to non-fatigued muscles, for example with ankle muscle fatigue we expected a decrease in peak moments, peak negative power and negative work around the ankle and corresponding increases around the knee and hip. Third, we hypothesized a conservative strategy in stepping down with fatigue, evidenced by more negative work at landing (Dieën et al., 2008) and a larger reduction of the forward angular and linear momenta (Dieën et al., 2007). Finally, we hypothesized a more conservative gait pattern with fatigue, reflected in an increased step width and reduced step duration (Hak et al., 2012), and a larger step length in the step down (Dieën et al., 2007).

5.3. Material and Methods

5.3.1. Participants

After signing informed consent, 10health volunteers (5 men and 5 women – age: 27.60±2.79 years; weight: 69.21±10.76 kg; height: 1.81±0.08m) participated in the study that had been approved by the local ethics committee. Participants reported no history of musculoskeletal disorders, which could affect performance of the experimental tasks, within the past 12 months.

5.3.2. Experimental Design

Data collection was performed on two days with a one-week interval (Figure 5.1). On the first day, the participants were familiarized with the study protocol and performed stepping down tasks before and after the first of two fatigue protocols. The two fatigue protocols aimed to induce fatigue of: a) the quadriceps muscle; b) the triceps surae muscle. The order of the fatigue protocols was balanced over subjects, to avoid order effects.

Participants were instructed not to perform intense physical activity within 48 hours before data collection.

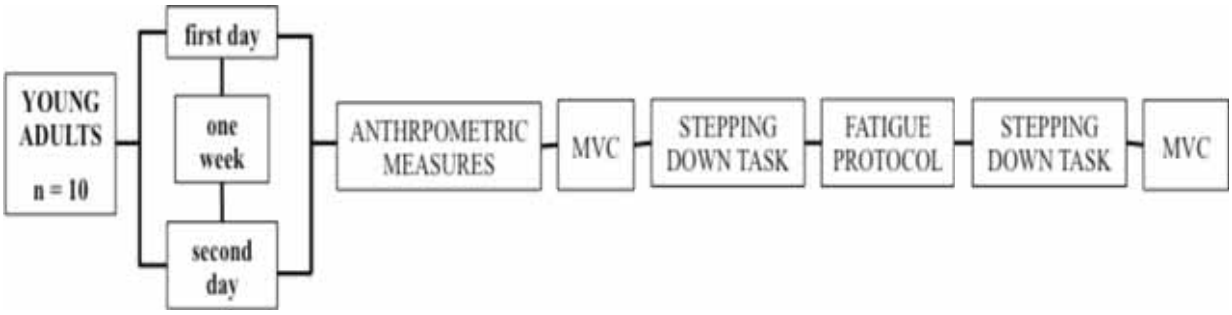

Figure 5.1. Experimental design. MVC - maximal voluntary contraction.

5.3.3. Fatigue Protocols

To induce quadriceps muscle fatigue, the participants performed a repeated sit-to-stand task from a standard chair (40cm high, 40cm wide, 35cm deep) without arm supports, with arms across the chest, at frequency of 0.5Hz controlled by a metronome (Helbostad et al., 2007). The instruction given to the participants was: stand up to an upright position with your knees fully extended, then sit back down and repeat this at the beat of the metronome until you can no longer perform the task.

To induce triceps surae muscle fatigue, the participants performed a repeated standing calf raise exercise (Berger et al., 2010) at 0.5Hz. During the task, participants were allowed to place their hands against the wall to avoid balance loss. The instruction given to the participants was: lift your heels off the ground as high as possible then return to the starting position and repeat this at the beat of the metronome until you can no longer perform the task. Preceding both fatigue protocols, participants performed some attempts to adapt to the task and the frequency.

The fatigue protocol was stopped when the participant indicated that he or she was unable to continue, or when the movement frequency fell below and remained below 0.5Hz after encouragement, or after 30min. No rest period was allowed between trials and testing was started as soon as possible after the fatigue protocol and the time between the fatigue protocol and the gait trials (< 3 min) was expected not to allow full recovery (Parijat and Lockhart, 2008b). Isometric force measurements were used to confirm that the muscle was fatigued, measuring the loss of strength (Barbieri et al., 2012c; Katsiaras et al., 2005; Petrella et al., 2005; Stackhouse et al., 2001). Finally, the endurance time during the fatigue protocol was recorded.

5.3.4. Isometric force measurements

Maximal voluntary forces of the quadriceps and triceps surae muscles of the right leg were measured using custom-made dynamometers (Pijnappels et al., 2008). Subjects performed two attempts of maximal voluntary isometric contractions (MVIC) before and after the fatigue protocol, with at least 2min rest between attempts. Subjects were asked to generate maximal isometric knee or ankle extension for 3-4s. For knee extension, the participants were seated in a backward inclined chair, with the hip joint at 90° (180° is full extension) and knee joint at 120° (180° is full extension) and the lower leg tightly strapped to a strain gauge transducer (KAP, E/200 Hz, Bienfait BV Haarlem, The Netherlands) placed ~ 25 cm distal from the knee joint, which measured the force exerted at the shin. For ankle extension, the participants were seated in an upright chair with the knee joint flexed at 90° and the ankle joint set at 20° dorsiflexion and, the fore-foot positioned on a 10 cm x 10 cm force transducer (AMTI M3-1000, Watertown, USA) that was mounted in the push-off platform. Forces were sampled at 1 kHz. The means of the two attempts before and after muscle fatigue were calculated for each participant.

5.3.5. Stepping task

Before and after the fatigue protocol, the participants performed five trials of stepping down a 10-cm elevation. Subjects walked at a self-selected speed over a raised platform of 10m and halfway they stepped down onto the lower part of the platform. At the 10-cm height difference, individuals are expected to alternate between toe and heel landing strategies (Dieën and Pijnappels, 2008). Before the actual experiment, the participant was accustomed to the testing environment. No rest period was allowed between trials and testing was started as soon as possible after the fatigue protocol. The starting point was adjusted individually to make sure that subjects stepped down with the right leg.

The strategy used to step down was determined from visual inspection of the videotapes recorded during the experiment by the same observer for all trials. Strategies were classified as toe landing or heel landing based on whether the heel or forefoot/toes first touched the ground.

An optical system with 3x3 cameras (Optotrak Northern Digital Inc., Waterloo, Ont., Canada) was used to record kinematics at a rate of 50 samples/s. Neoprene bands, with clusters of three infrared Light Emitting Diodes were placed on the pelvis (level of the posterior superior iliac spines), bilateral thigh, shank and heels. Cluster positions were related to anatomical landmarks based on separate pointer measurements (Cappozzo et al., 1995).

Ground reaction forces were recorded at 1000 samples/s using two 1.0x1.0m force plates, placed in the walking platform just before and after the 10-cm height difference. The kinematic data and ground reaction forces were synchronized and off-line reduced to 50 samples/s using a running average. Kinematic and force plate data were filtered with a bidirectional second order low-pass Butterworth filter with a cut-off frequency of 20Hz. The analysis focused on the first stance phase at the lower level (leading leg). Sagittal plane knee, ankle and hip joint angles, angular velocities, moments, power and work of the leading (right) leg were estimated using a 3D linked-segment model (Kingma et al., 1996) and peak values occurring within 200ms after ground contact of the leading leg at the lower level were determined (Dieën et al., 2008). Changes in linear and angular momentum after landing were calculated from the areas under the curve of ground reaction force and the external moment about the body center of mass, respectively (Dieën et al., 2007). In addition, the step length, step width, step duration of the landing step, and the heel-clearance during stepping down were analyzed. The heel-clearance was calculated as the distance of the calcaneus landmark to the step.

5.3.6. Statistics

The dependent variables of interest were statistically analyzed with SPSS 18.0 for Windows® ($\alpha < 0.05$). The data were normally distributed, as verified by the Shapiro-Wilk test. First, to verify the similarity of the data in the un-fatigued conditions on both days, the variables of interest were evaluated by paired sample t-tests. The same statistical test was used to compare the endurance times between fatigue protocols, and the MVIC values before and after fatigue. The frequencies at which a heel or toe landing strategies were used by each subject were compared between the conditions before and after fatigue, using Wilcoxon tests. The dependent variables during stepping down were compared using repeated measures multivariate ANCOVAs, with fatigue (before and after fatigue) as main factor and landing strategy (heel or toe landing) as covariate. Separate multivariate ANCOVAs were performed for each fatigue protocol and for joint kinetics, for the overall mechanics of the step down and for spatial and temporal gait parameters. When the ANCOVA pointed out significant differences, Tukey univariate tests were carried out, as proposed by Zar 1999.

5.4. Results

The participants performed the ankle fatigue protocol (Table 5.1) longer than the knee fatigue protocol (t_9=4.27, p<0.002). Four participants performed for 30min in the ankle fatigue protocol, while none performed for 30min in the knee fatigue protocol. After the fatigue protocol, the maximal voluntary isometric contraction had decreased both in the ankle (15.5%; t_9=5.20, p<0.001) and the knee (3.2%; t_9=3.46, p<0.007) fatigue protocol.

Table 5.1. Mean values and standard deviations of the endurance times and maximal voluntary isometric contractions (MVIC) before and after fatigue.

		Ankle fatigue	Knee fatigue
Endurance time (s)		1179±584.32#	405.80±435.15
MVIC (N*m)	**Before fatigue**	127.49±31.32*	250.37±11.49*
	After fatigue	107.49±28.97	242.39±9.34

The symbol # indicates significant differences between ankle and knee muscle fatigue; the symbol * indicates significant differences between the unfatigued and fatigued conditions.

Overall, the participants preferred stepping down the step using a heel landing. In contrast with our hypothesis, neither protocol caused significant differences in frequencies of the landing strategies (p > 0.28; Figure 5.2).

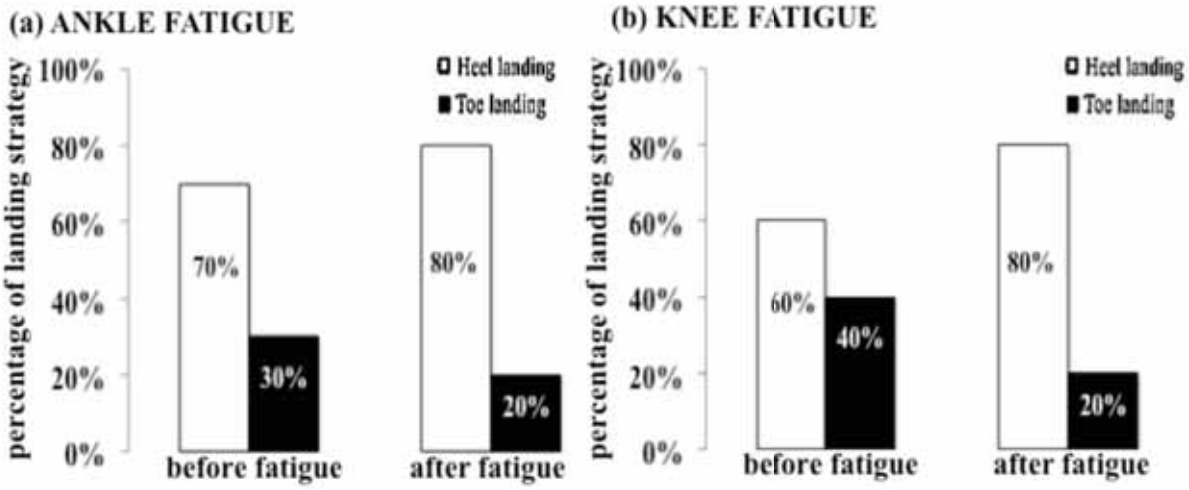

Figure 5.2. Use of heel and toe landing as a percentage of all trials before and after fatigue, for (a) ankle muscle fatigue, and (b) knee muscle fatigue.

There were no significant differences in the variables of interest between trials before the ankle and knee muscle fatigue protocols. For the ankle fatigue protocol (Table 5.2), the ANCOVA on joint kinetics revealed main effects of fatigue (Wilks' Lambda=0.50, $F_{9,40}$=4.34, $p<0.001$) and interactions between fatigue and landing strategy (Wilks' Lambda=0.61, $F_{9,40}$=2.83, $p<0.01$). In line with our hypothesis, a redistribution of work towards unfatigued muscle groups was indicated by main effects of fatigue on peak hip moments and negative work around the hip. In toe landing, a shift away from the ankle muscles was indicated by significant effects on peak ankle and knee moments, peak ankle power, and negative work around the knee, as well as a trend in negative work around the ankle. For heel landing, only a significant decrease in negative work around the knee and an increase in peak power around the hip were observed.

The ANCOVA on the overall mechanics of landing revealed a main effect of ankle muscle fatigue (Wilks' Lambda=0.73, $F_{4,45}$=4.02, $p<0.007$) and an interaction effect of fatigue and strategy (Wilks' Lambda=0.80, $F_{4,45}$=2.71, $p<0.04$). The interaction was caused by the total negative work, with a significant increase with fatigue in toe landing only (Table 5.2). The reduction in angular momentum at landing, however, decreased with fatigue irrespective of the landing strategy, while the changes in linear momentum were not affected by fatigue (Table 5.2).

The ANCOVA on spatial and temporal gait parameters revealed no main effect of fatigue (Wilks' Lambda=0.73, $F_{6,43}$=2.52, $p<0.03$), but an interaction effect of fatigue and strategy (Wilks' Lambda=0.71, $F_{6,43}$=2.79, $p<0.02$) was found. This effect was accounted for by an interaction effect on step width, with a significant increase in step width occurring in toe landing only (Table 5.2).

Table 5.2. Mean values and standard deviations of parameters characterizing the kinetics during landing (within 200ms of landing) and spatial-temporal parameters during the step of stepping down before and after ankle muscle fatigue according landing strategy (toe and heel landing).

	TOE LANDING		HEEL LANDING		Effect of fatigue	Interaction of factors
	Before fatigue	**After fatigue**	**Before fatigue**	**After fatigue**		
joint kinetics						
Peak ankle moment (Nm)	47.05±16.05*	37.37±12.92	-61.78±13.14	-60.06±12.75	0.07	**0.009**
Peak knee moment (Nm)	-94.46±25.47*	-105.81±31.84	-108.86±30.27	-109.37±32.36	0.06	**0.05**
Peak hip moment (Nm)	-42.76±21.01	-44.08±16.54	-39.97±11.45	-48.79±23.12	**0.04**	0.12
Peak negative ankle power (W)	-205.99±90.12*	-153.24±38.81	-216.64±72.43	-208.59±43.05	**0.01**	**0.05**
Peak negative knee power (W)	-212.94±82.91	-180.98±51.71	-224.76±71.34	-245.79±104.65	0.71	0.08
Peak negative hip power (W)	-77.87±51.12	-80.12±31.13	-59.50±26.69*	-91.13±30.83	**0.03**	**0.009**
Negative work ankle (J)	-18.46±8.56	-12.57±4.32	-18.46±8.56	-15.14±3.39	0.07	0.08
Negative work knee (J)	-17.05±5.96*	-25.86±15.83	-22.51±10.02*	-18.93±8.24	0.07	**0.001**
Negative work hip (J)	-6.30±4.477	-7.53±2.82	-8.93±6.56	-10.50±6.06	**0.05**	0.72
overall landing mechanics						
Negative work total (J)	-41.81±16.53*	-48.53±18.65	-43.64±10.75	-42.02±10.29	0.06	**0.002**
Negative angular momentum (Nms)	-8.46±3.61	-7.03±3.21	-6.63±5.37	-5.27±3.26	**0.02**	0.95
Negative horizontal momentum (Ns)	-26.94±7.27	-25.48±5.46	-26.78±6.88	-25.79±5.62	0.45	0.06
Vertical momentum (Ns)	217.23±30.73	213.95±43.62	233.49±62.23	229.17±52.86	0.95	0.92
spatial-temporal parameters						
Step length (cm)	76.74±8.21	77.28±9.71	80.56±11.22	79.28±9.71	0.69	0.23
Step width (cm)	10.72±4.22*	14.92±3.01	13.77±3.30	13.79±3.92	**0.009**	**0.009**
Step duration (s)	0.53±0.04	0.52±0.04	0.58±0.08	0.56±0.06	0.28	0.54
Heel-clearance (cm)	13.89±1.38	13.33±3.12	11.15±2.09	10.85±1.97	0.32	0.76

The symbol * indicates significant differences between the unfatigued and fatigued conditions.

Knee muscle fatigue had main effects on joint kinetics, overall mechanics of landing and on the spatial and temporal parameters only (Wilks' Lambda=0.43, $F_{9,40}$=5.89, p<0.001; Wilks' Lambda=0.80, $F_{4,45}$=2.81, p<0.03, Wilks' Lambda=0.59, $F_{6,43}$=4.84, p<0.01, respectively) and no interactions with strategy (Wilks' Lambda=0.37, $F_{9,40}$=7.37, p=0.08; Wilks' Lambda=0.85, $F_{9,40}$=1.89, p<0.12, Wilks' Lambda=0.67, $F_{6,43}$=3.50, p<0.07, respectively).

In line with our hypothesis, the energy absorption was increased around the ankle when the knee muscles were fatigued. In addition, peak power around the hip increased after muscle fatigue. Furthermore, increases in total negative work and step width and a decrease in step duration (Table 5.3) were in line with the use of a more conservative strategy in the fatigued condition.

Table 5.3. Mean values and standard deviations of parameters characterizing the kinetics during landing (within 200 ms of landing) and spatial-temporal parameters during the step of stepping down before and after knee muscle fatigue.

	KNEE FATIGUE		Effects of fatigue
	Before fatigue	**After fatigue**	
joint kinetics			
Peak ankle moment (Nm)	-20.44±53.97	-23.23±55.35	0.32
Peak knee moment (Nm)	-100.12±26.13	-98.82±23.25	0.81
Peak hip moment (Nm)	-43.73±26.20	-41.72±34.53	0.83
Peak negative ankle power (W)	-198.13±64.28	-203.61±76.21	0.54
Peak negative knee power (W)	-269.39±97.67	-264.61±96.05	0.90
Peak negative hip power (W)	-63.61±26.33*	-51.15±24.04	**0.001**
Negative work ankle (J)	-13.63±4.49*	-15.01±6.10	**0.05**
Negative work knee (J)	-19.67±10.41	-21.06±914	0.13
Negative work hip (J)	-5.23±3.83	-5.94±5.16	0.09
overall landing mechanics			
Negative work total (J)	-38.54±15.29*	-42.02±14.06	**0.01**
Negative angular momentum (Nms)	-6.22±2.71	-6.40±2.67	0.87
Negative horizontal momentum (Ns)	-26.32±5.71	-26.33±5.78	0.90
Vertical momentum (Ns)	220.35±45.43	226.65±48.87	0.06
spatial-temporal parameters			
Step length (cm)	77.48±8.70	77.39±7.95	0.82
Step width (cm)	12.71±5.05*	14.02±5.41	**0.01**
Step duration (s)	0.54±0.05*	0.52±0.04	**0.005**
Heel-clearance (cm)	11.78±2.10	11.87±2.22	0.83

The symbol * indicates significant differences between the unfatigued and fatigued conditions.

5.5. Discussion

We hypothesized that ankle and knee muscle fatigue would cause changes in kinematics and kinetics of stepping down that would reflect a shift of work away from the fatigued muscle groups. In contrast with this hypothesis, we found no change in the frequency of heel or toe landing after the fatigue protocols. However, changes in joint kinetics were in line with the expected shift in work away from the fatigued muscles (either ankle or knee muscles) towards (relatively) unfatigued muscles (hip and either knee or ankle muscles). Furthermore, we hypothesized that changes in the mechanics of stepping down with fatigue would reflect a strategy to reduce the risk of balance loss. Stepping down coincides with increases in forward linear and angular momenta, which are dealt with at landing (Dieën et al. 2007, 2008). Increases in the negative work in the leading leg at landing, found in most cases, are in line with this hypothesis. However, the reductions in the linear momenta at landing were not changed and in case of ankle muscle fatigue the reduction of angular momentum at landing was even decreased. This suggests that subjects were not successful at increasing control over the body's momentum at stepping down. Overall, subjects increased step width, which may reflect an attempt to enhance balance control, but they did not adjust step length (in both muscle fatigue) and step duration (only for ankle muscle fatigue).

The fatigue protocols used in the present study induced a significant reduction of muscle strength, especially the ankle muscle fatigue protocol (reduction of 15.7%). The longer endurance time in the ankle fatigue protocol may account for the larger reduction in strength. The reduction in strength could production of joint moments and hence absorption of the kinetic energy gained (Prilutsky et al., 1996; Devita and Skelly, 1992) and joint stabilization at landing (Murdock and Kozey, 2011; Granacher et al., 2010; Vila-Chã et al., 2011; Lewek et al., 2004) through eccentric actions. Our results indicated that after ankle fatigue eccentric contractions of the knee muscles contributed more to reducing the kinetic energy that is gained in stepping down and vice versa after knee muscle fatigue, albeit without the kinematic strategy changing completely from toe to heel landing or vice versa. With ankle muscle fatigue, also the hip muscle contribution to negative work was increased and a similar trend was seen with knee muscle fatigue.

After the muscle fatigue protocols, the participants widened the basis of support, which has also been found in individuals walking on level ground and crossing obstacles (Barbieri et al., 2012a; Parijat and Lockhart, 2008a,b; Helbostad et al., 2007). Increased step width provides a larger margin of safety in medio-lateral control of the body's center of mass

(Hak et al., 2012; Hof et al., 2007). Additionally, with knee muscle fatigue the participants reduced step duration, which also facilitates balance control in the medio-lateral direction (Hof et al., 2007; Hof et al., 2005). An increase in step length would facilitate control of the angular momentum gained in stepping down (Dieën et al., 2007) and hence control of balance in the forward direction. Such a change was not observed, possibly because it would conflict with a reduction in step duration.

Participants did increase the total energy absorption at landing, when the knee muscles were fatigued and when the ankle muscles were fatigued, although in the latter case only when a toe landing strategy was used, in line with a more conservative strategy. This suggests participants tended to overcompensate for the effects of fatigue to enhance control over stepping down. However, effects were small and the reduction in linear momentum at landing was not increased with fatigue. Moreover, angular momentum was even reduced less when the ankle muscles were fatigued. The participants did not change step length and heel-clearance after muscle fatigue in both protocols. Heel-clearance is the most obvious indicator of the risk of tripping in an uneven gait task (Patla and Rietdyk, 1993). High heel-clearance would be a safe strategy (Patla and Rietdyk, 1993; Lu et al., 2006; Silva et al., 2011). Moreover, increasing step length at stepping down facilitates the reduction of the angular momentum gained (Dieën et al., 2008). While step length and heel clearance were not increased, we have previously shown that variability of heel clearance increased with fatigue (Barbieri et al., 2012c). These findings combined may suggest that limited control of heel-clearance and related to that the control of angular momentum. The effect on angular momentum, however, appears minor from the point of view of fall risk, since a comparison of expected and unexpected stepping down showed much larger effects on the reduction of the angular momentum at landing, without falls occurring (Dieën et al., 2008). Nevertheless, this implies that subjects were only partially successful at enhancing balance control in the presence of fatigue.

Some limitations of this study are evident. First, we did not control the level of physical activity of participants, which could be a factor mediating the effects of muscle fatigue. However, a previous study on obstacle crossing did not show such effects (Barbieri et al., 2012a). Since participants performed ten trials of stepping down in the first day and ten more trials after one week, the results could be affected by practice. However, we controlled for this by balancing the order of the fatigue protocols over subjects. Although the fatigue protocols were designed to induce fatigue predominantly in the quadriceps and triceps surae muscles respectively, it is important to consider that other muscles are involved in and may be

fatigued by the functional task. Finally only young healthy adults were tested, which limits generalization to aged and diseased populations.

In conclusion, in stepping down with local leg muscle fatigue, young healthy adults compensated for fatigue effects by recruiting unfatigued muscle groups and adjusting their gait pattern to enhance balance control, which was only partially successful.

Chapter 6

The effect of muscle fatigue on the last stride before stepping down a curb

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6.1. Abstract

The stride before landing may be important during stepping down. The aim of this study was to analyze variability of the kinematics and muscle activity in the final stride before stepping down a curb, with and without ankle and knee muscle fatigue. Ten young participants walked at self-selected speed and stepped down a height difference (10-cm) in ongoing gait. Five trials were performed before and after a muscle fatigue protocol (one day: ankle muscle fatigue, another day: knee muscle fatigue). The analysis focused on the trailing leg during the last but one and the last step on the higher level. Kinematics and muscle activity were recorded. Fatigue increased variability of foot-step horizontal distance in the last step on the higher level of the trailing limb, as well as in the first steps on the lower level for both limbs. This appeared due to an increase in the range of motion of the knee joint after both fatigue protocols. Participants additionally showed an increased ankle and hip ROM and decreased knee ROM. Our results suggest a loss of control under fatigue reflected in a higher variability of trailing and leading limb-step horizontal distances, with compensatory changes to limit fatigue effects, such as a redistribution of movement over joints.

6.2. Introduction

Problems with transitions between levels in gait, such as when stepping from a curb, are common causes of falls (Ivers et al., 1998; Tinetti et al., 1995; Lord et al., 1993). In level walking, muscle fatigue destabilizes motor control and consequently increases variability and decreases the stability (Helbostad et al., 2007) of gait. Such problems might have even more impact in negotiating level changes. In stepping down, with quadriceps or triceps surae muscle fatigue, subjects appeared to use compensatory strategies to redistribute work performed to unfatigued muscles and to enhance balance control (Barbieri et al., 2012b). Leg muscle fatigue did not cause changes in stride length and foot placement before stepping over an obstacle in young adults (Barbieri et al., 2012a). However, it is unknown whether leg muscle fatigue affects the last stride (approach phase) before stepping down.

The approach to a curb may be of crucial importance in preventing falls, since the stepping strategy appears to be planned based on visual information obtained during the penultimate step (Buckley et al., 2011). Moreover, adequate foot placement in the last step before the curb may be fundamental, since errors may result in a misstep on the curb (Begg and Sparrow, 2000; Konczak et al., 1992). Step lengths of the last steps of the approach phase appear to be modulated to achieve optimal foot placement, to allow the last step on the high level, and to land close to the curb (Lythgo et al., 2007; Begg and Sparrow, 2000; Crosbie and Ko, 2000). Finally, foot placement and the stance phase of the trailing leg on the higher level co-determine foot placement of the leading leg on the lower level, which is crucial for reducing the angular momentum gained in stepping down (Dieën et al., 2007).

Therefore, the aim of the study was to analyze foot placement relative to the curb in the final stride before stepping down, with and without ankle and knee muscle fatigue. We additionally explored fatigue effects on kinematics and muscle activity (EMG) to reveal potential causes of changes in foot placement and potential compensatory adjustments. We expected an increased variability of foot placement of the trailing limb on the higher level and of the leading limb on the lower level.

6.3. Material and Methods

After signing informed consent, 10healthy volunteers (age: 27.60±2.79 years; weight: 69.21±10.76 kg; height: 1.80±0.08 m) participated in the present study that had been approved by the local ethics committee.

For each participant, data collection was performed on two days with a one-week interval. The participants performed stepping down tasks before and after one of two fatigue protocols: a) knee muscles: repeated sit-to-stand movements from a chair without arm supports, with arms across the chest, at a frequency of 0.5 Hz controlled by a metronome (Barbieri et al., 2012a,b); b) ankle muscles: repeated standing calf raise exercise (Barbieri et al., 2012b) at the same frequency. In the latter exercise, participants were allowed to touch the back of chair with their hands to ensure balance. The order of the fatigue protocols was balanced over subjects, to avoid order effects. The fatigue protocol was stopped when the participant indicated that he or she was unable to continue, when the movement frequency fell below and remained below 0.5 Hz after encouragement, or after 30 min. The endurance time during the fatigue protocol was recorded.

Before and after the fatigue protocol, the participants performed five trials of stepping down a 10-cm elevation. Subjects walked at self-selected speed over a raised platform over a length of 10m and halfway they stepped down onto the lower part of the platform. Starting position was adjusted to make sure that participants stepped down with the right leg. The participants wore their own shoes. No rest period was allowed between trials and testing was started as soon as possible after the fatigue protocol and the time between the fatigue protocol and the gait trials (< 3 min) was expected not to allow full recovery (Parijat and Lockhart, 2008b).

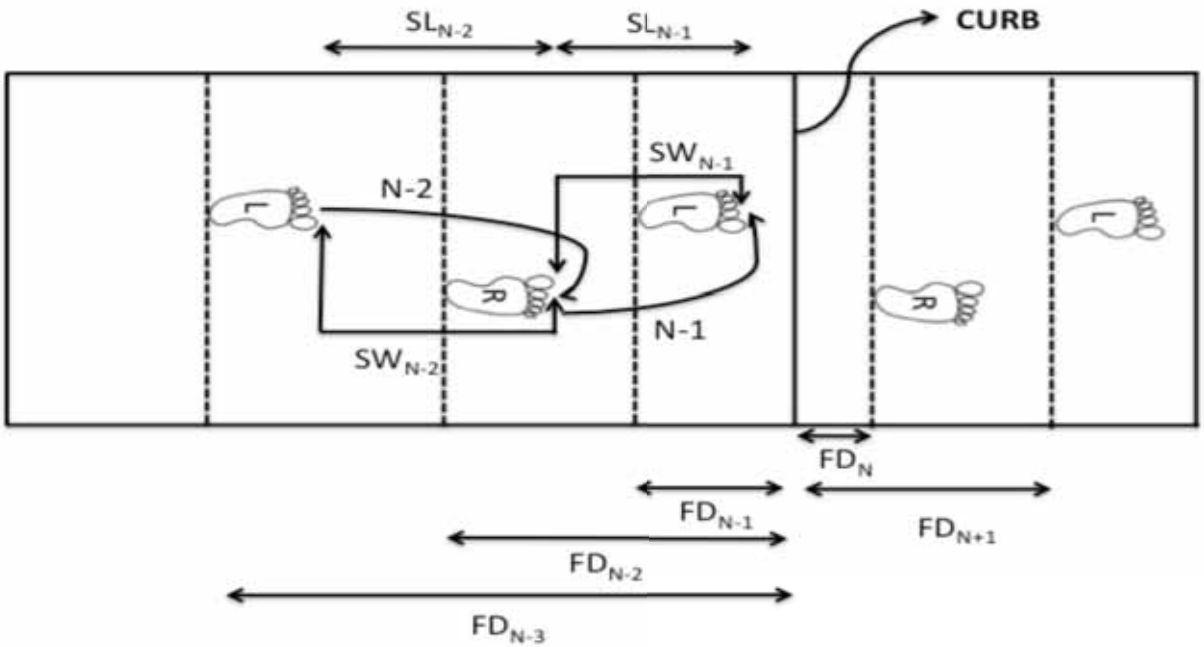

Figure 6.1. A top view of steps analyzed in the study. Dashed line represents the foot placement. SL – step length; SW – step width; FD – foot distance; L – left leg (trailing foot); R – right leg (leading foot).

An optical system with 3x3 cameras (Optotrak Northern Digital Inc., Waterloo, Ont., Canada) was used to record kinematics at a rate of 50Hz. Neoprene bands, with clusters of three infrared Light Emitting Diodes were attached to the participant's body, at the pelvis (level of the posterior superior iliac spines), and at the thigh, shank and heels of the right and left leg. Cluster positions were related to anatomical landmarks based on separate pointer measurements (Cappozzo et al., 1995). The accuracy of the Optotrak system was within 0.3 mm. To enhance reliability, camera positions were maintained in throughout data collection, markers were placed by the same researcher in all sessions and remained in place during a session.

Kinematic data were filtered with a bidirectional second order low-pass Butterworth filter with a cut-off frequency of 20Hz. Step-foot horizontal distances of the trailing and leading feet to the level change were determined in steps N-2, N-1, N and N+1 (Figure 1). The horizontal distances were calculated as the distance of the calcaneus landmark to the step. The step length, step width, step duration and step velocity were analyzed for each step. The coordinates of the Optotrak markers defined seven body segments: two feet, two lower legs, two upper legs, and a pelvis. Knee, ankle and hip joint angles of the both legs leg were estimated using a 3D linked-segment model (Kingma et al., 1996) and the ranges of angular motion (ROM) of the left hip, knee and ankle joints in the sagittal plane were calculated.

EMG was recorded, synchronized with kinematic data, using disposable Ag/AgCl surface-electrodes (BlueSensor; lead-off area 1.0cm2, inter-electrode distance 2.0cm). After abrasion and cleaning with alcohol, electrodes were attached over the left rectus femoris, biceps femoris, tibialis anterior and gastrocnemius lateralis in the left limb. Electrodes and EMG data collection followed to the SENIAM guidelines (Hermens et al., 2000). In addition, the same researcher positioned the electrodes before all measurements. EMG signals were band-pass filtered (10-500Hz), amplified (20 times, Porti-17TM, TMS, Enschede, The Netherlands; input impedance>1012Ω, common mode rejection ratio>90dB), and stored on disc (22 bits AD converted, resolution 71.5 nV/bit, sample rate 1000 samples/s). Off-line, EMG signals were band-pass filtered between 20 to 300Hz and rectified and low-pass filtered at 15Hz. The average amplitudes in each complete step were determined and values were normalized to peak values of the corresponding signals in the unfatigued trials of each participant. The between trial variability of kinematic, ROM and muscle activity was expressed as the standard deviation

Before and after the fatigue protocol, muscle strength of the quadriceps and triceps surae muscles was measured, according to the muscle that we intended to fatigue, using

custom-made dynamometers (Pijnappels et al., 2008). Subjects were firmly secured with straps fastening hips and shoulders. For knee extension, the participants were seated in a backward inclined chair, with a 90° hip angle (180° is full extension) and 120° knee angle (180° is full extension) and the lower leg tightly strapped to a strain gauge a strain gauge transducer (KAP, E/200 Hz, Bienfait BV Haarlem, The Netherlands) placed ~25 cm distal from the knee joint, which measured the force exerted at the shin. For ankle extension, the participants were seated in an upright chair with their knee 90° flexed and their ankle in 20° dorsiflexion and, the fore-foot positioned on a 10 x 10 cm force transducer (AMTI M3-1000, Watertown, USA) that was mounted in the push-off platform. Forces were samples at 1 kHz. Two attempts of maximal voluntary isometric contractions (MVIC) were made with the left limb before and after the stepping down trial. The means of the two attempts were calculated for each participant.

The dependent variables of interest were statistically analyzed with SPSS 18.0 for Windows® ($\alpha<0.05$). Normal distribution of the data was verified by the Shapiro-Wilk test. The endurance times in the two fatigue protocols, and the MVIC values before and after fatigue were compared through Student t-tests for paired samples. The other dependent variables and their standard deviation were compared through one way ANOVAs for repeated measures with fatigue as the independent factor, with three levels: before fatigue (data averaged over two session), ankle muscle fatigue, and knee muscle fatigue. Tukey Post-hoc tests were used to find the differences among levels.

6.4. Results

The participants performed the ankle fatigue protocol longer (19.6±9.7min) than the knee fatigue protocol (6.7±7.2min; $t_9=4.27$, $p<0.002$). After the fatigue protocol, the maximal voluntary isometric contraction had decreased by on average 15% for the ankle (pre-fatigue: 128.59±45.27N*m; ankle muscle fatigue: 109.70±28.17N*m; $t_9=2.34$, $p<0.04$) and by on average 4% for the knee (pre-fatigue: 242.94±9.43 N*m; knee muscle fatigue: 233.20±7.49 N*m; $t_9=5.27$, $p<0.001$).Before fatigue, the trials before ankle and knee muscle fatigue were similar and not significantly different for all gait variables.

For the foot-distance (Figure 6.2), ANOVAs indicated an effect of fatigue on the trailing (left) foot-step distance in N-1 ($F_{2,98}=7.52$; $p<0.002$) and N+1 ($F_{2,98}=5.75$; $p<0.005$), without significant differences for the leading foot-step distance. The foot-distance was increased in step N-1 ($p<0.02$), and decreased in N+1 ($p<0.02$) with ankle muscle fatigue.

With knee muscle fatigue, there was no change in the foot-distance. Both ankle and knee muscle fatigue caused increased variability of foot-distance in step N-1 and N+1 ($F_{2,18}$=4.50; p<0.03, and $F_{2,18}$=3.98; p<0.04, respectively) for the trailing foot and in step N for the leading foot ($F_{2,18}$=9.19; p<0.005).

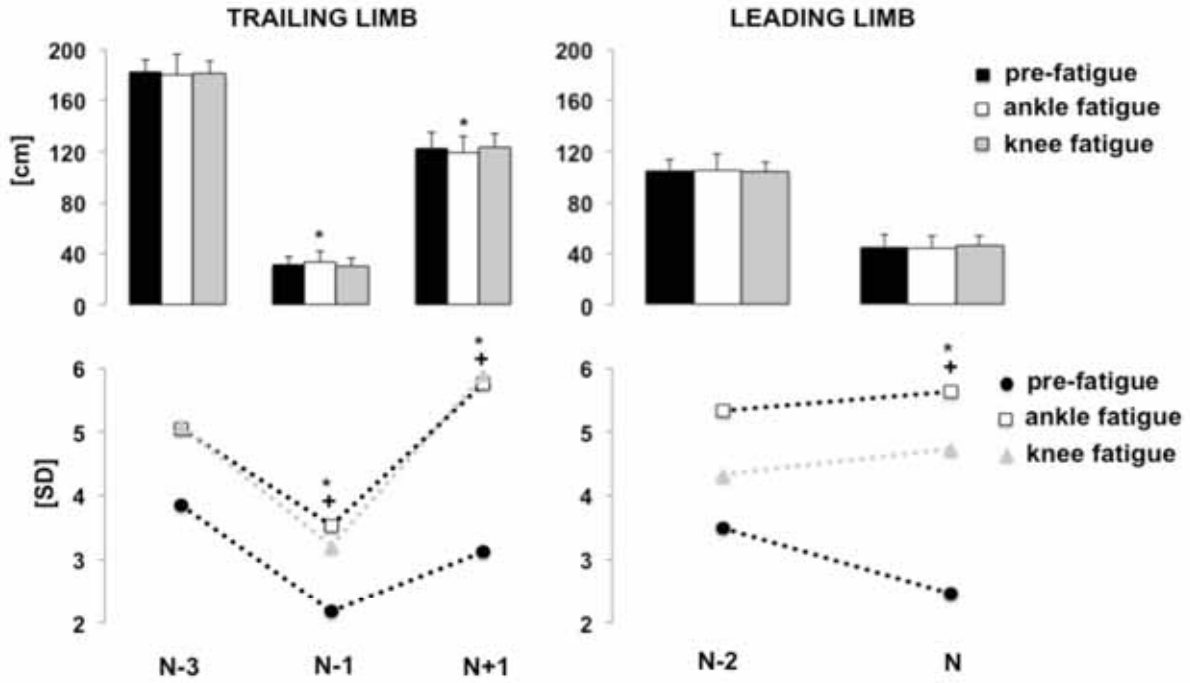

Figure 6.2. Foot-step distance for trailing (left column) and leading (right column) limbs. The top panels represent the means and standard deviations for each step before and after the fatigue protocols. The lower panels represent the variability (standard deviation) for each step before and after the fatigue protocols. Asterisk (*) indicates significant differences between pre-fatigue and ankle muscle fatigue. Plus (+) indicates significant differences between pre-fatigue and knee muscle fatigue.

ANOVAs indicated an effect of fatigue on the spatial-temporal parameters, joint ROM and EMG (Table 6.1). After both fatigue protocols, the participants showed decreased knee ROM ($F_{2,98}$=76.37; p<0.001; and $F_{2,98}$=41.26; p<0.001, respectively) and increased ankle ROM ($F_{2,98}$=50.75; p<0.001; and $F_{2,98}$=43.19; p<0.001, respectively) for both steps (N-2 and N-1).

With ankle muscle fatigue, the participants reduced step length ($F_{2,98}$=10.24; p<0.001) and step duration ($F_{2,98}$=6.95; p<0.02) and increased the activity of biceps femoris ($F_{2,98}$=22.83; p<0.001) in N-2, and increased the activity of rectus femoris ($F_{2,98}$=10.01; p<0.001) in N-1. In addition, they increased hip ROM ($F_{2,98}$=11.60; p<0.001; $F_{2,98}$=12.13; p<0.001, respectively) in both steps.

With knee muscle fatigue, the participants increased step width ($F_{2,98}$=7.39, p<0.002; and $F_{2,98}$=8.02; p<0.003, respectively) and decreased the activity of biceps femoris ($F_{2,98}$=22.83; p<0.001, and $F_{2,98}$=10.29; p<0.001, respectively) and tibialis anterior ($F_{2,98}$=9.74; p<0.001, and $F_{2,98}$=4.81; p<0.01, respectively) in both steps. Besides, they decreased step duration ($F_{2,98}$=4.28; p<0.03), and the activity of rectus femoris ($F_{2,98}$=10.01; p<0.001) and gastrocnemius lateralis ($F_{2,98}$=3.64; p<0.03), and increased step velocity ($F_{2,98}$=8.92; p<0.001), and hip ROM ($F_{2,98}$=11.60; p<0.001) in N-1.

With respect to between trial variability (Table 6.2), with ankle muscle fatigue, increased variability of knee ROM ($F_{2,18}$=81097; p<0.004), and decreased variability of hip ROM ($F_{2,18}$=5.30; p<0.04) were found in N-1. With knee muscle fatigue, variability of knee ROM ($F_{2,18}$=9.11; p<0.009) was increased in N-2.

Table 6.1. Mean and standard deviations of spatial-temporal parameters, joint ROM and EMG parameters before (pre-fatigue) and after fatigue (ankle and knee muscle fatigue). The first p-values are comparison between pre-fatigue and ankle muscle fatigue in the Post-hoc test; the second p-values are comparison between pre-fatigue and knee muscle fatigue in the Post-hoc test.

		pre-fatigue	ankle fatigue	p-values	knee fatigue	p-values
step length	N-2	78.49±5.67	75.97±6.20	**0.001**	77.52±5.14	0.09
	N-1	72.32±4.63	70.93±7.78	0.23	72.46±4.46	0.99
step width	N-2	13.78±4.38	14.99±4.04	0.07	16.11±5.95	**0.001**
	N-1	16.60±4.63	17.28±3.74	0.64	19.12±5.64	**0.001**
step duration	N-2	0.56±0.06	0.55±0.07	**0.02**	0.55±0.05	0.83
	N-1	0.58±0.05	0.58±0.05	0.99	0.56±0.05	**0.03**
step velocity	N-2	142.25±19.50	141.06±20.01	0.99	142.02±15.24	0.99
	N-1	125.18±12.73	121.97±14.37	0.08	129.89±16.64	**0.04**
ankle ROM (°)	N-2	21.75±5.56	30.24±6.57	**0.001**	30.43±8.27	**0.001**
	N-1	21.84±4.47	28.96±7.34	**0.001**	31.58±8.06	**0.001**
knee ROM (°)	N-2	66.18±4.85	49.70±8.93	**0.001**	52.96±5.47	**0.001**
	N-1	66.34±4.55	48.03±10.60	**0.001**	55.04±13.01	**0.001**
hip ROM (°)	N-2	28.67±4.38	34.52±5.20	**0.001**	31.16±9.96	0.11
	N-1	28.73±7.04	34.20±4.54	**0.001**	34.04±9.60	**0.001**
RMS rectus femoris (%)	N-2	17.94±6.18	19.80±8.48	0.51	16.08±10.71	0.33
	N-1	23.52±12.45	30.70±17.45	**0.04**	19.39±14.04	**0.01**
RMS biceps femoris (%)	N-2	22.06±5.73	32.63±20.11	**0.001**	18.19±9.48	**0.006**
	N-1	14.47±10.19	13.57±8.84	0.99	7.70±5.37	**0.001**
RMS tibialis anterior (%)	N-2	26.26±15.38	24.24±9.55	0.98	17.43±9.41	**0.002**
	N-1	12.29±4.49	12.30±5.37	0.97	9.92±5.39	**0.02**
RMS gastrocnemius lateralis (%)	N-2	10.66±5.16	12.67±9.86	0.08	8.71±6.40	0.23
	N-1	20.94±4.73	19.85±8.51	0.96	17.22±9.67	**0.01**

6.5. Discussion

The aim of the study was to analyze the effects of ankle and knee muscle fatigue on foot placement in the last stride before stepping down a curb in ongoing gait. The main finding of this study was a higher variability of foot-step horizontal distance in the last step on the higher level of trailing limb as well as in the first step on the lower level for both limbs with muscle fatigue. This suggests a loss of control and consequently an increased risk of making a misstep. We additionally explored kinematics and muscle activity to reveal potential causes of changes in foot placement and potential compensatory changes that would limit fatigue effects. An increased variability of knee ROM was found which may form the cause of the increased variability in foot placement. In addition, the participants made adjustments in the spatial-temporal gait parameters, which appeared to be aimed at increasing safety. Participants reduced step length and step duration, and increased step width and step velocity with muscle fatigue, which would facilitate medio-lateral balance control. In addition, participants increased ankle and hip ROM and decreased knee ROM. There were no changes in the variability of EMG parameters after fatigue, but average muscle activity changed with muscle fatigue.

The fatigue protocols used in the present study induced a significant reduction of muscle force, with the most pronounced change resulting from the ankle muscle fatigue protocol. The longer endurance time in the ankle fatigue protocol may account for the larger reduction in strength. In turn, this may account for the more pronounced changes in gait after the ankle muscle fatigue protocol, but this might also to be due to a primary role of the triceps surae muscle in balance control (Helbostad et al., 2010).

Table 6.2. Variability (standard deviation) of spatial-temporal parameters, joint ROM and EMG parameters before (pre-fatigue) and after fatigue (ankle and knee fatigue). The first p-values are comparison between pre-fatigue and ankle muscle fatigue in the Post-hoc test; the second p-values are comparison between pre-fatigue and knee muscle fatigue in the Post-hoc test.

		pre-fatigue	ankle fatigue	p-values	knee fatigue	p-values
step lengtht	N-2	1.42±0.46	1.59±0.80	0.89	1.71±0.50	0.99
	N-1	1.37±0.49	1.59±0.72	0.99	1.22±0.30	0.96
step width	N-2	1.66±0.40	1.56±0.68	0.99	1.80±1.27	0.99
	N-1	1.53±0.69	1.45±0.81	0.99	1.16±0.49	0.06
step duration	N-2	0.02±0.007	0.02±0.007	0.98	0.02±0.01	0.99
	N-1	0.02±0.01	0.02±0.01	0.99	0.02±0.01	0.98
step velocity	N-2	6.40±2.36	5.24±2.29	0.65	6.48±3.65	0.99
	N-1	3.35±0.97	5.76±2.64	0.12	6.39±3.49	0.06
ankle ROM	N-2	3.90±1.33	3.91±1.20	0.99	4.90±2.27	0.93
	N-1	2.75±0.61	3.67±1.80	0.55	3.46±1.74	0.66
knee ROM	N-2	3.30±0.78	7.45±3.40	**0.01**	5.00±1.03	**0.01**
	N-1	3.73±1.61	9.13±3.96	**0.01**	5.59±2.22	0.09
hip ROM	N-2	3.32±1.82	2.65±1.17	0.41	4.14±3.07	0.65
	N-1	4.78±2.24	3.20±1.10	**0.04**	7.53±5.41	0.29
RMS rectus femoris	N-2	4.03±3.46	6.78±4.07	0.44	5.65±2.90	0.99
	N-1	3.40±1.69	4.68±2.38	0.36	4.48±1.98	0.47
RMS biceps femoris	N-2	3.75±2.48	4.43±2.76	0.99	5.98±3.78	0.23
	N-1	3.61±1.17	4.08±2.45	0.98	3.32±1.56	0.98
RMS tibialis anterior	N-2	2.45±1.68	3.06±2.31	0.98	6.67±4.18	0.17
	N-1	3.81±1.72	2.66±1.19	0.47	3.70±2.52	0.99
RMS gastrocnemius lateralis	N-2	2.69±1.62	8.22±6.71	0.17	3.71±2.28	0.99
	N-1	3.58±0.84	6.86±4.06	0.36	9.21±5.76	0.06

Variability of distance of the trailing limb (left foot) horizontal distance to the step was larger after both muscle fatigue protocols. High variability might indicate a loss of control and a high risk of falling for example due to placing the foot (partly) over the edge (Lythgo et al., 2007). The mean distance to the curb on the high level (step N-1) was somewhat increased in ankle muscle fatigue, perhaps as a compensatory strategy to deal with this increased variability, but as a result the mean distance on the lower level was decreased.The increased variability of placement of the leading limb on the lower level also suggests a reduced control over the right foot placement, which might explain why subjects reduced the forward angular momentum at landing less in presence of fatigue Barbieri et al., 2012b). Since no consistent changes were found in the variability of the EMG data, these cannot be related to foot placement variability. The kinematic data suggest that the increased

variability in foot placement was mainly due to an increase in variability of knee motion, with the variability actually tending to go down in hip and ankle. This is somewhat surprising, as a direct effect of fatigue on the ankle kinematics might have been expected. However, the increased variability in foot placement increases the variability of knee ROM, which could result in an inconsistent strategy during walking but also an attempt to find a better strategy. Possibly, the bi-articular nature of the gastrocnemius muscle may have contributed to increased knee kinematic variability with ankle muscle fatigue.

The changes in joint kinematics and joint kinematic variability combined suggest that the control of both the left stance phase (N-2) and the left swing phase (N-1) is adapted to shift movement from the knee to the hips and ankles. After ankle muscle fatigue, further adjustments occurred in the last but one step (N-2), where participants reduced step duration and step length. This might be regarded as an anticipatory strategy facilitating the foot placement in relation to the curb (c.f. Patla et al., 1991). In addition, a tendency towards shortened step length was also found in N-1, contributing to the significant increase in distance of the left foot to the curb in ankle fatigue. The increased step width and decreased step duration observed with knee muscle fatigue, which have previously been observed with fatigue in normal gait (Barbieri et al., 2012a; Helbostad et al. 2010), would facilitate medio-lateral balance control (Hak et al., 2012; Hof et al., 2007). Possibly, the knee muscle fatigue protocol impaired medio-lateral control more than the ankle protocol.

The increased the muscle activity of the biceps femoris in step N-2 (stance phase) and rectus femoris in step N-1 (swing phase) with ankle muscle fatigue might compensate for calf muscle fatigue, and might serve to contribute to propulsion by hip extension and improve control in the placement of the limb respectively (Vila-Chã et al., 2011). The sit-to-stand task used to induce knee muscle fatigue probably also demands substantial activity of the calf muscle. This may explain the decrease of muscle activity of both calf and quadriceps muscles with knee muscle fatigue. The decrease in the biceps femoris and tibialis activity with knee muscle fatigue might indicate a compensatory strategy (Kellis and Kouvelioti, 2009) to improve knee and ankle mechanical efficiency (Murdock and Hubley-Kozey, 2012; Padua et al., 2006).

Although the findings shed some light on the effects of muscle fatigue in stepping down, some limitations are evident. We analyzed only the last stride on the higher level, while possibly participants began adjustments in preceding steps. However, a previous study has shown that the major adjustments of foot placement before stepping down occur in the last stride (Lythgo et al., 2007). Next, we analyzed the contribution of the left (trailing leg) only.

The effects of fatigue on the mechanics of the leading limb at landing were addressed in a previous study. Furthermore, we analyzed only one curb height (10 cm). The limited sample size (ten young adults in each group) and the potential random variation caused by variability especially between days may have limited statistical power. Finally, a fairly large number of tests were used without correction for multiple testing in our secondary analysis aimed at finding causes and compensations for fatigue effects on foot placement. Considering these limitations, generalization of negative results as well as the results from the secondary analysis of kinematics and EMG data should be done with care.

In conclusion, the variability of placement of the trailing and leading limb relative to the curb increased with fatigue, suggesting a loss of control. This increase appears due to an increased variability of knee motion. Simultaneously, kinematic changes, such as adjustments of step width and step duration and an increased ankle and hip ROM and decreased knee ROM were found that might be aimed at limiting these fatigue effects.

Chapter 7

EPILOGUE

The aim of the thesis was to analyze the effects of muscle fatigue on mechanics and motor control of walking in different environments. Series of fatigue and walking experiments were conducted, in order to obtain the required information. The investigations in this thesis addressed the following topics: the effects of quadriceps muscle fatigue on walking in different environments, the role of effects of fatigue in different muscular group during stepping down, and the impact of physical activity level and aging in control of gait under muscle fatigue. In this epilogue, the findings and conclusions from the studies performed are briefly summarized and revisited. Furthermore, recommendations are given for future research.

7.1. Effects of quadriceps muscle fatigue on walking in different environments

This thesis showed that quadriceps muscle fatigue modifies the gait pattern fairly independent of the task, with similar modulations in the different environments. In walking on a level surface, during obstacle crossing and during stepping down quadriceps fatigue caused a wider basis of support and a reduction of stride duration. These adjustments appear to suggest that knee muscle fatigue impairs medio-lateral control during gait (Chapter 3, 5 and 6). Thus, the individuals adjust the parameters to improve the balance to avoid falling. Furthermore, these results suggest that the relatively low reductions in muscle strength (between 3% and 12%) found this thesis already challenge the stability and safety of walking. The reduction in strength could impair production of joint moments and hence absorption of the kinetic energy (Prilutsky et al., 1996; DeVita and Skelly, 1992) and joint stabilization (Murdock and Kozey, 2011; Granacher et al., 2010; Vila-Chã et al., 2011; Lewek et al., 2004) through eccentric actions.

Increased step width provides a larger margin of safety in controlling medio-lateral movements of the body's center of mass (Hak et al., 2012; Hof et al., 2007). Reduced stride duration facilitates control of the body center of mass in the fore-aft direction and also facilitates balance control in the medio-lateral direction (Hof et al., 2007; Hof et al., 2005). Even though, sometimes, such as during walking on level surface and during obstacle crossing, the reduced stride duration coincides with an increased speed (Bruijn et al., 2009), reducing stride duration appears to be the preferred strategy to deal with balance threats (Hak et al., 2012). An increase in step length would facilitate control of balance in the forward direction. However, such a change was not observed, possibly because it would conflict with a reduction in step duration.

Knee muscle fatigue did not affect the placement of the feet in crossing an obstacle and stepping down a curb. The horizontal distances and toe-clearance were not modulated after knee muscle fatigue in both types of walking. This may suggest that horizontal and vertical foot-obstacle distances are controlled variables and knee muscle fatigue was not able to disrupt the control of these variables. Probably, a combination with other impairments such as due to aging (as revealed in Chapter 4) could generate deviations in horizontal distance and toe-clearance. On the other hand, knee muscle fatigue did appear to increase the variability of trailing and leading limb horizontal distance. High variability may indicate a loss of control and a high risk of falling (Lythgo et al., 2007). So, the individuals need to improve the control using compensatory changes in joint movement (ankle, knee and hip) and muscle activity (Chapter 6).

7.2. Ankle muscle fatigue versus knee muscle fatigue: mechanics and control on walking during stepping down

The experimental studies of this thesis corroborated with the findings of Chapter 2, showed that the effects of muscle fatigue during stepping down are dependent on the muscles that are fatigued. The findings of this thesis showed that the mechanics and control during the last stride before stepping down and in landing phase were dependent on whether ankle muscles or knee muscles were fatigued, although it should be kept in mind that levels of fatigue were also different between conditions. Figure 7.1 shows an overview of the main findings about the effect of fatigue in the two muscle groups.

It should be noted that the joint used to absorb kinetic energy in stepping down with ankle muscle fatigue was dependent on whether a heel or toe landing strategy was used. Participants tended to overcompensate the effects of fatigue, increasing the total energy absorption at landing. In addition, the variability of trailing and leading foot-step horizontal distance was higher after both fatigue protocols, which indicates a reduced control of foot placement.

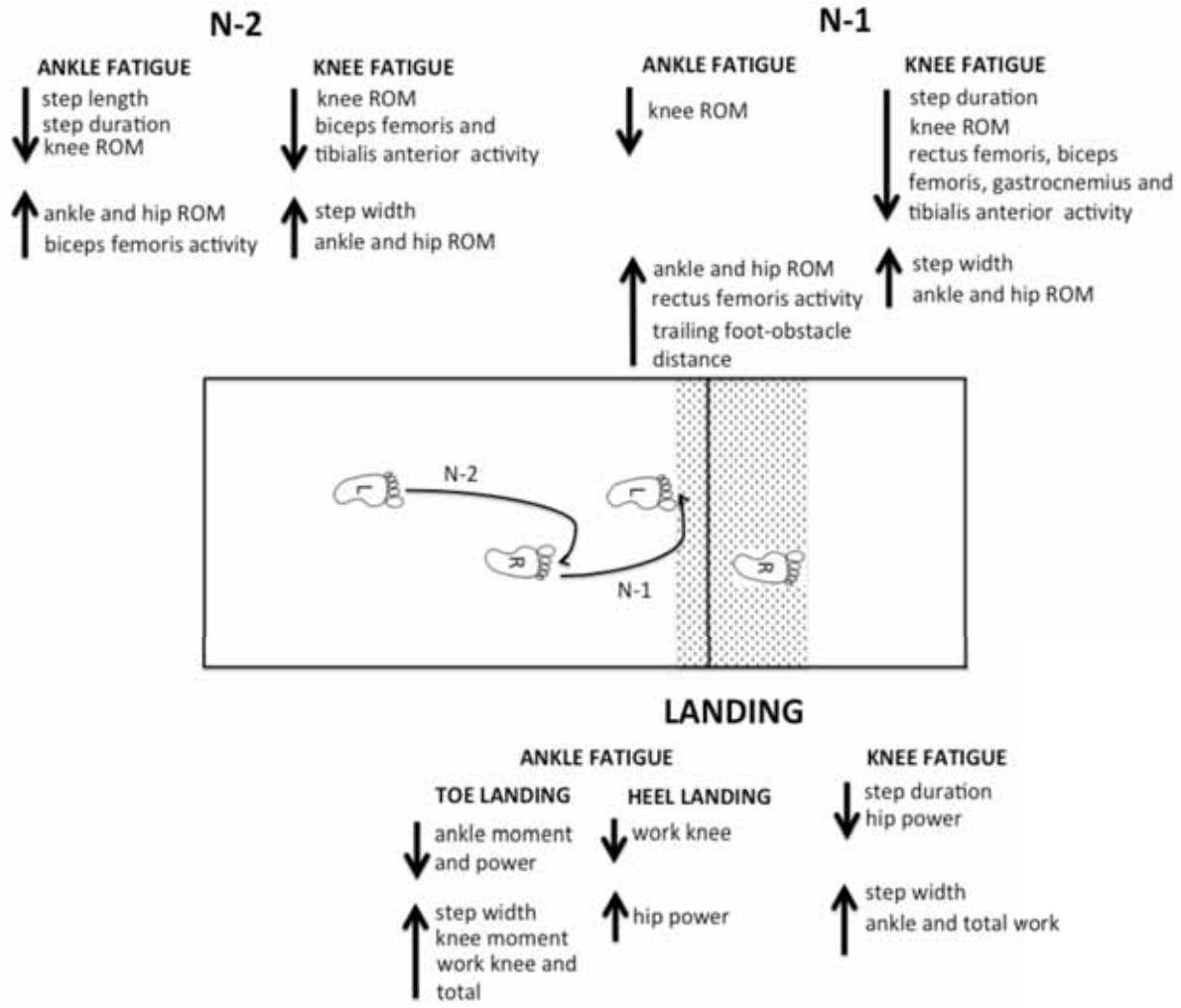

Figure 7.1. Overview of findings on the last strides before stepping down (Chapter 6) and on the landing phase (Chapter 5). Arrows indicate increase or decrease of the variable. R – right foot; L – left foot.

The finding of wider basis of support was consistent after knee muscle fatigue. The individuals increased the step width both during the last stride before stepping down and at landing, which seems to confirm that knee muscle fatigue impairs medio-lateral control more than ankle muscle fatigue. Furthermore, the individuals used ankle and hip joint strategies, which were less fatigued, to improve safe. In stair descent, negative power at the knee and ankle of the landing leg reduces the kinetic energy (McFadyen and Winter, 1998; Riener et al., 2002). Apparently, knee joint continued to provide stability and attenuating impact loading (Syed and Davis, 2000; Lewek et al., 2002) since it was found no change in the knee moment and workafter knee muscle fatigue. However, the lower muscle showed less activity after muscle fatigue (Chapter 6) that explained mainly the use of ankle strategies to attenuate impact.Leg alignment and muscle activation determine leg stiffness at landing (Hortobagyi

and DeVita, 1999; 2000). The decreased of biceps femoris and tibialis activity indicate a compensatory strategy (Kellis and Kouveloiti, 2009) to improve ankle mechanical efficiency (Padua et al., 2006; Murdock and Hubley-Kozey, 2011).

Ankle muscle fatigue provides anticipatory strategy during stride before stepping down facilitating the foot placement in relation to the curb (c.f. Patla et al., 1991). Furthermore, the most interesting finding after ankle muscle fatigue was the absorption of kinetic energy according to landing strategy. In toe landing, the individuals increased eccentric contractions of the knee muscles and knee joint work to reduce the kinetic energy that is gained in stepping down. This strategy aims to reduce the use of ankle joint, which is quite demanding with the high moments and negative power for ankle joint in toe landing (Dieën et al., 2008), due to the ankle muscle fatigue.

As regarding heel landing, the individuals reduced less effectively (the negative work was almost similar between before and after muscle fatigue) the kinetic energy during landing after fatigue, using hip muscle strategy. This could be explained in part by more energy absorbed in toe landing as compared to heel landing (Dieën et al., 2008). Thus, the individuals did not need to change so much the behavior after ankle muscle fatigue when they landing using heel strategy, whichshifts the demands to the larger proximal muscle groups and is less demanding especially for the plantar flexor muscles (Dieën et al., 2008).

Despite the effective reduction of kinetic energy after both fatigue protocols, the high variability of trailing and leading foot-step horizontal distance may indicate a loss of control and a higher risk of falling with muscle fatigue. The increased variability in trailing foot placement was mainly due to an increase in variability of knee motion, with the variability actually tending to go down in hip and ankle. Less adequate leading foot placement may explain why subjects reduced the forward angular momentum at landing less in presence of fatigue (Chapter 6).

7.3. Impact of muscle fatigue in the physical activity level and aging

The effects of knee muscle fatigue on even and uneven walking of young adults were independent of physical activity level. Despite the better muscular capacity of active individuals, as reflected by the longer endurance times, muscle strength before and after fatigue were not different between active and inactive individuals. Young adults with age from 20 to 30 years old still were not impacted by an inactive life (Weineck, 2009). Probably, in older adults the motor control after muscle fatigue would be different between active and inactive individuals.

In contrast, the effects of knee muscles fatigue were age-related in walking over even and uneven terrains. The modulations in both tasks after fatigue started over 40 years old with a risky strategy for older individuals (over 60 years old).The age group between 40 to 60 years old shows the biggest reduction in physical capacity, mainly strength and resistance (Weineck, 2009; Deschenes, 2004; Izquierdo et al., 1999; Metter et al., 1997). Adequate muscle strength in lower limb muscles is required for safely crossing an obstacle (Petrella el al., 2005). Obviously that over 60 years old the decrease in performance is the most sharp due to aging. Over 40 years old has reduced gradual in the muscle mass, bone and joint movement (Weineck, 2009) that impairs the performance in daily activities. Muscle fatigue also decreases muscle strength and destabilizes motor performance (Gates and Dingwell, 2008; Selen et al., 2007), which are important components of balance control (Parijat and Lockhart, 2008a,b; Helbostad et al., 2007; Lord et al., 1993). Thus, increasing age combined with fatigue effects exacerbated the loss of motor control over 40 years old, independently even or uneven walking.

7.4. Main considerations and future studies

The main findings of this thesis were that:

a) Knee muscle fatigue negatively affects medio-lateral balance control independently of type of gait, i.e. on even and uneven surfaces (obstacle crossing and stepping down). However, young adults did modulate the spatial-temporal and kinetic parameters, angular movement, muscle activity and energy absorption, to maintain stability.

b) Compensatory muscle strategies were used according to the muscle groups that were fatigued. In stepping down with local leg muscle fatigue, young healthy adults compensated the fatigue effects by recruiting unfatigued muscle groups adjusted their gait pattern to enhance balance control, which was, however, only partially successful. In addition, the variability of trailing and leading foot-step horizontal distances increased with fatigue, suggesting a reduced precision control. Simultaneously, compensatory strategies were used to improve the safety of stepping down, such as adjustments of step width and step duration.

c) Physical activity level did not mediate the effects of knee muscle fatigue on walking on even and uneven surfaces in young adults. On the other hand, the aging process impacts the walking over even and uneven terrains after knee muscles fatigue. The modulations in both tasks after fatigue, even and uneven gait, started over 40 years old with a risky strategy for older individuals (over 60 years old).

Muscle fatigue is a relevant factor in daily activities. Although the findings of this thesis shed some light on the effects of muscle fatigue on even walking, obstacle crossing and stepping down, future studies are necessary to confirm our findings, and improve the knowledge on its effects.

Such future studies may investigate the effects of muscle fatigue on walking with different height of obstacle and step, since this thesis used only one height (15 cm for obstacle, and 10 cm for step). Previous studies indicated that the height of an obstacle (Lu et al., 2006) and step (Dieën and Pijnappels, 2009) affects the mechanics, control and strategy choice during obstacle crossing and stepping down. Another aspect relevant is the gait velocity, which was not controlled in this study, and also affects performance of these tasks (Dieën and Pijnappels, 2009).

In Chapters 3 and 4, only men participated in the study. Studies on the effects of muscle fatigue in women might show different findings. Anatomic variations have been found between males and females concerning muscle cross-sectional area and strength (Blazevich et al., 2006), bone shape (Fehring et al., 2009; Hoshino et al., 2011) and passive knee joint stabilizers (Biscevic et al., 2005), which may influence the motor control under muscle fatigue. In addition, despite of the physical activity level was not important for young adults (Chapter 3), the combination between aging and physical activity level for older adults could detail the effects of muscle fatigue.

Finally, the understanding of fatigue recovery could be important information for the individual to perform a new activity. A comprehensive and descriptive understanding of fatigue recovery may be fundamental in determining whether aged humans can perform and repeat requisite movements successfully (Allman and Rice, 2002). Thus, future studies may indeed the fatigue recovery.

REFERENCES

ABBISS, C.R.; LAURSEN, P.B. Models to explain fatigue during prolonged endurance cycling. **Sports Medicine**. v. 35, p. 865-898, 2005.

ALLMAN, B.L.; RICE, C.L. Neuromuscular fatigue and aging: central and peripheral factors. **Muscle Nerve**. v. 25, n. 6, p. 785-796, 2002.

AMADUCCI, C. M.; MOTA, D.D.; PIMENTA, C.A. Fatigue among nursing undergraduate students. **Revista da Escola de Enfermagem – USP**. v. 44, n. 4, p. 1052-1058, 2010.

BAECKE, J.A.; BUREMA, J.; FRIJTERS, J.E. A short questionnaire for the measurement of habitual physical activity in epidemiological studies. **American Journal of Clinical Nutrition**. v. 36, p. 936-942, 1982.

BARBIERI, F.A.; SANTOS, P.C.R.; VITÓRIO, R.; van DIEËN, J.H.; GOBBI, L.T.B. Effect of muscle fatigue and physical activity level in motor control of the gait of young adults. **Gait and Posture**. Submitted, 2012a.

BARBIERI, F.A.; GOBBI, L.T.B.; LEE, Y.J.; PIJNAPPELS, M.; van DIEËN, J.H. Effect of triceps surae and quadriceps muscle fatigue on the mechanics of landing in stepping down in ongoing gait. **Ergonimics**. Submitted, 2012b.

BARBIERI, F.A.; GOBBI, L.T.B.; LEE, Y.J.; PIJNAPPELS, M.; van DIEËN, J.H. The effect of muscle fatigue on the last stride before stepping down a curb. **Gait and Posture**. In press, 2012c.

BAUDRY, S.; KLASS, M.; PASQUET, B.; DUCHATEAU, J. Age-related fatigability of the ankle dorsiflexor muscles during concentric and eccentric contractions. **European Journal of Applied Physiology**. v. 100, p. 515–525, 2007.

BEGG, R.K.; SPARROW, W.A. Gait characteristics of young and older individuals negotiating a raised surface: implications for the prevention of falls. **Journal of Gerontology Series A: Biological Sciences and Medical Sciences**. v. 55, n. 3, p. M147-M154, 2000.

BENAVIDES, F.G.; BENACH, J.; EZ-ROUX, A.V.; ROMAN, C. How do types of employment relate to health indicators? Findings from the Second European Survey on Working Conditions. **British Medicine Journal**. v. 54, p. 494-501, 2000.

BENTLEY, T.A.; HASLAM, R.A. Slip, trip and fall accidents occurring during the delivery of mail. **Ergonomics**. v. 41, p. 1859-1872, 1998.

BERARD, J.R.; VALLIS, L.A. Characteristics of single and double obstacle avoidance strategies: a comparison between adults and children. **Experimental Brain Research**. v. 175, p. 21-31, 2006.

BERG, W.P.; ALESSIO, H.M.; MILLS, E.M. Circumstances and consequences of falls in independent community-dwelling older adults. **Age and Ageing**. v. 26, p. 261-268, 1997.

BERGER, L.L.; REGUEME, S.C.; FORESTIER, N. Unilateral lower limb muscle fatigue induces bilateral effects on undisturbed stance and muscle EMG activities. **Journal of Electromyography and Kinesiology**. v. 20, p. 947-952, 2010.

BIGLAND-RITCHIE, B.; WOODS, J.J. Changes in muscle contractile properties and neural control during human muscular fatigue. **Muscle Nerve**. v. 7, n. 9, p. 691-699, 1984.

BISCEVIC, M.; TOMIC, D.; STARC, V.; SMRKE, D. Gender differences in knee kinematics and its possible consequences. **Croatian Medicine Journal**. v. 46, p. 253-260, 2005.

BLAZEVICH, A.J.; GILL, N.D.; ZHOU, S. Intra- and inter-muscular variation in human quadriceps femoris architecture assessed in vivo. **Journal of Anatomy**. v. 209, p. 289-310, 2006.

BOOTH, F.W.; THOMASON, D.B. Molecular and cellular adaptation of muscle in response to exercise: perspectives of various models. **Physiological Reviews**, v. 71, p. 541-585, 1991.

BRACH, J.S.; BERTHOLD, R.; CRAIK, R.; VANSWEARINGEN, J.M.; NEWMAN, A.B. Gait variability in community-dwelling older adults. **Journal of the American Geriatrics Society**. v. 49,p. 1646-1650, 2001.

BRADSHAW, E.J.; SPARROW, W.A. Effects of approach velocity and foot-target characteristics on the visual regulation of step length. **Human MovementScience**. 20: p. 401-426, 2001.

BRUIJN, S.M.; van DIEËN, J.H.; MEIJER, O.G.; BEEK, P.J. Is slow walking more stable? **Journal of Biomechanics**. v. 42,p. 1506-1512, 2009.

BUCKLEY, J.G.; TIMMIS, M.A.; SCALLY, A.J.; ELLIOTT, D.B.When is visual information used to control locomotion when descending a kerb? **PLoS One**. v. 6, p. e19079, 2011.

CAPPOZZO, A.; CATANI, F.; CROCE, U.D.; LEARDINI, A. Position and orientation in space of bones during movement: Anatomical frame definition and determination. **Clinical Biomechanics**. v. 10, p. 171-178, 1995.

CHALDER, T.; BERELOWITZ, G.; PAWLIKOWSKA, T.; WATTS, L.; WESSELY S.; WRIGHT, D. Development of a fatigue scale. **Journal of Psychosomatic Research**. v. 372, p. 147–153, 1993.

CHEN, M.K. The epidemiology of self-perceived fatigue among adults. **Preventive Medicine**. v. 15, n. 1, p.74-81, 1986.

COCKER, K.A.; DE BOURDEAUDHUIJ, I.M.; CARDON, G.M. What do pedometer counts represent? A comparison between pedometer data and data from four different questionnaires. **Public Health Nutrition**. v. 12, p. 74-81, 2009.

COHEN, S.; KESSLER, R.C.; GORDON, L.U. Measuring Stress, A Guide for Health and Social Scientists. **Oxford University Press**, Oxford. 1995.

CROSBIE, J.; KO, V. Changes in the temporal and distance parameters of gait evoked by negotiation of curbs. **Australian Journal of Physiotherapy**. v. 46, n. 2, p. 103-112, 2000.

DAWSON, D.; MCCULLOCH, K. Managing fatigue: it's about sleep. **Sleep Medicine Reviews**. v. 9, n. 5, p. 365-380, 2005.

DESCHENES, M.R. Effects of aging on muscle fibre type and size. **Sports Medicine**. v. 34, n. 12, p. 809-824, 2004.

DeVITA, P.; HORTOBAGYI, T. Age increases the skeletal versus muscular component of lower extremity stiffness during stepping down. **Journals of Gerontology Series A: Biological Sciences and Medical Sciences**. v. 55, n. 12, p. B593-600, 2000.

DeVITA, P.;BLANKENSHIP-HUNTER, P.; SKELLY, W.A. Effects of a functional knee brace on the biomechanics of running. **Medicine Science and Sports Exercise**. v. 24, p. 797-806, 1992.

DI FABIO, R.P.; KURSZEWSKI, W.M.; JORGENSON, E.E.; KUNZ, R.C. Footlift asymmetry during obstacle avoidance in high-risk elderly. **Journal of American Geriatrics Society**, v. 52, p. 2088-93, 2004.

DIEËN, J.H.v.; PIJNAPPELS, M. Effects of conflicting constraints and age on strategy choice in stepping down during gait. **Gait and Posture.** v. 29, p. 343-345, 2009.

DIEËN, J.H.v.; SPANJAARD, M.; KÖNEMANN, R.; BRON, L. PIJNAPPELS, M. Mechanics of toe and heel landing in stepping down in ongoing gait. **Journal of Biomechanics**. v. 41, p. 2417-2421, 2008.

DIEËN, J.H.v.; SPANJAARD, M.; KÖNEMANN, R.; BRON, L.; PIJNAPPELS, M. Balance control in stepping down expected and unexpected level changes. **Journal of Biomechanics**. v. 40, 3641-3649, 2007.

DIEËN, J.H.v., KINGMA, I.; van DER BUG, J.C.E. Evidence for a role of antagonistic cocontraction in controlling trunk stiffness during lifting. **Journal of Biomechanics**. v. 36, p. 1829-1836, 2003.

EDWARDS, R.H.T. Human muscle function and fatigue. **Ciba Foundation Symposium**. v. 82, p. 1-18, 1981.

EGERTON, T.; BRAUER, S.G.; CRESSWELL, A.G. Fatigue after physical activity in healthy and balance-impaired elderly. **Journal of Aging and Physical Activity**. v. 17, p. 89-105, 2009.

ENOKA, R.M.; DUCHATEAU, J. Muscle fatigue: what, why and how it influences muscle function. **Journal of Physiology**. v. 586, p. 11-23, 2008.

FEASSON, L.; CAMDESSANCH, J.; EL MHANDI, L.; CALMELS, P.; MILLET, G.Y. Fatigue and neuromuscular diseases. **Annals of Physical and Rehabilitation Medicine**. v. 49, p. 375-384, 2006.

FEHRING, T.K.; ODUM, S.M.; HUGHES, J.; SPRINGER, B.D.; BEAVER, W.B. Jr. Differences between the sexes in the anatomy of the anterior condyle of the knee. **Journal of Bone and Joint Surgery American**. v. 91, p. 2335-2341, 2009.

FLORINDO AA, HALLAL PC, MOURA EC, MALTA DC. Practice of physical activities and associated factors in adults, Brazil, 2006. **Revista de Saúde Pública**. v. 43, p. 65-73, 2009.

FRANKLIN, D.W.; LIAW, G.; MILNER, T.E.; OSU, R.; BURDET, E.; KAWATO, M. Endpoint stiffness of the arm is directionally tuned to instability in the environment. **Journal of Neurosciences**. v. 27, n. 29, p.7705-7716, 2007.

GALNA, B.; PETERS, A.; MURPHY, A.T.; MORRIS, M.E. Obstacle crossing deficits in older adults: a systematic review. **Gait and Posture**. v. 30,p. 270-275, 2009.

GANDEVIA SC. Spinal and supraspinal factors in human muscle fatigue. **Physiological Review**. v. 81, p. 1725-1789, 2001.

GATES, D.H.; DINGWELL, J.B. The effects of neuromuscular fatigue on task performance during repetitive goal-directed movements. **Experimental Brain Research**. v. 187, p. 573–85, 2008.

GERIN-LAJOIE, M.; RICHARDS, C.L.; McFADYEN, B.J. The negotiation of stationary and moving obstructions during walking: anticipatory locomotor adaptations and preservation of personal space. **Motor Control**. v. 9,p. 242-269, 2005.

GOBBI, L.T.B.; SILVA, J.J.; BARBIERI, F.A. Do men and women use similar adaptive locomotion to clear static and dynamic obstacle? **Human Movement**. v. 12,p. 75-80, 2011.

GOBBI, L.T.; CANDIDO, R.P.; MENUCHI, M.R.; KLEINER, A.F. Obstacle stepping and body scale modulating parameters. **Perceptual and Motor Skills**. v. 109, n. 2, p. 441-451, 2009.

GOTSHALK, L.A.; KRAEMER, W.J.; MENDONCA, M.A.; VINGREN, J.L.; KENNY, A.M.; SPIERING, B.A.; VOLEK,J.S. Creatine supplementation improves muscular performance in older women. **European Journal of Applied Physiology**. v. 102,p. 223-231, 2008.

GRANACHER, U.; Wolf, I.; Wehrle, A.; Bridenbaugh, S.; Kressig, RW. Effects of muscle fatigue on gait characteristics under single and dual-task conditions in young and older adults. **Journal of NeuroEngineering and Rehabilitation**. v.7, p. 56, 2010.

GREAVES, C.J.; SHEPPARD, K.E.; ABRAHAM, C.; HARDEMAN, W.; RODEN, M.; EVANS, P.H. Systematic review of reviews of intervention components associated with increased effectiveness in dietary and physical activity interventions. **BMC Public Health**. v. 11, p. 116, 2011.

HAGELIN, C.L.; WENGSTRÖM, Y.; RUNESDOTTER, S.; FÜRST, C.J. The psychometric properties of the Swedish Multidimensional Fatigue Inventory MFI-20 in four different populations. **Acta Oncologica**. v.46, p. 97-104, 2007.

HAK, L.; HOUDIJK, H.; STEENBRINK, F.; MERT, A.; VAN DER WURFF, P.; BEEK, P.J., van DIEËN, J.H. Speeding up or slowing down? Gait adaptations to preserve gait stability in response to balance perturbations. **Gait and Posture**. v. 36, p. 260-264, 2012.

HANCOCK, P.A.; DESMOND, P.A. **Stress, Workload, and Fatigue**. Lawrence Erlbaum Associates, London. 2000.

HATTON, A.L.; MENANT, J.C.; LORD, S.R.; LO, J.C.; STURNIEKS, D.L. The effect of lower limb muscle fatigue on obstacle negotiation during walking in older adults. **Gait and Posture**. 2012, In Press.

HEDEL, H.J.; BIEDERMANN, M.; ERNI, T.; DIETZ, V. Obstacle avoidance during human walking: transfer of motor skill from one leg to the other. **Journal of Physiology**. v. 1, n. 543, p. 709-717, 2002.

HELBOSTAD, J.L.; STURNIEKS, D.L.; MENANT, J.; DELBAERE, K.; LORD, S.R.; PIJNAPPELS, M. Consequences of lower extremity and trunk muscle fatigue on balance

and functional tasks in older people: a systematic literature review. **BMC Geriatrics**. v. 10,p. 56, 2010.

HELBOSTAD, J.L.; LEIRFALL, S.; MOE-NILSSEN, R.S.; LETVOLD, O. Physical fatigue affects gait characteristics in older persons. **Journal of Gerontology Series A: Biological Sciences and Medical Science**, v. 62, p. 1010-1015, 2007.

HELBOSTAD, J.L.; MOE-NILSSEN, R. The effect of gait speed on lateral balance control during walking in healthy elderly. **Gait and Posture**. v. 18, p. 27-36, 2003.

HERMENS, H.J.; FRERIKS, B.; DISSELHORST-KLUG, C.; RAU, G. Development of recommendations for SEMG sensors and sensor placement procedures. **Journal of Electromyography and Kinesiology**. v. 10,p. 361-374, 2000.

HOCKS, A.L.; KENT-BRAUN, J.; DITOR, D.S. Sex differences in human skeletal muscle fatigue. **Exercise and Sport Sciences Reviews**. v. 29, p. 109–112, 2001.

HOF, A.L.; GAZENDAM, M.G.; SINKE, W.E. The condition for dynamic stability. **Journal of Biomechanics**. v. 38,p. 1-8, 2005.

HOF, A.L.; van BOCKEL, R.M.; SCHOPPEN, T.; POSTEMA, K. Control of lateral balance in walking. Experimental findings in normal subjects and above-knee amputees. **Gait and Posture**. v. 25, p. 250-258, 2007.

HORTOBAGYI, T.; DeVITA, P. Altered movement strategy increases lower extremity stiffness during stepping down in the aged. **Journals of Gerontology Series A: Biological Sciences and Medical Sciences**. v. 54, p. B63–B70, 1999.

HORTOBAGYI, T.; DeVITA, P. Muscle pre- and coactivity during downward stepping are associated with leg stiffness in aging. **Journal of Electromyography and Kinesiology**. v. 10, p. 117-126, 2000.

HOSHINO, Y.; WANG, J.; LORENZ, S.; FU, F.H.; TASHMAN, S. Gender difference of the femoral kinematics axis location and its relation to anterior cruciate ligament injury: a 3D–CT study. **Knee Surgery, Sports Traumatology, Arthroscopy**. v. 20, n. 7, p. 1282-1288, 2011.

HUNTER, S.; WHITE, M.; THOMPSON, M. Techniques to evaluate elderly human muscle function: a physiological basis. **Journal of Gerontology Series A: Biological Sciences and Medical Sciences**. v. 53, p. B204–B216, 1998.

HURLEY, B.F. Age, gender, and muscular strength. **Journal of Gerontology Series A: Biological Sciences and Medical Sciences**. v. 50A, p. 41-44, 1995.

IVERS, R.Q.; CUMMING, R.G.; MITCHELL, P.; ATTEBO, K. Visual impairment and falls in older adults: the Blue Mountains Eye Study. **Journal of the American Geriatrics Society**. v. 46, n. 1, p. 58-64, 1998.

IZAWA, J.; RANE, T.; DONCHIN, O.; SHADMEHR, R. Motor adaptation as a process of reoptimization. **Journal of Neurosciences**. v. 28, n. 11, p. 2883-2891, 2008.

IZQUIERDO, M.; IBANEZ, J.; GOROSTIAGA, E., GARRUES, M.; ZÚÑIGA, A.; ANTÓN, A.; LARRIÓN, J.L.; HÄKKINEN, K. Maximal strength and power characteristics in isometric and dynamic actions of the upper and lower extremities in middle-aged and older men. **Acta Physiologica Scandinavica**. v. 167, p. 57-68, 1999.

JANSEN, S.E.; TOET, A.; WERKHOVEN, P.J. Human locomotion through a multiple obstacle environment: strategy changes as a result of visual field limitation. **Experimental Brain Research**. v. 212, n. 3, p. 449-456, 2011.

KANG, H.G.; DINGWELL, J.B. Separating the effects of age and walking speed on gait variability. **Gait and Posture**, v. 27, p. 572-7, 2008.

KATSIARAS, A.; NEWMAN, A.B.; KRISKA, A.; BRACH, J.; KRISHNASWAMI, S.; FEINGOLD, E.; GOODPASTER, B.H. Skeletal muscle fatigue, strength, and quality in the elderly: the Health ABC Study. **Journal of Applied Physiology**. v. 99, p. 210-216, 2005.

KAVANAGH, J.J.; MORRISON, S.; BARRETT, R.S. Lumbar and cervical erector spinae fatigue elicit compensatory postural responses to assist in maintaining head stability during walking. **Journal of Applied Physiology**. v. 101, p. 1118-1126, 2006.

KELLIS, E.; KOUVELIOTI, V. Agonist versus antagonist muscle fatigue effects on thigh muscle activity and vertical ground reaction during drop landing. **Journal of Eletromyography and Kinesiology**. v.19, p. 55-64, 2009.

KENT-BRAUN, J.A. Skeletal muscle fatigue in old age: whose advantage? **Exercise and Sport Sciences Reviews**. v. 37, n. 1, p. 3-9, 2009.

KINGMA, I.; TOUSSAINT, H.M.; DE LOOZE, M.P.; van DIEËN, J.H. Segment inertial parameter evaluation in two anthropometric models by application of a dynamic linked segment model. **Journal of Biomechanics**. v. 29, p. 693-704, 1996.

KONCZAK, J.; MEEUWSEN, H.J.; CRESS, M.E. Changing affordances in stair climbing: the perception of maximum climb ability in young and older adults. **Journal of Experimental Psychology Human Perception and Performance**. v. 18, n. 3, p. 691-697, 1992.

KOVACS, C.R. Age-related changes in gait and obstacle avoidance capabilities in older adults: a review. **Journal of Applied Gerontology**. v. 24, n. 1, p. 21, 2005.

KRELL, J.; PATLA, A.E. The influence of multiple obstacles in the travel path on avoidance strategy. **Gait and Posture**. v. 16, p. 15-19, 2002.

KROENKE, K.; WOOD, D.R.; MANGELSDORFF, A.D.; MEIER, N.J.; POWELL, J.B. Chronic fatigue in primary care. Prevalence, patient characteristics, and outcome. **Journal of the American Medical Association**. v. 260, p. 929–934, 1988.

LANZA, I.R.; RUSS, D.W.; KENT-BRAUN, J.A. Age-related enhancement of fatigue resistance is evident in men during both isometric and dynamic tasks**. Journal of Applied Physiology**. v. 97, n. 3, p. 967-975, 2004.

LATTANZIO, P.J.; PETRELLA, R.J.; SPROULE, J.R.; FOWLER, P.J. Effects of fatigue on knee proprioception. **Clinical Journal of Sport Medicine.** 1997; 7: 22-27.

LATTIER, G.; MILLET, G.Y.; MARTIN, A.; MARTIN, V. Fatigue and recovery after high-intensity exercise part I: neuromuscular fatigue. **International Journal of Sports Medicine**. v. 25, p. 450-456, 2004.

LAWRIE, S.M.; MANDERS, D.N.; Geddes, J.R. et al. A population based incidence study of chronic fatigue. **Psychological Medicine**. v. 27, p. 343–353, 1997.

LAUFER, Y. Effect of age on characteristics of forward and backward gait at preferred and accelerated walking speed. **Journal of Gerontology Series A: Biological Sciences and Medical Sciences**. v. 60, n. 5, p. 627-632, 2005.

LEE, H.J.; CHOU, L.S. Detection of gait instability using the center of mass and center of pressure inclination angles. **Archives of Physical Medicine and Rehabilitation**. v. 87,p. 569-575, 2006.

LEWEK, M.D.; RUDOLPH, K.S.; SNYDER-MACKLER, L. Quadriceps femoris muscle weakness and activation failure in patients with symptomatic knee osteoarthritis. **Journal of Orthopaedic Research**. v. 22, p. 110-115, 2004.

LEWEK, M.; RUDOLPH, K.; AXE, M.; SNYDER-MACKLER, L. The effect of insufficient quadriceps strength on gait after anterior cruciate ligament reconstruction. **Clinical Biomechanics**. v. 17, p. 56-63, 2002.

LIAO, S.; FERRELL, B.A. Fatigue in an older population. **Journal of American Geriatrics Society**. v. 48, p. 426-430, 2000.

LIN, D.; NUSSBAUM, M.A.; SEOL, H.; SINGH, N.B.; MADIGAN, M.L.; WOJCIK, L.A. Acute effects of localized muscle fatigue on postural control and patterns of recovery during upright stance: influence of fatigue location and age. **European Journal of Applied Physiology**. v.106, p. 425-434, 2009.

LOCKHART, T.E.; SPAULDING, J.M.; PARK, S.H. Age-related slip avoidance strategy while walking over a known slippery floor surface. **Gait and Posture**. v. 26, n. 1, p. 142-149, 2007.

LOCKHART, T.E.; SMITH, J.L.; WOLDSTAD, J.C. Effects of aging on the biomechanics of slips and falls. **Human Factors**. v. 47, p. 708-729, 2005.

LOGE, J.H; EKEBERG, O.; KAASA, S. Fatigue in the general Norwegian population: normative data and associations. **Journal of Psychosomatic Research**. v. 45, p.53–65, 1998.

LORD, S.R.; WARD, J.A.; WILLIAMS, P.; ANSTEY, K.J. An epidemiological study of falls in older community-dwelling women: the Randwick falls and fractures study. **Australian Journal of Public Health**. v.17, n. 3, p. 240-245, 1993.

LOWREY, C.R.; WATSON, A.; VALLIS, L.A. Age-related changes in avoidance strategies when negotiating single and multiple obstacles. **Experimental Brain Research**, v. 182, p. 289-99, 2007.

LU, T.W.; CHEN, H.L.; CHEN, S.C. Comparisons of the lower limb kinematics between young and older adults when crossing obstacles of different heights. **Gait and Posture**. v. 2, n. 4, p. 471-479, 2006.

LYTHGO, N.; BEGG, R.; BEST, R. Stepping responses made by elderly and young female adults to approach and accommodate known surface height chances. **Gait and Posture**. v. 26, p. 82-89, 2007.

MBOUROU, G.A.; LAJOIE Y, TEASDALE N. Step length variability at gait initiation in elderly fallers and non-fallers, and young adults. **Gerontology**. v. 49, p. 21-26, 2003.

McFADYEN, B.J.; PRINCE, F. Avoidance and accommodation of surface height changes by healthy, community-dwelling, young, and elderly men. **Journal of Gerontology Series A: Biological Sciences and Medical Sciences**. v. 57, n. 4, p. B166-74, 2002.

McFADYEN, B.J.; WINTER, D.A. An integrated biomechanical analysis of normal stair ascent and descent. **Journal of Biomechanics**. v. 21, p. 733-744, 1998.

McKENZIE, N.C.; BROWN, L.A. Obstacle negotiation kinematics: age-dependent effects of postural threat. **Gait and Posture**. v. 9, n. 3, p. 226-234, 2004.

McNEIL, C.J.; RICE, C.L. Fatigability is increased with age during velocity-dependent contractions of the dorsiflexors. **Journal of Gerontology Series A: Biological Sciences and Medical Sciences**. v. 62, p. 624-629, 2007.

MENS-VERHULST, J.; BENSING, J. Distinguishing between chronic and nonchronic fatigue, the role of gender and age. **Social Science and Medicine**. v. 47, p. 621–34, 1998.

MERLETTI, R.; FARINA, D.; GAZZONI, M.; SCHIERONI, M.P. Effect of age on muscle functions investigated with surface electromyography. **Muscle Nerve**. v. 25, n. 1, p. 65-76, 2002.

METTER, E.J.; CONWIT, R.; TOBIN, J.; FORZARD, J.L. Age-associated loss of power and strength in the upper extremities in women and men. **Journal of Gerontology Series A: Biological Sciences and Medical Sciences**. v. 52, p. B267-76, 1997.

MITCHELL, M. Falls prevention among the elderly: an update from Age UK. **British Journal of Community Nursing**. v. 16, n. 6, p. 300-301, 2011.

MURDOCK, G.H.; HUBLEY-KOZEY, C.L. Effect of a high intensity quadriceps fatigue protocol on knee joint mechanics and muscle activation during gait in young adults. **European Journal of Applied Physiology**. v.112, p. 439-449, 2012.

NIANG, A.E.; McFADYEN, B.J. Effects of physical activity level on unobstructed and obstructed walking in young male adults. **Gait and Posture** 2005; 22: 75-81.

NILSSON, J.; THORSTENSSON, A. Ground reaction forces at different speeds of human walking and running. **Acta Physiologica Scandinavica**. v. 136, p. 217-227, 1989.

NORRIS, J.A.; GRANATA, K.P.; MITROS, M.R.; BYRNE, E.M.; MARSH, A.P. Effect of augmented plantar flexion power on preferred walking speed and economy in young and older adults. **Gait and Posture**, v. 25, p. 620-7, 2007.

O'CONNOR, C.M.; THORPE, S.K.; O'MALLEY, M.J.; VAUGHAN, C.L. Automatic detection of gait events using kinematic data. **Gait and Posture**. v. 25, p. 469-474, 2007.

OLSON, M.W. Trunk extensor fatigue influences trunk muscle activities during walking gait. **Journal of Electromyography and Kinesiology**. v. 20, p. 17-24, 2010.

ORENDURFF, M.S.; SEGAL, A.D.; KLUTE, G.K.; BERGE, J.S.; ROHR, E.S.; KADEL, N.J. The effect of walking speed on center of mass displacement. **Journal of Rehabilitation Research and Development**. v. 41, p. 829-834, 2004.

OWINGS, T.M.; GRABINER, M.D. Variability of step kinematics in young and older adults. **Gait Posture**. v. 20, n. 1, p. 26-29, 2004.

PADUA, D.A.; ARNOLD, B.L.; PERRIN, D.H.; GANSNEDER, B.M.; GARCIA, C.R.; GRANATA, K.P. Fatigue, vertical leg stiffness, and stiffness control strategies in males and females. **Journal of Athletic Training**. v. 41, n. 3, p. 294-304, 2006.

PAI, Y.C.; PATTON, J. Center of mass velocity-position predictions for balance control. **Journal of Biomechanics**. v. 30, n. 4, p. 347-354, 1997.

PAILLARD, T.; CHAUBET, V.; MAITRE, J.; DUMITRESCU, M.; BOREL, L. Disturbance of contralateral unipedal postural control after stimulated and voluntary contractions of the ipsilateral limb. **Neuroscience Research**. v. 68, p. 301-306, 2010.

PARIJAT, P.; LOCKHART, T.E. Effects of quadriceps fatigue on the biomechanics of gait and slip propensity. **Gait and Posture**. v.28, p. 568-573, 2008a.

PARIJAT, P.; LOCKHART, T.E.; Effects of lower extremity muscle fatigue on the outcomes of slip-induced falls. **Ergonomics**. v.51, p.1873-1884, 2008b.

PATLA, A.E. Strategies for dynamic stability during adaptive human locomotion. **IEEE Engineering in Medicine and Biology Magazine.** v. 22, p. 48-52, 2003.

PATLA, A.E.; RIETDYK, S. Visual control of limb trajectory over obstacles during locomotion: effect of obstacle height and width. **Gait and Posture**. v. 1, p. 45-60, 1993.

PATLA, A.E.; PRENTICE, S.D.; ROBINSON, C.; NEUFELD, J. Visual Control Of Locomotion: Strategies for changing direction and for going over obstacles. **Journal of Experimental Psychology: Human Perception and Performance**. v. 17, n.3, p. 603-634, 1991.

PAWLIKOWSKA, T.; CHALDER, T.; HIRSCH, S.R.; WALLACE, P.; WRIGHT, D.J.; WESSELY, S.C. Population based study of fatigue and psychological distress. **British Medical Journal**. v. 308, p. 763–766, 1994.

PETRELLA, J.K.; KIM, J.S.; TUGGLE, S.C.; HALL, S.R.; BAMMAN, M.M. Age differences in knee extension power, contractile velocity, and fatigability. **Journal of Applied Physiology**. v. 98, p. 211-220, 2005.

PETROFSKY, J.S.; BWEIR, S.; ANDAL, A.; CHAVEZ, J.; CRANE, A.; SAUNDERS, J.; LAYMON, M. Joint acceleration during gait in relation to age. **European Journal of Applied Physiology**. v. 92, n. 3, p. 254-262, 2004.

PIJNAPPELS, M.; VAN DER BURG, J.C.E.; REEVES, N.D.; van DIEËN, J.H. Identification of elderly fallers by muscle strength measures. **European Journal of Applied Physiology**. v. 102, p. 585-592, 2008.

PRILUTSKY, B.I.; HERZOG, W.; LEONARD, T.R.; ALLINGER, T.L. Role of the muscle belly and tendon of soleus, gastrocnemius, and plantaris in mechanical energy absorption and generation during cat locomotion. **Journal of Biomechanics.** 29, 417-434, 1996.

RATEL, S.; DUCHE, P.; WILLIAMS, C.A. Muscle fatigue during high-intensity exercise in children. **Sports Medicine**. v. 36, p. 1031-1065, 2006.

REAM, E.; RICHARDSON, A. Fatigue: a concept analysis. **International Journal of Nursing Studies**. v. 33, n. 5, p. 519-529, 1996.

RIBEIRO, F.; MOTA, J.; OLIVEIRA, J. Effect of exercise-induced fatigue on position sense of the knee in the elderly. **European Journal of Applied Physiology**. v. 99, n. 4, p. 379-385, 2007.

RIENER, R.; RABUFFETTI, M.; FRIGO, C. Stair ascent and descent at different inclinations. **Gait and Posture**. v. 15, p. 32-44, 2002.

RILEY, P.O.; DELLACROCE, U.; KERRIGAN, D.C. Effect of age on lower extremity joint moment contributions to gait speed. **Gait and Posture**. v. 14, n. 3, p. 264-270, 2001.

ROOS, M.R.; RICE, C.L.; VANDERVOORT, A.A. Age-related changes in motor unit function. **Muscle and Nerve**. v. 20, p. 679-690, 1997.

SADEGHI, S.; GHAVANINI, M.; ASHRAF, A.; JAFARI, P. Effects of age and leg length upon central loop of the gastrocnemius-soleus H-reflex latency. **BMC Neurology**. v. 3, p.4-11, 2004.

SANTOS-EGGIMANN, B.; CUÉNOUD, P.; SPAGNOLI, J.; JUNOD, J. Prevalence of frailty in middle-aged and older community-dwelling Europeans living in 10 countries **Journal of Gerontology Series A: Biological Sciences and Medical Sciences**. v. 64, n. 6, p. 675-681, 2009.

SELEN, L.P.J.; BEEK, P.J. DIËEN, J.H.v. Fatigue induced changes of impedance and performance in target tracking. **Experimental Brain Research**. v.181, p. 99–109, 2007.

SHAFFER, S.W.; HARRISON, A.L. Aging of the somatosensory system: a translational perspective. **Physical Therapy**. v.87, n. 2, p.193-207, 2007.

SHKURATOVA, N.; MORRIS, M.E.; HUXHAM, F. Effects of age on balance control during walking. **Archives of Physical Medicine and Rehabilitation**. v. 85, n. 4, p. 582-588, 2004.

SILVA, J.J.; BARBIERI, F.A, GOBBI, L.T. Adaptive locomotion for crossing a moving obstacle. **Motor Control**. v.15, p. 419-433, 2011.

SIU, K.C.; CHOU, L.S.; MAYR, U.; DONKELAAR, P.; WOOLLACOTT, M.H. Does inability to allocate attention contribute to balance constraints during gait in older adults? **Journal of Gerontology Series A: Biological Sciences and Medical Sciences**. v. 63, n. 12, p. 1364-1369, 2008.

SMETS, E.M.; GARSSEN, B.; BONKE, B.; DE HAES, J.C. The Multidimensional Fatigue Inventory (MFI) psychometric qualities of an instrument to assess fatigue. **Journal of Psychosomatic Research**. v. 39, p. 315-325, 1995.

STACKHOUSE, S.K.; STEVENS, J.E.; LEE, S.C.; PEARCE, K.M.; SNYDER-MACKLER, L.; BINDER-MACLEOD, S.A. Maximum voluntary activation in nonfatigued and fatigued muscle of young and elderly individuals. **Physical Therapy**. v. 81, p. 1102-1109, 2001.

STASZKIEWICZ, R.; RUCHLEWICZ, T.; FORCZEK, W.; LASKA, J. The impact of changes in gait speed and step frequency on the extent of the center of mass displacements. **Acta of Bioengineering and Biomechanics**. v. 12, p. 13-20, 2010.

SWAEN, G.M.; VAN AMELSVOORT, L.G.; BULTMANN, U.; KANT, I.J. Fatigue as a risk factor for being injured in an occupational accident: results from the Maastricht Cohort Study. **Occupational and Environmental Medicine**. v. 60, n. 1, p. i88-92, 2003.

SYED, I.Y.; DAVIS, B.L. Obesity and osteoarthritis of the knee: hypotheses concerning the relationship between ground reaction forces and quadriceps fatigue in long-duration walking. **Medicine Hypotheses**. v. 54, p. 182-185, 2000.

TAIMELA, S.; KANKAANPAA, M.; LUOTO, S. The effect of lumbar fatigue on the ability to sense a change in lumbar position. A controlled study. **Spine**. v. 24, p. 1322-1327, 1999.

THEOU, O.; JONES, G.R.; OVEREND, T.J.; KLOSECK, M.; VANDERVOORT, A.A.. An exploration of the association between frailty and muscle fatigue. **Applied Physiology, Nutrition, and Metabolism**. v. 33, n. 4, p.651-665, 2008.

TINETTI; MARY E.; DOUCETTE, J.T.; CLAUS, E.B. The contribution of predisposing and situational risk factors to serious fall injuries. **Journal of the American Geriatrics Society**. v. 43, n. 11, p. 1207-1213, 1995.

TRALONGO, P.; RESPINI, D.; FERRAU, F. Fatigue and aging. **Critical Reviews in Oncology/Hematology**. v. 8, p. S57-S64, 2003.

TRENDALL, J. Concept analysis: chronic fatigue. **Journal of Advanced Nursing**. v. 32, n. 5, p.1126-1131, 2000.

TRESILIAN, J.R. The accuracy of interceptive action in time and space. **Exercise and Sport and Sciences Review**. v. 32, p.167-173, 2004.

VESTERGAARD, S.; NAYFIELD, S.G.; PATEL, K.V.; ELDADAH, B.; CESARI, M.; FERRUCCI, L.; CERESINI, G.; GURALNIK, J.M. Fatigue in a representative population of older persons and its association with functional impairment, functional limitation, and disability. **Journal of Gerontology Series A: Biological Sciences and Medical Sciences**. v. 64, n. 1, p. 76-82, 2009.

VILA-CHÃ, C.; RIIS, S.; LUND, D.; MOLLER, A.; FARINA, D.; FALLA, D. Effect of unaccustomed eccentric exercise on proprioception of the knee in weight and non-weight bearing tasks. **Journal of Electromyography and Kinesiology**. v. 21, p. 141-147, 2011.

VINER, R.M.; CLARK, C.; TAYLOR, S.J.; BHUI, K.; KLINEBERG, E.; HEAD, J.; STANSFELD, S.A. Longitudinal risk factors for persistent fatigue in adolescents. **Archives of Pediatrics and Adolescent Medicine**. v. 162, p. 469-475, 2008.

VITÓRIO, R.; PIERUCCINI-FARIA, F.; STELLA, F.; GOBBI, S.; GOBBI, L.T.B. Effects of obstacle height on obstacle crossing in mild Parkinson's disease. **Gait and Posture**. v. 31, p. 143-146, 2010.

WATT, T.; GROENVOLD, M.; BJORNER, J.B.; NOERHOLM, V.; RASMUSSEN, N.A.; BECH, P.J. Fatigue in the Danish general population. Influence of socio demographic factors and disease. **Journal of Epidemiology and Community Health**. v. 54, n. 11, p. 827-833, 2000.

WEINECK, J. **Sports Biology**. Spitta, 10th edition, 2009.

WOLFSON, L.; JUDGE, J.; WHIPPLE, R.; KING,M. Strength is a major factor in balance, gait, and the occurrence of falls. **Journal of Gerontology Series A: Biological Sciences and Medical Sciences**. v. 50A, p.64-67, 1995.

YASSIERLI; NUSSBAUM, M.A.; IRIDIASTADI, H.; WOJCIK, L.A. The influence of age on isometric endurance and fatigue is muscle dependent: a study of shoulder abduction and torso extension. **Ergonomics**. v. 50, n. 1, p. 26-45, 2007.

YEN, H.C.; CHEN, H.L.; LIU, M.W.; LIU, H.C.; LU, T.W. Age effects on the inter-joint coordination during obstacle-crossing. **Journal of Biomechanics**. v. 13, n. 42, p. 2501-2506, 2009.

YOSHINO, K.; MOTOSHIGE, T.; ARAKI, T.; MATSUOKA, K. Effect of prolonged free-walking fatigue on gait and physiological rhythm. **Journal of Biomechanics**. v. 37,p.1271-1280, 2004.

ZAR, J.**Bioestatiscal Analysis**. Prentice-Hall, Upper Saddle River. 1999.