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DESIGNING FUNCTIONAL TRAINING PROGRAMS TO IMPROVE MUSCLE CHARACTERISTICS IN OLDER ADULTS USING ELECTROMYOGRAPHY

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Abstract (English)

Aging is accompanied by a gradual loss of functional ability and independence, which has a negative effect on individual quality of life and presents a significant and increasing burden on our society. The age-related loss of muscle mass and strength, also known as sarcopenia, is a major contributor to this loss of functional ability. Older women are particularly susceptible to sarcopenia due to the post-menopausal acceleration in loss of muscle mass. This is reflected by a relatively high rate of falling incidents and concurrent injuries like hip fractures in older women compared to men.

Physical exercise is considered to be the most effective way to combat sarcopenia. Muscle plasticity, and therefore the ability to improve strength, appears to be well preserved with age. By improving muscle strength we can improve the functional limits of older adults and increase the reserve capacity for safe performance of everyday tasks. However little is known about the best training type and intensity to improve muscle mass and strength in older adults. Furthermore, training-based adaptations in older adults are often highly task-specific, meaning that improvements strength do not necessarily translate to improvements in functional ability. Evidence from previous intervention studies indicates that training programs for older adults should combine resistance exercise and task-specific exercise to achieve optimal results. However, time-constraints and limited long-term adherence of older adults to resistance exercise present a challenge for designing effective prevention training programs. Bench-stepping is a weight-bearing exercise with high functional similarity to activities of daily life such as stair negotiation. Because it is a weight-bearing exercise that requires vertical displacement of the body's center of mass, it also shows potential for transfer effects on muscle mass and strength. However, previous studies investigating the effects of bench-stepping and stair based exercise have found little to no improvements in muscle mass and strength, likely due to sub-optimal training intensities. Kinetic analyses show that increasing step height beyond heights commonly encountered in daily life results in significant increases in peak power output. This indicates that, by using incremental step heights, bench-stepping could be a viable and task-specific exercise to improve muscle mass and strength. An important factor to take into account is that different muscles play specific roles during motor tasks such as stair negotiation and that muscle weakness in any of these muscles can compromise correct and safe task performance. Unfortunately, previous studies found that correct and safe task performance of everyday tasks in older adults is often compromised, as indicated by modulation of their motor strategies. Although bench-stepping with incremental step heights may improve overall power output, it is essential to assess which stepping modalities (e.g. step height, step direction) are required to sufficiently recruit all muscles involved. However, due to the mechanical indeterminacy of the musculoskeletal system and the inability to measure individual muscle loading in vivo it remains hard to directly assess if bench-stepping with incremental step heights

can elicit sufficient muscle loading to increase mass and strength in individual major lower limb muscles of older adults.

The core of this doctoral thesis consists of four studies, divided into three sections. In **Section 2.1.** we used EMG to compare peak muscle activation between bench-stepping and resistance exercises performed at 60% of one-repetition maximum (1-RM), which is the recommended intensity for hypertrophy and strength gains defined by the American College of Sports Medicine. Using this comparison, we assessed the training potential provided by different step heights and directions. 1-RM measurements are commonly applied to calculate the relative intensity of exercises. However, older adults have more difficulty performing maximum contractions. Moreover, previous research has found that EMG signals obtained from maximum contractions can be unreliable. This has important implications for the selection of appropriate signal normalization, which is an essential methodological consideration when comparing muscle activation between subjects and estimating individual muscle loads. In study 1, comparisons between maximum isometric and (sub-)maximum dynamic contractions revealed that differences in maximum excitation between different contractions types are age-dependent and that normalization to sub-maximum dynamic contractions appears to be the best approach for older adults. In study 2, nineteen older women (69.3 ± 3.4 years) performed stepping trials with step heights of 10, 20 and 30 cm in forward and lateral directions and upper leg resistance exercises. Our results revealed that, for most upper leg muscles, a step height of 20-30 cm was required to achieve similar EMG amplitudes to resistance exercise at the recommended threshold of 60% 1-RM. For the gluteus medius, which is an important muscle for medio-lateral stability, a step height of at least 30 cm was required to reach threshold EMG amplitudes. Although these findings could be used to design effective prevention training programs for older women, they are still only based on an approximation of relative training intensities. Therefore, a randomized controlled trial was needed to assess the clinical impact.

In **Section 2.2.** we used the findings from study 2 to design a bench-stepping program, dubbed the Strength Training for Elderly through Elevated stePping (STEEP) program. By adapting a task-specific exercise modality such as bench-stepping to incorporate both incremental step heights and forward and lateral stepping directions, we aimed to simultaneously improve muscle mass (volume), strength, power, functional ability and balance performance in older women. Forty-five community-dwelling older women (68.8 ± 3.9 years) were assigned to the intervention (STEEP) group or a non-exercise (CONTROL) group. The STEEP group received 12 weeks of bench-step exercise and training intensity was primarily determined by incrementing step heights. Results from this intervention study showed that the STEEP program increased muscle volume, isometric peak torque, power, unloaded rate of velocity development and improved performance on all functional tests with exception of

countermovement jump height and static balance. Additionally, low drop-out and positive scores on feelings related to the exercises indicated a high likelihood for long-term training adherence in older women. These findings show that bench-stepping with step heights that exceed those encountered in daily life can counteract the age-related declines in muscle mass, strength and functional ability in community-dwelling older women.

In response to the age-related declines in muscle strength, older adults tend to modulate their motor strategies. This allows them to perform tasks such as stair ascent within their functional limits and compensate for reduced balance control. In **Section 2.3.** we investigated if muscle synergy analysis could detect age-related differences in motor strategies of older adults during step ascent. Our results showed that synergy analysis during more challenging tasks, such as bench-stepping with increased step height, was able to detect subtle age- and step height-related differences in synergy organization and activation patterns, but did not show differences in synergy number. Therefore, assessment of synergy recruitment during more challenging tasks, such as bench-stepping with increased step height, might provide a way to detect early-onset deterioration of functional performance. However, additional longitudinal studies are needed to assess if synergy analysis during step ascent can identify older adults with increased risk of developing disability to target for prevention training.

Overall, this thesis shows that we need to rethink the resistance training/functional training dichotomy and that task-specific exercise can be adapted to simultaneously improve muscle characteristics and functional ability. By employing EMG analyses, we can overcome challenges with regard to estimation of training intensity imposed by the redundancy of the musculoskeletal system.

Samenvatting (Nederlands)

Veroudering gaat gepaard met een geleidelijk verlies van functionaliteit en zelfstandigheid. Dit heeft een negatieve invloed op de kwaliteit van leven en vormt een belangrijke en toenemende belasting op onze samenleving. Het ouderdoms-gerelateerde verlies van spiermassa en kracht, ook bekend onder de term sarcopenie, is een belangrijke oorzaak van verminderde functionaliteit. Oudere vrouwen zijn bijzonder vatbaar voor sarcopenie vanwege de versnelde afname van spiermassa als gevolg van de menopauze. Dit heeft als gevolg dat oudere vrouwen een hoger risico hebben op valincidenten en daardoor een hogere incidentie van letsels zoals heupfracturen vergeleken met mannen.

Fysieke activiteit wordt gezien als de meest effectieve manier om sarcopenie tegen te gaan. De plasticiteit van de spieren, en daarmee de mogelijkheid om spierkracht te verbeteren, blijkt te worden behouden naarmate men ouder wordt. Door hun spierkracht te verbeteren kunnen ouderen hun functionele limiet verhogen waardoor de reserve capaciteit die nodig is voor het veilig uitvoeren van alledaagse taken behouden blijft. Helaas is het tot op heden nog onduidelijk welk type oefeningen en intensiteiten het beste zijn om spierkracht en massa van ouderen te verbeteren. Daarnaast blijkt dat verbeteringen als gevolg van training vaak zeer taak-specifiek zijn bij ouderen. Dit houdt in dat een verbetering van kracht niet direct hoeft te leiden tot een verbetering van functionele prestatie. Eerdere studies tonen aan dat trainingsprogramma's voor ouderen de beste uitkomsten bieden wanneer deze zowel krachttraining als taak-specifieke oefeningen bevatten. Helaas vormen trainingstijd en de beperkte trainingstrouw geassocieerd met krachttraining bij ouderen een belangrijk obstakel bij het ontwerpen van effectieve preventietraining programma's. Bench-stepping is een oefening die functioneel vergelijkbaar is met traplopen en waarbij het verplaatsen van het eigen lichaamsgewicht zorgt voor de trainingsprikkel. Deze verticale verplaatsing van het lichaamsgewicht kan potentieel leiden tot hypertrofie en verbeteringen van de spierkracht. Desondanks laten voorgaande studies beperkte tot geen verbeteringen zien in spiermassa en kracht als gevolg van bench-stepping of traplooptraining. Dit is waarschijnlijk te wijten aan de sub-optimale trainingsintensiteit van de oefeningen in deze studies. Kinetische analyses laten zien dat hogere staphoogtes dan we tegenkomen in het dagelijkse leven een significant effect hebben op de vereiste power. Dit kan betekenen dat het gebruik van hogere staphoogtes van bench-stepping een effectieve en taak-specifieke oefening kunnen maken om spiermassa en kracht te verbeteren. Hierbij moet er echter rekening gehouden worden met de specifieke rol die individuele spieren vervullen tijdens motorische taken zoals traplopen, en dat spierzwakte in deze spieren kan lijden tot incorrecte en onveilige uitvoering. Helaas laten voorgaande studies zien dat correcte en veilige uitvoering van dagelijkse taken door ouderen vaak al is aangetast, wat aangetoond wordt door modulaties in hun motor strategieën. Ondanks dat bench-

stepping met toenemende staphoogtes kan leiden tot verbetering in de totale power is het belangrijk om te onderzoeken welke modaliteiten (b.v. staphoogte en staprichting) benodigd zijn om alle betrokken spieren voldoende aan te spreken. Aangezien het moeilijk is om voor iedere beweging op een directe manier precies in te schatten hoeveel belasting er wordt geplaatst op de individuele spieren, weten we echter niet of de trainingsintensiteit bij verschillende staphoogtes daadwerkelijk voldoende is om kracht en massa van individuele beenspieren van ouderen te verbeteren.

De kern van deze doctoraatsthesis bestaat uit vier studies, verdeeld over drie secties. In **Sectie 2.1.** gebruikten we EMG om pieken in spieractivatie te vergelijken tussen bench-stepping en krachttraining met een belasting van 60% van het één-repetitie maximum (1-RM), de intensiteit die voorgeschreven wordt door de American College of Sports Medicine om hypertrofie en verbetering in spierkracht te bewerkstelligen. Deze vergelijking stelde ons in staat om de potentieële trainingsstimulus van verschillende staphoogtes en -richtingen te bepalen. 1-RM metingen worden regelmatig gebruikt om de relatieve intensiteit van oefeningen vast te stellen. Ouderen ervaren echter meer moeite met het uitvoeren van maximale contracties. Daarnaast laat eerder onderzoek zien dat EMG signalen uit maximale contracties vaak onbetrouwbaar zijn. Dit kan belangrijke gevolgen hebben voor het selecteren van een geschikte methode voor signaal normalisatie, een essentiële methodologische overweging bij het vergelijken van spieractivatie tussen personen en voor het inschatten van individuele spierbelasting. In studie 1 toonden vergelijkingen tussen isometrische en (sub-)maximale dynamische contracties aan dat de verkregen verschillen in maximale excitatie leeftijdsafhankelijk zijn en dat normalisering aan de hand van sub-maximale contracties de beste benadering is voor ouderen. Studie 2 beschrijft dat negentien oudere vrouwen (69.3 ± 3.4 jaar) stepping uitvoerden, met staphoogtes van 10, 20 en 30 cm in zowel voorwaartse als zijwaartse richting, en krachtoefeningen voor de spieren van het bovenbeen. Uit de resultaten van deze studie bleek dat, voor de meeste bovenbeenspieren, een staphoogte van 20-30 cm benodigd was om EMG amplitudes te vinden die vergelijkbaar zijn met amplitudes tijdens krachtoefeningen met een voorgeschreven intensiteit van 60% 1-RM. Voor de gluteus medius, een belangrijke spier voor medio-laterale stabiliteit, was een staphoogte van 30 cm in zijwaartse richting benodigd om de drempelwaarden in EMG amplitudes te bereiken. Deze bevindingen kunnen worden gebruikt om effectieve preventietraining voor oudere vrouwen te ontwerpen maar deze bevindingen zijn echter slechts benaderingen van de trainingsintensiteit. Om die reden was een gerandomiseerde interventiestudie nodig om de klinische impact te kunnen vaststellen.

In **Sectie 2.2.** werden de bevindingen van studie 2 toegepast om een bench-stepping programma, genaamd 'Strength Training for Elderly through Elevated stePping' (STEEP), te

ontwikkelen. Door een taak-specifieke trainingsvorm zoals bench-stepping aan te passen met hogere staphoogtes in zowel voorwaartse als zijwaartse richting hebben we getracht om zowel spiermassa (volume), kracht, power, functionaliteit als balans prestatie in oudere vrouwen gelijktijdig te verbeteren. Vijfenvestig zelfstandig levende oudere vrouwen (68.8 ± 3.9 jaar) werden toegewezen aan de interventiegroep (STEEP) of een CONTROLE groep die geen training ontving. Het STEEP programma bestond uit 12 weken bench-step training waarbij de trainingsbelasting grotendeels werd bepaald door toenemende staphoogtes. De resultaten toonden aan dat het STEEP programma verbeteringen teweeg kan brengen in spiervolume, isometrische piek torsiekracht, power, onbelaste snelheidsontwikkeling en prestatie op alle functionele taken met uitzondering van spronghoogte en statische balans. Daarnaast vonden we lage drop-out en positieve trainings-gerelateerde gevoelens, goede indicatoren voor langdurige trainingstrouw bij oudere vrouwen. Kortom, bench-stepping met hogere staphoogtes is effectief voor het tegengaan van leeftijds-gerelateerde verliezen van spiermassa, kracht en functionaliteit bij zelfstandig levende oudere vrouwen.

Een gevolg van leeftijds-gerelateerde verliezen in spierkracht is de modulatie van motorische strategieën door ouderen. Modulatie stelt hen in staat om taken zoals traplopen toch te kunnen uitvoeren ondanks hun verminderde functionele limieten en balans. In **Sectie 2.3.** onderzochten we of analyse van spiersynergieën mogelijke leeftijdsgerelateerde verschillen in motorische strategieën tijdens opstapbewegingen kon helpen blootleggen. De resultaten laten zien dat uitdagende taken, zoals bench-stepping met hogere staphoogtes, subtiele leeftijds- en staphoogte-gerelateerde verschillen kan aantonen in synergie organisatie en activatie patronen, maar niet in het aantal geëxtraheerde synergieën. Het analyseren van synergie rekrutering tijdens functionele taken met hogere belasting, zoals bench-stepping met hogere staphoogtes, stelt ons mogelijkwerwijs in staat om vroegtijdige achteruitgang van functionaliteit te detecteren. Aanvullende studies zijn echter noodzakelijk om te onderzoeken of synergy analyse tijdens opstaptaken ouderen kan identificeren die reeds een verhoogd risico hebben op functionele beperking voor gerichte preventietraining.

De studies van deze thesis geven aanleiding om de dichotomie tussen krachttraining en functionele training te heroverwegen en dat taak-specifieke oefeningen kunnen worden aangepast om zowel spierkarakteristieken als functionele prestaties te verbeteren. Met behulp van EMG kunnen we uitdagingen met betrekking tot het bepalen van trainingsintensiteit, opgelegd door de redundantie van het musculoskeletale systeem, overwinnen.

Chapter 1

GENERAL INTRODUCTION AND OUTLINE

1.1. Background

As we get older, our body undergoes gradual but significant changes. One of the most significant changes is the age-related loss of muscle mass. The process of age-related muscle wasting is also known as 'sarcopenia'. The term sarcopenia was first coined by Rosenberg and is derived from the Greek words for flesh (sarx) and poverty (penia) [1]. It is a non-pathological process which is correlated with a sedentary lifestyle and can eventually lead to physical disability. However, this definition does not provide any clinical indication about the risk of physical disability. Therefore, the term sarcopenia is also used as an operational definition in clinical practice to indicate severely reduced muscle strength and functional ability. Unlike the process definition, this operational definition includes specific threshold values for diagnosis of sarcopenia, which are described in the recently revised European consensus on definition and diagnosis of sarcopenia [2]. However, because the main focus of this thesis is prevention by training to improve muscle characteristics in healthy community-dwelling older adults, I will exclusively refer to sarcopenia as the process of age-related muscle wasting. The process of sarcopenia starts in the third decade of life and is accelerated after the age of 45 [3]. It appears to affect the lower limbs to a greater extent than the upper limbs (with decreases of lean body mass ranging around 15% and 10% respectively), and can be influenced by a multitude of factors such as decreased hypertrophic capacity through declines in anabolic hormones

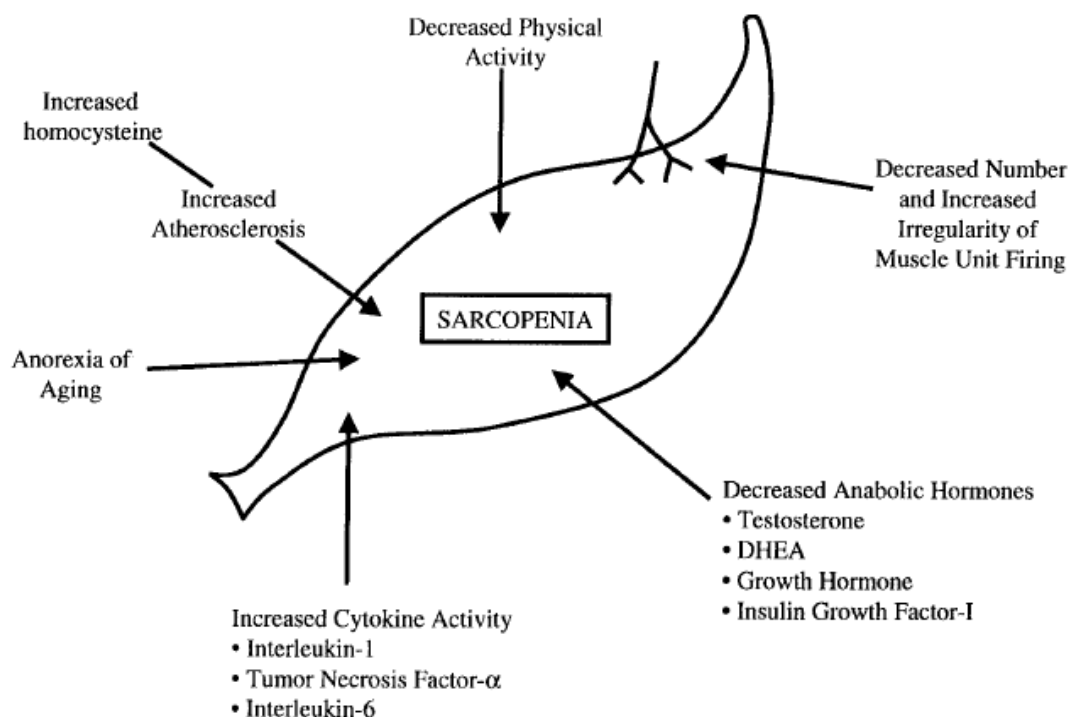


Figure 1: risk-factors for sarcopenia, adapted from Morley et al., 2001 [4].

and reduced synthesis of myosin heavy chain proteins, and increased atrophy caused by increased activity of inflammatory cytokines (Figure 1) [3,4].

Low physical activity appears to play a key role in the progression of sarcopenia and it is estimated that there is an approximate decline of 30% in muscle mass and 20% in cross-sectional area between 20 to 80 years of age due to decreases in both size and number of muscle fibers. This decrease is characterized by disproportionate atrophy of type II muscle fibers, altered muscle architecture and motor unit denervation [4–6]. Denervated muscle fibers are subsequently recruited by surviving motor units. The decreased number of motor units results in a loss of accuracy in force production through increased irregularity of firing rates [7–9]. Motor unit denervation is selective with a net conversion of fast type II muscle fibers into slow type I fibers, resulting in a loss of power for everyday tasks [6,10]. This might explain why declines in muscle strength, which are most prominent in the extensor muscles of the lower extremities [11], are generally larger than can be explained by the reduction in muscle mass alone [12] and are exceeded by the relative declines in power [13,14]. Consequently, Manini and Clark proposed to use the term sarcopenia to exclusively describe age-related muscle wasting and coined the term ‘dynapenia’ to independently define the age-related loss of muscle strength [15]. Reduced muscle strength and the ability to rapidly produce force (power) of the lower limbs are important predictors of falls, functional disability and mortality in older adults [16–19]. There are several muscle groups that play an important role in a variety of functional tasks. For example, the calf muscles control static balance [20,21], while the hip musculature stabilizes the hip and controls medio-lateral stability during various dynamic tasks [22–25]. It is generally accepted that the knee extensor muscles are crucial for performance in dynamic tasks such as walking, stair negotiation, rising from a chair and balance control [26–29] and contribute most to moment generation during the pull-up phase of stair ascent [30]. Age-related declines in muscle strength and power of the knee extensors have shown to correlate significantly with functional ability [31].

The target population for this thesis was healthy, community-dwelling older women (65+). Older women are particularly vulnerable to sarcopenia and its consequences due to post-menopausal accelerated loss of muscle mass [32], which is reflected by a relatively high rate of falling incidents and concurrent debilitating injuries like hip fractures, compared to men [33,34]. The loss of functional ability can have a profound negative influence on perceived quality of life [18] and presents a significant and increasing financial burden on our aging society [33]. With the global population of older adults growing from 600 million in 2000 to an estimated 2 billion by the year 2050 [35], it is imperative that muscle strength, power and functional ability are maintained as long as possible.

At present, there is no pharmacological treatment for sarcopenia. Fortunately, physical activity has shown to be an effective way to counter the progression of sarcopenia [18]. Even though muscle size may decline with age, previous research suggests that surviving fibers are still prone to plasticity and can compensate to maintain optimal force-generating capacity. Muscle plasticity appears to be well preserved with age and has been demonstrated in individuals up to 85 years of age [32,36,37]. Because older adults operate closer to their functional limits when performing activities of daily life, control of strength output and the 'reserve' capacity needed to adjust for perturbations and other environmental factors that threaten balance maintenance are reduced. Improving these limits increases the reserve capacity for safe performance [38–40]. However, little is known about the optimal type and intensity of exercises to improve muscle mass, strength and functional ability in older women. Therefore, the main focus of this thesis was to explore the potential training effects of exercise to prevent sarcopenia in older women.

This general introduction will first reflect on various exercise modalities to maintain and improve muscle mass, strength and functional ability in older adults.

1.2. Exercise modalities for older adults

Despite the fact that exercise has been established as an effective way to combat physical disability in older adults, different exercise modalities are usually employed to target very specific physical and functional outcomes. These outcomes include important predictors of functional ability such as muscle strength and power, but also direct measures of functional ability and balance performance. Additionally, the likelihood of exercise initiation and adherence should not be overlooked. As Lord and Close stated in their perspective piece "New horizons in falls prevention" in "Age and Ageing" (p. 493), 'there is robust evidence that exercise can reduce fall risk in older adults.', 'However, adherence and initiation are lacking due to the programs being perceived as dull, and without consideration of sustaining appropriate activity levels in the long term' [41]. This chapter discusses some of the most common exercise modalities for prevention training and assesses outcomes, accessibility and potential thresholds for training initiation and adherence.

1.2.1. Resistance exercise

Progressive resistance training is generally perceived as the best method for counteracting age-related loss of muscle mass and strength [33]. Guidelines set for older adults by the American College of Sports Medicine recommend ≥ 2 days of resistance exercise per week at 40-50% one-repetition maximum (1-RM) for beginners, progressing to 60-80% 1-RM for intermediate to advanced

levels to achieve and maintain musculoskeletal and neuromotor fitness. Resistance exercise at 60% of 1-RM is explicitly defined as the minimum threshold for gains in muscle mass and strength in older adults with intensities of 70-85% being recommended for optimal effects [42]. High-intensity resistance exercise is also considered a safe and effective training method for older adults [43]. Despite this, older adults and practitioners remain reluctant to engage in, and to prescribe high-load exercises [44,45]. Recent research suggests that high external resistances might not be essential to induce neuro-muscular adaptations as long as maximal effort, indicated by momentary muscle fatigue or muscle failure, is achieved [46–48]. Training to maximal effort at lower loads has shown to elicit similar hypertrophic response and strength gains as high load resistance exercise and may be a more viable way to recruit the entire motor unit pool. This may be due to the gradually increasing need to recruit larger motor units to compensate for fatigue in the initially recruited motor units during sustained effort [49].

However, there are several crucial downsides to resistance exercise for older adults. First, improvements in muscle strength through resistance training do not necessarily translate to improvements in functional ability [50,51]. Although some studies showed improved gait speed, timed get-up-and-go tasks and stair climbing [36,47,52], others report little to no effect on functional ability [22,51,53,54]. Balance performance in particular appears to remain relatively unaffected by resistance exercise, only 22% of resistance training interventions resulted in significant improvements in balance performance [22,55]. This is likely due to a lack of task-specificity in studies that reported no impact of resistance exercise on functional ability [51,53,56]. Second, there appears to be a relatively high threshold for resistance exercise initiation and adherence in older adults. Evasion rates are especially high in machine-based resistance exercise [45]. In a study by Van Roie et al., long-term adherence was found to be low, regardless of training intensity, despite high self-reported motivation [57]. These findings raise the question: even if resistance exercise has proven to be effective to improve muscle mass and strength in older adults, is it a viable approach to maintain functional ability on a population level?

1.2.2. Task-specific exercise

In contrast with resistance exercises, exercises that are functionally similar (task-specific) to activities of daily life (ADLs) have consistently shown to improve functional ability in older adults [50]. There is a wide variety of functional exercises available, such as stair climbing, obstacle clearance, bench-stepping and balance training [50,53,56,58–61]. Most of these task-specific exercises are weight-bearing, meaning that the training stimulus is provided by horizontal/vertical displacement of the body's center of mass (CoM), or its maintenance within the base of support [55,62]. Task-specific

exercises have shown to be highly effective in improving functional ability [51,63–65]. However, functional training programs do not necessarily improve muscle mass and strength [55,64]. This may be attributable to relatively low task intensities, leading to insufficient muscle loading. For this reason, several studies have attempted to increase muscle loading by adding weighted vests, with varying success [60,66,67]. The large diversity and generally unconstrained nature of task-specific exercises makes it hard to determine whether the training intensity is sufficient to improve muscle mass and strength. In contrast, for resistance exercise, recommendations of relative intensity required to achieve muscle hypertrophy and gains in strength and power can be clearly expressed as a percentage of the individual maximum achievable intensity (1-RM) [42]. Unfortunately, obtaining a reliable estimate of an individual's maximum during task-specific exercises is hampered due to decreased balance performance and associated safety issues with maximum exertion in unsupported weight-bearing conditions [68], the mechanical indeterminacy of muscle-joint-systems [69] and the increased co-activation of the antagonist muscles with age [70]. There is little direct evidence comparing motivational thresholds and adherence rates of older adults in functional training programs versus resistance exercise. Nevertheless, most functional exercise programs have some distinct advantages over (machine-based) resistance exercise. These advantages include the possibility for group-based training, which has shown to have more favorable participation (84%) and adherence rates (69.1–75%) in older adults [71–73], and high accessibility through home-based training [73].

1.2.3. Combined exercise

The previous two sections have shown that different exercise modalities tend to target specific performance aspects and present distinct advantages and disadvantages for training older adults. Logically, this has led researchers to explore the effects of combined programs on muscle strength, power and functional ability. Kraemer et al. found that 12 weeks of combined resistance training and bench-stepping improved muscle morphology, strength and cardiovascular fitness to a greater extent than bench-stepping alone. Unfortunately they did not explore the effects on functional ability [74]. Freiburger et al. reported significant improvements in functional ability and strength (measured using a chair-rise test) in community-dwelling older adults after 16 weeks of combined training [75]. In a 1-year randomized controlled trial, Karinkanta et al. found a high degree of task-specificity to strength and balance training in community-dwelling older women and showed that combined training significantly improved performance on both outcomes [76]. These findings were in line with a study by Manini et al. who found that 10 weeks of resistance training elicited largest improvements in knee extension and flexion work, whereas 10 weeks of functional training elicited largest improvements in functional ability. Combined training improved both strength and functional ability, although each aspect was not improved to the same level as with single-component training [51].

Ultimately, simultaneous improvements of lower limb muscle mass, strength and functional ability may allow older adults to perform high-risk activities of daily life, such as stair negotiation, more safely and efficiently [28]. The importance of simultaneously improving strength and functional ability for important age-related challenges such as fall prevention is reflected by best practice recommendations from Sherrington et al., which indicate that interventions that include balance challenging exercises and strength training elicit the largest improvements [65]. Therefore, combined training appears to be an optimal solution to improve functional ability as well as fall risk indices in older adults. However, adherence rates to combined training programs might still suffer from the motivational thresholds associated with the resistance exercise components mentioned in section 1.2.1. Additionally, increased exercise duration might introduce an additional motivational barrier for exercise participation and adherence in older adults [57,77]. Thus, the remaining challenge in designing training programs for older adults aimed at prevention of sarcopenia and congruent functional declines is to design time-efficient programs with low participation thresholds that improve strength through task-specific exercises.

1.2.4. Bench-stepping as a task-specific exercise to improve muscle characteristics

Taking into account the need for time-efficient training modalities, we explored the feasibility and potential to improve muscle characteristics of several task-specific weight bearing exercises for older women (more detailed discussion in section 3.2.1. of the general discussion). Ultimately, bench-stepping was selected because it is accessible, easy to perform with little to no instructions and produces only low to moderate joint loading in older women [78]. Bench-stepping is a weight-bearing exercise with high functional similarity to activities of daily life such as stair negotiation [58], which has already been shown to have high potential for osteogenic stimulation due to the brief bouts of impact loading involved [79,80]. Muscle forces generated during step ascent with increasing step heights indicate a high potential to improve muscle mass and strength by using step heights that exceed those encountered in daily life (>18-22 cm). An increase of 5 cm in step height (from 20 to 25 cm) resulted in significant increases in peak power, indicating that training intensity can be gradually scaled [58]. However, it is currently unclear which step heights would be sufficient to elicit hypertrophy and strength gains. Furthermore, step direction may play an important role for muscular and task-specific improvements. Step ascent in forward direction, which is most common in daily life (e.g. during stair negotiation), generates greater dynamic hip moments compared to gait and sit-to-stand tasks in older adults [81], and provides a challenge to medio-lateral stability [82]. In addition, studies have found that step ascent in lateral direction elicits greater activation of the gluteus medius and quadriceps, likely due to increased movement of the center of mass in the frontal plane, compared to forward stepping [62,83]. Because of the important role of the hip abductors in medio-lateral balance control

[38,84], step training in lateral direction may also be an effective way to enhance balance performance. Therefore, when assessing the potential of bench-stepping exercise to improve muscle strength and functional ability, both step height and step direction need to be taken into account.

1.2.5. The role of exercise design on motivation and long-term adherence

The previous sections in this chapter show that differences between exercise types are not limited to their physiological impact, but can also have distinct effects on motivation and long-term training adherence. This is especially relevant for older adults, who require consistent physical activity in order to counter accelerated muscle wasting and functional declines. However, prevalence of inactivity is highest among adults above the age of 65 and even after training initiation, attrition rates are high in the first six months with 50% of participants dropping out before they achieve significant health benefits [77]. Limited motivation and long-term adherence may hamper effectiveness of resistance exercise on a population level. But what factors determine motivation and affect long-term adherence to a training program, and how can we improve them? Previous research has found that there are age-specific barriers and motivating factors for adherence [77]. Besides obvious age-related afflictions such as poor concentration, memory loss and degenerative joint disease that may limit training participation, time commitment appears to be a major barrier for older adults [57,73,85]. In addition, Schutzer and Graves reported that sweating, labored breathing and muscle soreness were often perceived to do more harm than good and that older women in particular were raised to perceive exercise as not 'ladylike' [77]. In contrast, high levels of perceived self-efficacy during exercise and the ability to perform exercise in a group-based setting appear to improve long-term training adherence [72,77]. Furthermore, high social cohesion in group-based exercise has been shown to result in significantly higher adherence rates [86]. Finally, the addition of music to the training program can also improve adherence in older adults by reducing monotony, perceived difficulty and even discomforts [77,87]. From these findings we can conclude that, to achieve optimal long-term adherence, training programs for older women should be time-efficient, involve low cardiovascular strain and muscle soreness, produce high self-efficacy and should be administered in group based settings, preferably guided by music. Bench-stepping incorporates most of these elements, which will likely result in good long-term adherence. However, research on the level of perceived self-efficacy associated with bench-stepping exercise is lacking and requires further investigation.

1.3. Electromyography for assessment of training potential, neuro-motor skills and training

One of the main inferences from the previous section is that training programs to improve muscle mass, strength and functional ability in older adults should simultaneously be hypertrophic and

task-specific. Bench-stepping could be a viable exercise modality to achieve this. Unfortunately, it is hard to assess the potential training effects of weight bearing exercises such as bench-stepping on muscle mass and strength directly, without performing a training intervention, because it is not possible to measure muscle loading in vivo without using invasive procedures [69]. Fortunately, there are several ways to assess muscle loading during different exercises. For example, inverse dynamics can be applied to calculate joint moments and estimate individual muscle loading using optimization models. However, such models cannot account for individual differences in activation patterns [88]. Alternatively, surface electromyography (EMG) can be applied to assess individual muscle recruitment and provide an estimate of the relative amount of muscle loading [89].

EMG signal amplitude is indicative of the number of active motor units within the detection range of the electrodes and their firing rate, and is generally used as a measure of neuromuscular activation [89,90]. Exercise intensity can be defined as a percentage of maximal contraction strength and is often estimated using the normalized EMG amplitude [91–94]. This approach might provide a solution to the problem of otherwise unobtainable in-vivo measurements of muscle loading and allows for comparisons of training potential for individual muscles between functionally different exercises. However, the EMG/force relationship is not straightforward. Assuming that the EMG measured at the electrode is an accurate reflection of the volume of active motor units and firing rates, the EMG/force relationship is still dependent on factors such as contraction velocity and muscle fiber length [91]. The first part of this section will discuss the potential and challenges of using EMG to assess the training potential of functionally different exercises to improve muscle mass and strength in older women. An additional advantage of EMG is that it can provide information about age-related neurological changes that can affect functional ability. Older adults tend to modulate their motor strategies to compensate for reduced functional capacity [51,95], but also display other compensatory motor patterns, including increased antagonist co-contractions [8,29]. Therefore, the second part of this section addresses the potential for EMG to explore age-related differences in motor strategies employed during functional tasks.

1.3.1. Benefits and challenges of electromyography for comparisons between exercise types

Randomized controlled trials are considered to be the gold standard for developing evidence-based guidelines. However, they can be expensive and time consuming. Measuring muscle activation using EMG provides a more feasible method of estimating the training potential of different exercises [96]. As stated above, surface EMG may provide a useful tool to estimate muscle activation in vivo as it does not require invasive procedures. Even if the relationship between EMG and force produced is influenced by contractile conditions [91], by knowing the relative activation required to perform an

exercise compared to a maximum contraction, the strengthening potential of an exercise can be inferred [93]. It is assumed that the relative activation provides a reliable estimate of the total volume of muscle fiber recruitment and motor unit firing rates [94]. More specifically, it can provide an indication of the potential of an exercise to recruit type II (fast-twitch) muscle fibers. Type II muscle fibers are larger than type I (slow-twitch) muscle fibers and have two to four times higher contraction velocity, thus contributing most to power generation within the muscle [97]. According to Henneman's size principle, larger muscle fibers have a higher recruitment threshold [98]. This implies that, by assessing maximum activation elicited by an exercise, the ability of that exercise to recruit larger, more powerful muscle fibers can be inferred. This in turn indicates the potential of that exercise to improve muscle mass and strength [92,93]. For resistance exercise, the threshold for hypertrophy and strength gains is defined by the American College of Sports Medicine to be 60% of the one-repetition maximum (1-RM) [42,92]. As mentioned before, for weight bearing exercises it is hard to define a reference value for intensity, such as a 1-RM, for individual muscles due to the mechanical indeterminacy of the muscle-joint system [69], which makes it hard to elicit consistent maximum activation. In contrast, most open-chain resistance exercises consist of contractions by isolated muscles or synergistic muscle groups, making it easier to define the relative muscle load. However, by defining training intensity as a percentage of 1-RM determined during resistance exercise, and comparing the corresponding EMG output, we can approximate the training intensity of weight bearing exercises and thus their potential to improve muscle characteristics [91,93]. It is worth noting that this comparison between functionally different exercise types can only be made in a non-fatigued state. As mentioned in section 1.2.1., training to maximal effort generally elicits the largest improvements of muscle characteristics. This is probably because fatigue leads to a loss of contractile force in the less powerful motor units, eventually creating the need to recruit larger and more powerful motor units following Henneman's 'Size Principle' [47,98]. Muscle fatigue is accompanied by a reduced frequency and changes in the amplitude of the surface recorded EMG [99–101]. The shift in the EMG frequency is primarily associated with a reduction in muscle fiber propagation velocity but other factors may also play a role [99,101]. However, evidence on the changes in EMG amplitude is conflicting and deemed unreliable by some researchers [101]. This makes it hard to reliably assess the training potential of an exercise over multiple repetitions. Nevertheless, measuring EMG in a non-fatigued state can provide an initial indication of the relative exercise intensity in more complex biomechanical contexts. This information can then be applied to design training programs that ensure sufficient recruitment to improve mass and strength of specific muscles.

One of the most important aspects when comparing EMG output between subjects, or within subjects between different exercises, is signal normalization. This means that, in order to assess the

potential of an exercise to elicit sufficient muscular activation to obtain strength gains, obtained EMG signals have to be normalized to a reference value. Signal normalization also improves test-retest reliability [102]. The most common way of normalizing EMG signals is by expressing them as a percentage of the amplitude obtained during a maximum voluntary isometric contraction. This method is so commonly employed because it is easy to administer, although it is still unclear if normalization to maximum voluntary isometric contractions provides the best reliability [102]. Alternatively, it is possible to normalize EMG amplitudes to a maximum dynamic contraction. Dynamic contractions have shown to elicit higher activation than isometric contractions in healthy adults, reduce between-subject variance and provide a better estimation of individual muscle work during a dynamic task [102]. However, it is unknown whether these findings are consistent in older adults. Previous studies have found that older adults have more difficulty performing maximum voluntary contractions [99,103,104] and that there is an increased amount of antagonist co-activation [58], increasing stiffness at the joint and increasing the relative workload to perform dynamic contractions. In addition, submaximal contractions have been shown to produce superior reliability compared to maximum contractions, producing more stable and therefore preferable reference values [100,102]. Therefore, before we could compare EMG from functionally different exercises to assess their potential to improve muscle mass and strength, further investigation was required to determine the best normalization method for EMG obtained from older adults.

1.3.2. Muscle synergy analysis to assess motor strategies

The previous section discussed how EMG can be used to assess the training potential of functional exercises to improve muscle mass and strength of individual muscles. This can provide trainers and physical therapists with essential information about which exercises work best to improve functional capacity in older adults. However, we should not ignore the role of age-related neurological changes that can result in altered motor strategies [105] and the potential for training-based neurological adaptations when it comes to negating the effects of sarcopenia on functional ability. Previous studies have found that older adults use adapted movement strategies during normal gait which were attributed to altered neuromuscular activation patterns [56]. In response to diminished functional capacity, older adults adopt altered movement strategies in order to operate within their maximum capacity and complete everyday tasks [95,106]. Knowing how different exercise modalities affect motor strategy selection may help to elucidate why some exercises may be more effective to improve functional ability than others. For example, Cook et al. used EMG to compare lateral and forward stepping and found that recruitment patterns were task-specific [83]. A study by Wang et al. found that forward stepping targeted muscles around the hip joint while lateral stepping targeted muscles around the knee and ankle joints. Both movements may be relevant exercises for older adults

because they require simultaneous coordination of the hip, knee and ankle musculature and mimic stair-climbing activity [81]. In addition to employing altered motor strategies to overcome age-related loss of muscle strength, older adults appear to develop seemingly adverse motor recruitment patterns. An important example is the increase in antagonist co-contraction during dynamic multi-joint tasks that challenge postural control, leading to increased hip, knee and ankle joint stiffness and joint contact forces, which increases the risk and progression of osteoarthritis, lowers net force output and increases energy cost of motion [8,29,58,107–112]. It is likely that the increased amount of antagonistic co-activation and congruent joint stiffness in older adults, compared to younger adults when performing similar tasks, is a trade-off to compensate for a decreased ability to maintain postural control and recover balance after a postural perturbation (Figure 2) [18,109]. However, increased antagonist co-activation is only one example of age-related effects on motor strategy selection and further research is needed to elucidate how age affects motor strategy selection for different exercise modalities and intensities.

Analysis of EMG patterns of individual muscles may provide valuable information on age effects on motor ability. However, EMG datasets can be large and highly variable, making them hard to interpret, thus reducing their clinical usefulness [113]. The dimensionality of EMG datasets can be reduced using a mathematical approach known as muscle synergy analysis [114]. This approach defines synergies, also known as motor modules, as a group of muscles that is activated by a single neural

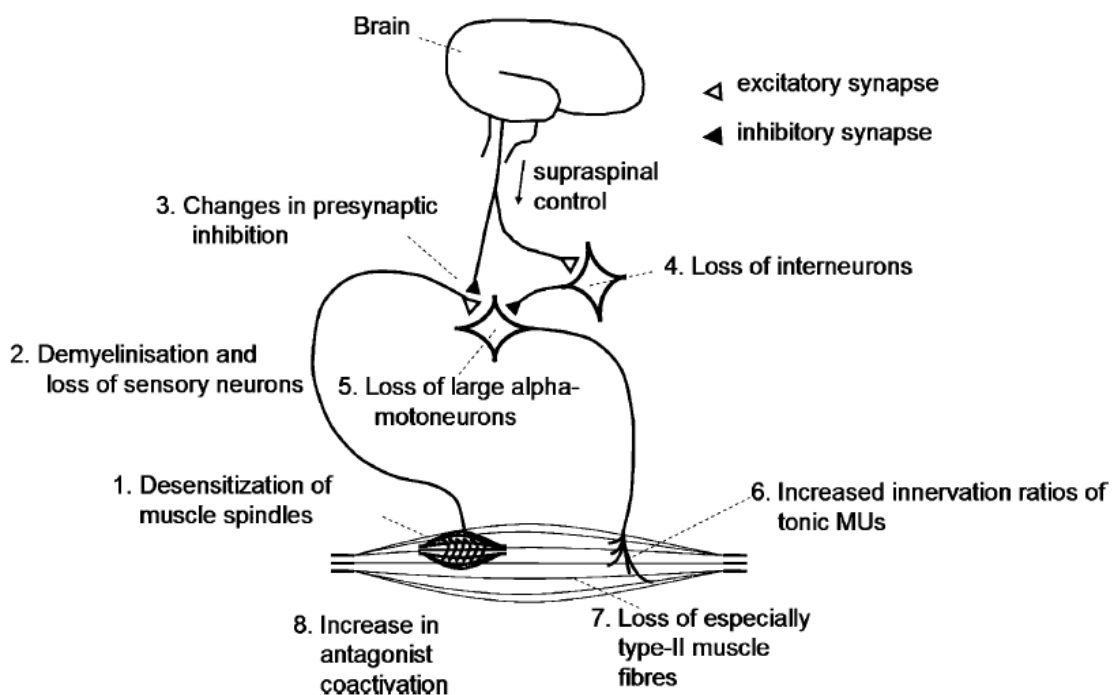


Figure 2: Age-related neuro-muscular changes that can result in impaired static and dynamic postural control. Adapted from Granacher et al., 2008 [18].

command output [115]. Some researchers posit that the modular recruitment of muscles can provide insights into control strategies employed by the central nervous system to facilitate flexible, quick and accurate responses to the dynamic environment [116,117]. Others have questioned this assumption and suggested that muscle synergies are merely an effect of task constraints and optimized performance criteria imposed on motor control strategies [115]. In spite of this debate, muscle synergy analysis can provide important insights about age-related differences in motor strategies underlying individual task performance and ultimately help to improve diagnostics of motor dysfunction, fall risk assessment, and subject-specific evidence-based interventions [113,118].

1.4. Objectives and general outline

The main aim of this doctoral thesis was to find and assess an optimized training program with respect to muscle mass, strength and functional adaptations in older women. It is a compilation of four scientific articles divided into three sections. **Section 2.1.** uses EMG to compare the potential of functionally different exercises to increase muscle mass and strength in older women. **Section 2.2.** investigates the effect of a 12-weeks bench-stepping exercise program with incremental step heights on force/velocity characteristics of the knee extensors, functional ability and balance performance in older women. **Section 2.3.** uses muscle synergy analysis to detect age-related changes in motor ability of older women. A brief description of the rationale and primary aims of each section is provided in the following paragraphs. An overview of the study samples included for each study is provided in Table 1.

1.4.1. Section 2.1.: Electromyography as a tool to assess training potential for muscle mass and strength during weight bearing exercise

The main aim of this section was to assess the potential of weight bearing exercise to improve muscle mass and strength in older women. To achieve this goal, maximum muscle activation during bench-stepping tasks at different step heights and directions was recorded using EMG and compared to threshold intensities of 40, 60 and 80% 1-RM in single- and multi-joint open kinetic chain exercises. An important methodological consideration when comparing EMG signals between different exercise modalities lies in choosing the most suitable normalization method. Several approaches are commonly used to normalize EMG signals from dynamic tasks. The most common approach is to normalize the signals to a reference maximum voluntary excitation obtained through either isometric or dynamic contractions [100,102,119]. However, for older subjects it is more difficult to perform maximum contractions [99,103,104]. Therefore, **Study 1** assessed whether differences in maximum excitation between isometric and dynamic contractions are age-dependent and, if so, how this affects between-subject variance and percentage of trials exceeding 100% of maximum voluntary excitation.

Subsequently, **Study 2** focused on the comparison of muscle activation during different bench-stepping modalities with activation elicited by resistance exercise at 60% 1-RM, which is the threshold for gains in muscle mass and strength as defined by the American College of Sports Medicine [42]. Bench-stepping was chosen specifically because it is a weight bearing exercise which functionally resembles high-risk activities of daily life such as obstacle clearance and stair negotiation [58,81].

1.4.2. Section 2.2.: Bench-stepping exercise as a way to improve muscle mass, strength and functional ability in older women

The findings from Study 2 provided essential information about the appropriate step heights and step directions that should be incorporated to provide a meaningful training stimulus for improvements in muscle mass and strength, and the use of additional increments in step height to increase task intensity for training progression. Based on these findings, a 12-week bench-stepping exercise program for older adults (65+), dubbed the Strength Training for Elderly using Elevated stePping (STEEP) program, was developed. The unique aspect of this program was the use of incremental step heights, rather than increased training volume, to simultaneously improve muscle mass and force/velocity characteristics of the knee extensors and functional ability. The main aim of **Study 3** was to determine the effectiveness of task requirements defined in paper 2 by investigating if the STEEP program could indeed improve functional and balance performance, muscle mass and force/velocity characteristics of the knee extensors in older women. Additionally, this paper incorporated a questionnaire to assess feelings towards the STEEP program, to provide an indication about self-efficacy, and to assess if the STEEP program would be likely to suffer from lower drop-out rates than resistance exercise [57].

1.4.3. Section 2.3.: Neuro-motor strategies for step ascent in older women

Training programs with high task-specificity to activities of daily life have proven to be the most effective way to improve functional ability in older adults [51,120]. However, previous studies have found that older adults tend to modulate their motor strategies, which allows them to perform activities of daily life (e.g. stair negotiation) within their functional limits [95,106]. The purpose of **Study 4** is to assess if muscle synergy analysis can detect age-related differences in motor strategies during step ascent at different step heights. Analyses of synergy numbers, organization and temporal recruitment patterns could provide a useful metric for diagnosis of motor deficits and effectiveness of an intervention [113,118]. Assessment of muscle synergy recruitment during more challenging tasks such as step ascent might provide a way to detect early-onset deterioration of functional performance and aid in targeting prevention training programs at subjects most at risk [118]. Consequently, the effectiveness of functional exercise interventions such as the STEEP program could be further

optimized by targeting specific muscles/synergies and adjusting parameters such as step height and direction to match the subject's needs.

Table 1: Overview of the subject characteristics and Godin leisure time exercise questionnaire scores (GLTEQ) per study sample.

	Young	Old	Old control
Studies 1 and 2			
Age (years)	22.9 ± 1.6	69.1 ± 3.1	-
Number - Gender	10 females	19 females	-
BMI (kg/m ²)	21.9 ± 2.6	25.9 y ± 3.6	-
GLTEQ	-	31.2 ± 22.8	-
Study 3			
Age (years)	-	68.8 ± 4.0	6.9 ± 4.0
Number - Gender	-	24 females	21 females
BMI (kg/m ²)	-	26.8 ± 4.7	25.1 ± 3.4
GLTEQ	-	24.5 ± 24.8	22.8 ± 14.5
Study 4			
Age (years)	22.5 ± 1.6	67.0 ± 2.5	-
Number - Gender	10 females	11 females	-
BMI (kg/m ²)	22.9 ± 2.8	24.7 ± 2.2	-
GLTEQ	-	-	-

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Chapter 2

RESEARCH ARTICLES

Section 2.1. Electromyography as a tool to assess training potential for muscle mass and strength during weight bearing exercise

Paper 1: Differences in maximum voluntary excitation between isometric and dynamic contractions are age dependent

Submitted as:

Remco J. Baggen, Jaap H. van Dieën, Sabine M. Verschueren, Evelien Van Roie, Christophe Delecluse. (2019). Differences in maximum voluntary excitation between isometric and dynamic contractions are age dependent. *Journal of Applied Biomechanics*, accepted.

Abstract

In older populations, obtaining true maximum voluntary excitation appears more difficult than in young populations. The aims of this study were to determine whether differences between maximum voluntary excitation obtained from voluntary isometric contractions (MVIC) versus (sub-)maximum voluntary dynamic contractions (s-)MVDC are age-dependent, and how normalizing EMG signals to corresponding maximum voluntary excitations affects variance between participants and the likelihood of normalized signals exceeding 100%. MVIC, s-MVDC and MVDC were recorded in ten young women, and MVIC and s-MVDC in nineteen older women. A significant age x contraction mode interaction effect was found for vastus lateralis ($p = 0.037$). In young women MVDC elicited highest maximum voluntary excitation for vastus lateralis and rectus femoris ($p < 0.05$). In older women, no differences in maximum voluntary excitation were found ($p > 0.05$). Normalization to dynamic contractions resulted in lower between-participant variance of EMG amplitudes, though not for all muscles, and decreased the amount of normalized signals exceeding 100% in young women. These findings indicate that differences in maximum voluntary excitation across contraction modes are age-dependent. Therefore, one should be cautious when comparing normalized signals between age groups, but overall dynamic contractions may be preferable above isometric contractions for normalization purposes.

Introduction

Surface electromyography (EMG) is commonly used to measure muscle activation during task performance. It is often used to indirectly estimate individual muscle forces during a contraction [1] instead of measuring force directly (e.g. with a dynamometer). This is likely because direct force measurements are difficult to obtain and are subject to effects of co-contraction of synergistic and antagonistic muscles that modulate the net force produced [2]. However, the absolute value of surface EMG signals (obtained in V or mV) can be affected by many factors such as variation in EMG electrode placement, skin preparation, and impedance of the skin interface and tissue layer between electrodes and muscle [1,3]. To allow for comparisons of muscle activation between participants and within participants between different measurement sessions, EMG signals need to be normalized [4]. Normalization is usually performed by expressing the magnitude of activation from a specific muscle as a percentage of the EMG signal obtained from a reference contraction of the same muscle [5].

The most commonly applied method of normalization is by expressing activation as a percentage of maximum voluntary excitation, obtained during a maximum voluntary contraction [6,7]. This maximum voluntary contraction can be performed either isometrically (MVIC) or dynamically

(MVDC). To date, there is no clear consensus on which EMG normalization method is the best. A general conclusion could be that both MVIC and MVDC have advantages and disadvantages [5]. Even though physical limitations might make it difficult to obtain a 'true' maximum voluntary excitation [8], one should strive to normalize to a value that is as close as possible to the true maximum. This will reduce the number of normalized signals obtained from dynamic activities that exceed 100% of the predetermined maximum and limit between-participant variance, enabling researchers to more accurately assess individual muscle contributions to a motor task, and provide more accurate force estimations [1,7,9].

In most research and clinical settings, signal normalization is performed using MVICs [4]. This method is commonly applied since it is easy to perform in a standardized manner [7,10]. MVICs are often recorded at specific joint angles, despite the fact that the ability to achieve maximum excitation may depend on joint angle and this dependency may differ between synergistic muscles [11]. This limitation can be addressed by measuring maximum voluntary excitation at several joint angles to allow angle-specific normalization. However, this is rarely performed since it is a time consuming process, and muscle fatigue may affect EMG signals obtained [11]. The absence of joint angle-specific methods could cause severe underestimation of the true maximum voluntary excitation, resulting in normalized signals that exceed the predetermined 'maximum' excitation obtained through MVIC [7]. For some muscles, studies have found activation reaching up to 300% of predetermined maximum voluntary excitation during dynamic task performance [7], leading to overestimations of the proportion of individual muscle capacity required for dynamic task performance [5]. Additionally, participants are usually unfamiliar with isometric contractions, which can lead to a 20-30% reduction in maximum contraction performance [10]. In contrast with MVIC, normalizing to a MVDC usually results in fewer recordings that exceed 100% of the predetermined maximum [5,12]. MVDCs can be performed with an isokinetic dynamometer, but one-repetition maximum (1-RM) testing is more common [13].

An important issue when selecting a normalization method is that little is known about how factors like age affect the difference between isometric and dynamic normalization. Age-related differences in maximum excitation may in part be accounted for by differences in thickness of subcutaneous fat layers and skin impedance [3], which is why signal normalization is essential when comparing between age groups. Nevertheless, these confounders would be expected to have an equal impact on maximum voluntary excitation regardless of the contraction mode. However, if the age-related decline in maximum excitation obtained from isometric contractions would differ from that obtained from dynamic contractions, comparisons of outcomes obtained from different normalization methods would be inherently skewed. Differences in the ability to assess 'true' maximum activation

are likely to be more pronounced in populations such as older adults and patients with pain-related inhibition, because it is more difficult for these populations to perform maximum voluntary contractions (either isometrically or dynamically) [14–16]. For this reason, normalization to a well-defined sub-maximum contraction is often advised. This reference contraction should not exceed 80% of maximum because EMG signals and force are exceptionally unstable above this level [1,6]. Examining the age-related differences between normalization methods is especially relevant in the female population as the age-related loss of muscle mass, which is generally accelerated after menopause [17], inevitably results in a lower number of motor units firing simultaneously, while conductivity between the skin and electrodes is decreased due to a relative increase in subcutaneous adipose tissue [16].

So far, no studies have investigated if differences in maximum voluntary excitation between isometric and dynamic contractions are age-dependent. Therefore, the first objective of this study was to determine if there is an interaction effect of age and contraction mode. The second objective was to assess how normalization using different contraction modes would affect between-participant variance of normalized EMG signals and which method resulted in the least amount of normalized signals exceeding 100%. We hypothesized that dynamic contractions would yield higher EMG amplitudes than isometric contractions, that age would show a significant interaction effect with contraction mode, and that normalization to dynamic contractions would result in lower between-participant variance, and a lower amount of normalized signals exceeding 100% for both age groups.

Methods

Participants

Ten healthy young women ($22.9\text{y} \pm 1.6$) and nineteen healthy community-dwelling older women ($69.1\text{y} \pm 3.1$) were recruited around Leuven, Belgium. Data from the older women were reported previously [18]. Potential participants were excluded if they had any medical contraindications for resistance exercise or if they had participated in a structured strength training program in the last six months. This study was approved by the Human Ethics Committee of KU Leuven in accordance with the Declaration of Helsinki. All participants provided signed informed consent before participation.

Protocol

All data were collected at the Movement and posture Analysis Laboratory Leuven (MALL). EMG was recorded from the rectus femoris, vastus lateralis and gluteus medius. Electrode placement sites

were first shaved and thoroughly scrubbed with isopropyl alcohol. Bipolar pre-gelled disposable surface EMG electrodes (Ambu® BlueSensor P Ag/Ag-Cl electrodes, Ballerup, DK) were then placed, in parallel to the muscle fiber direction, on the muscle belly with an inter-electrode distance (center to center) of 25 mm. EMG was amplified 1000x and band-pass filtered between 10–500 Hz. EMG was recorded with a telemetric system (ZeroWire®, Aurion, Milan, IT) with a sampling rate of 1000 samples/s. Subsequently, all recorded EMG signals were high-pass filtered with a 1st order Butterworth filter with a cut-off at 20 Hz [1], full-wave rectified and smoothed with a 100 ms moving average window using MATLAB R2014b (MathWorks®, Natick, USA).

Prior to testing, all participants performed a 5-minute warm-up on a cycle ergometer with moderate resistance at 70-80 RPM. After warming-up, individual 1-RM was estimated for each resistance exercise using a formula by Brzycki [19]. In order to ensure accuracy of the estimates, five-repetition maximum (86% 1-RM) was the minimum intensity used to calculate the 1-RM. The testing protocol consisted of a unilateral seated knee extension and a unilateral standing hip abduction, performed with an adapted cable jungle (Technogym®, Gambettola, IT) (Figure 1). Due to limitations of older adults in performing maximum contractions [1,16], the weight corresponding with 80% 1-RM (s-MVDC), which was the maximum intensity employed in the older cohort, was calculated. Consequently, to allow for comparisons between both age groups, s-MVDCs were also included for the young cohort.

MVIC values for the vastus lateralis and rectus femoris were recorded in seated position with a knee angle of 90° while the hip and ankle were fixated. For the gluteus medius, participants laid on a bed sideways with their dominant side up. The hip and ankle were fixed with the knee fully extended. MVIC was recorded twice during 5 seconds of maximal contraction and the highest value was used for normalization. For (s-)MVDC, each participant performed three separate repetitions of knee extension and hip abduction at an intensity of 80% and 100% of 1-RM. The order of exercise intensities was randomized to avoid fatigue bias. Each repetition was timed at one second concentric action and one second eccentric action, indicated by a metronome, to avoid differences in peak excitation due to repetition speed. Participants also performed three repetitions of forward and lateral stepping onto an elevated platform for each riser height (10, 20 and 30 cm). Stepping was timed at one second for ascent, one second stance and one second descent, indicated by a metronome to match concentric contraction speed with the 1-RM trials. The EMG signals obtained from these stepping tasks were normalized to the maximum voluntary excitation obtained from each contraction mode to assess between-participant variance. The amount of dynamic trials for which activation exceeded 100% of maximum voluntary excitation provided an indication of underestimation of the true maximum by each normalization method. Forward stepping was chosen specifically because of its functional

similarity to stair climbing [20,21], a daily activity which requires a relatively high effort for older adults [22,23]. Lateral stepping was added because it was found to elicit additional gluteus medius activation [18].



Figure 1: Older participant performing standing hip abduction (left) and seated knee extension (right).

Data analysis

Statistical analysis was performed with SPSS (IBM® SPSS v23 Statistics for Windows, Armonk, USA). All data were checked for normality with a Kolmogorov-Smirnov test. Non-normalized signals more than 2 standard deviations from the mean were removed from the analyses. Two-way ANOVA was used to test for main effects of contraction mode and for age x contraction mode interaction effects. In view of the sample size [24], post hoc tests consisted of paired samples t-tests within groups. Within-group analyses of the normalized signals were performed using Friedman tests for the young adults and Wilcoxon Signed Rank tests for the older adults. Overall level of significance was set at $p = 0.05$.

Results

A significant main effect of contraction mode on obtained peak excitation was found for vastus lateralis ($p = 0.001$) and rectus femoris ($p = 0.018$) but not for gluteus medius ($p = 0.964$). There was a significant age x contraction mode interaction effect on vastus lateralis peak excitation ($p = 0.037$) but not on rectus femoris and gluteus medius peak excitation ($p > 0.05$; Table 1).

For young women, MVDC elicited significantly higher excitation than MVIC in vastus lateralis and rectus femoris, and s-MVDC elicited higher excitation than MVIC, although this difference was only found to be significant in vastus lateralis. Excitation obtained from MVDC in the quadriceps muscles was also significantly higher than s-MVDC. The same trend was visible for gluteus medius, but these differences were not statistically significant (Table 1). Normalized data from the stepping trials (Figure 2) show that signals from the vastus lateralis were significantly higher when normalized to isometric contractions compared with signals normalized to either maximum or sub-maximum dynamic contractions (with more excursions above 100%). Normalization to isometric contractions also resulted in the highest between-participant variance. The same trend was visible for the rectus femoris. However, differences were not statistically significant for each step height. No differences or signals exceeding 100% were found for gluteus medius.

In contrast with the results obtained in the young cohort, no significant differences were found in maximum voluntary excitation between both normalization methods for the older adults in any of the three muscles (Table 1). Normalized signals (Figure 2) show no significant differences between methods. However, both methods resulted in frequent excursions above 100% (~40 and 54% of all normalized trials) in vastus lateralis and, to a lesser extent, in rectus femoris and gluteus medius. Variance of the normalized signals was lower for s-MVDC in each task, with exception of the gluteus medius during lateral stepping.

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Table 1: Mean and standard deviation of peak EMG per muscle obtained from each normalization method (MVIC, s-MVDC and MVDC) for young and (MVIC and s-MVDC) for older women.

		Peak amplitude (mV)			Significance of Difference			Interaction effect ^a
Muscle		MVIC	s-MVDC	MVDC	MVIC/s-MVDC	MVIC/MVDC	s-MVDC/MVDC	
Vastus lateralis	Young women	2.1 ± 0.7	3.6 ± 1.8	4 ± 1.8	0.040	0.009	0.011	0.037
	Older women	1.8 ± 0.9	2 ± 0.6		0.117			
	Women							
	Sig. Diff. Y/O	0.126	0.005					
Rectus femoris	Young women	2.6 ± 1.9	3.4 ± 1.4	4.1 ± 1.8	0.177	0.009	0.029	0.249
	Older women	1.6 ± 0.9	1.9 ± 0.6		0.099			
	Women							
	Sig. Diff. Y/O	0.164	< 0.001					
Gluteus medius	Young women	3.3 ± 1.5	3.4 ± 2.2	3.6 ± 2.3	0.887	0.585	0.076	0.721
	Older women	1.5 ± 1	1.4 ± 0.7		0.968			
	Women							
	Sig. Diff. Y/O	< 0.001	< 0.001					

The *p*-values of differences between methods for young and older women are displayed on the right and *p*-values of difference between age groups for each method are displayed below. Significant differences are indicated in bold. ^a age x contraction mode.

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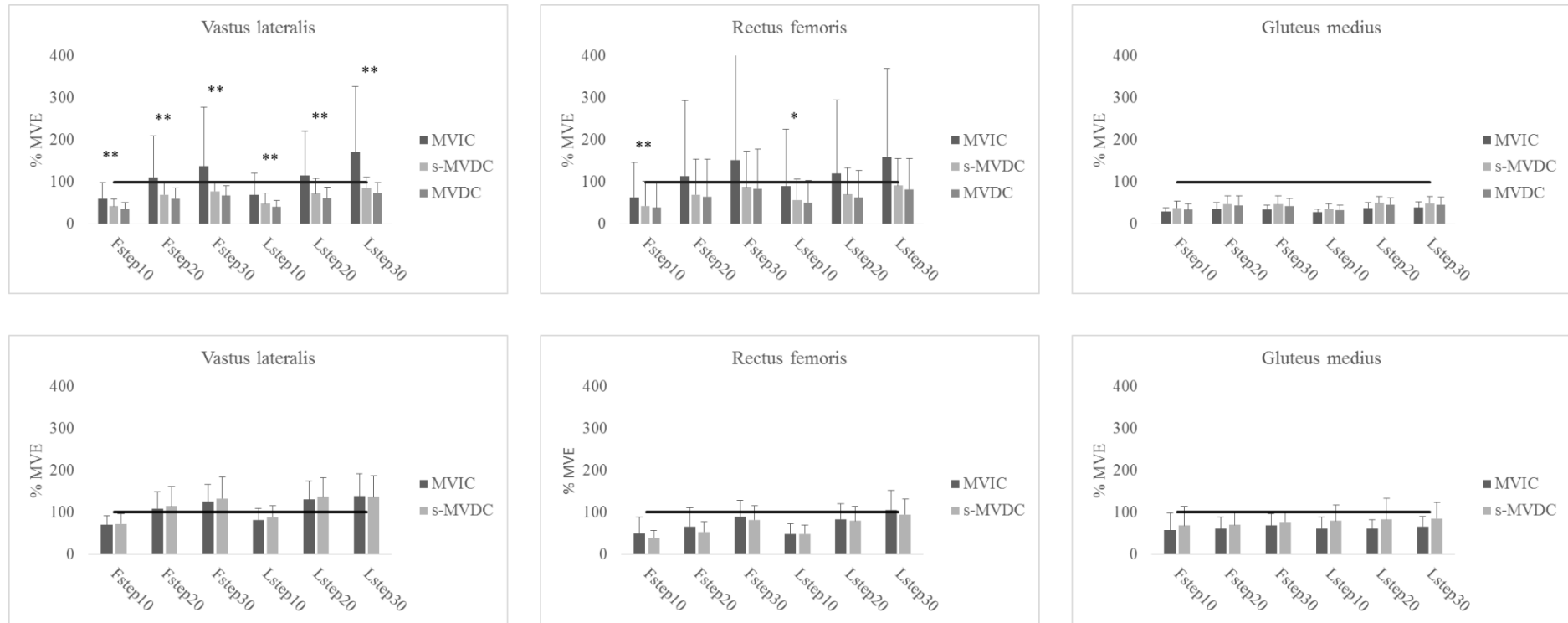


Figure 2: Mean and standard deviations of EMG (in % of maximum voluntary excitation; MVE), recorded during dynamic tasks, normalized to maximum voluntary excitation obtained from MVIC or (s-)MVDC, for young (top) and older women (bottom). Dynamic tasks consisted of forward (Fstep) and lateral (Lstep) stepping at step heights of 10, 20 and 30 cm. * indicates significant effect of normalization method at $p < 0.05$, ** indicates significance at $p < 0.01$.

Discussion

Despite the available knowledge about the advantages and disadvantages of using isometric or dynamic contractions for signal normalization [5], no studies have investigated whether differences in maximum voluntary excitation between contraction modes are age-dependent and the implications for signal normalization. Therefore, the main aims of this study were to determine if age shows an interaction effect with contraction mode and which normalization method results in the lowest between-participant variance and least amount of signals exceeding 100%. These are important considerations when selecting the most appropriate way to normalize EMG signals from dynamic trials in young and older populations.

The results from this study show that differences in maximum excitation between contraction modes are age-dependent in the vastus lateralis, and that in both age groups, dynamic contractions elicit excitation equal to, or greater than isometric contractions. Additionally, dynamic normalization resulted in lower between-participant variance, though not for all muscles, and resulted in less signals exceeding 100% in young women.

One important concern with the comparison between isometric and dynamic contractions is that joint angles may affect the detection volume due to changes in relative position of the muscle to the electrodes [7]. This study used MVICs recorded at a single joint angle, which is the most common approach to isometric normalization and is least time-consuming and susceptible to effects of fatigue [11]. Second, even though MVDC appears to be the best method to reduce variance between participants, there are still some practical downsides which might limit clinical applicability compared to MVIC. For example, 1-RM estimation requires more time to perform and is likely more expensive due to the fact that some form of equipment, like an isokinetic dynamometer or a strength training device, is required to assess maximum voluntary excitation. 100% 1-RM contractions are also hard to achieve by older adults and might lead to injuries [14–16]. Therefore, MVDCs were not included in the older cohort. Third, this study did not take into account the possibility that older adults modulate motor strategies due to reduced musculoskeletal capacity to allow stepping task performance within their individual constraints [25]. The relatively high excitation of the gluteus medius and larger number of dynamic trials exceeding 100% MVE in the elderly, as opposed to the young cohort, for all normalization methods might be attributable to altered motor strategies. Finally, this study only included data obtained from young and older women since women show higher age-related declines in muscle mass [17].

In the young cohort, both MVDC and (s-)MVDC in vastus lateralis, and MVDC in rectus femoris elicited significantly higher excitation than MVIC and a similar but non-significant trend was found for the gluteus medius. These results are in line with findings by Hodder and Keir [7] who found that maximum dynamic contractions more often yielded higher amplitudes than isometric contractions. Excitation of the gluteus medius during the dynamic contractions may also be higher due to increased recruitment needed for pelvic stabilization in the weight bearing position, opposed to the side-lying position more commonly used during isometric contractions [26]. When normalizing to a maximum contraction, the general assumption is that the obtained reference value should reflect 100% of the individual muscle's capacity [6]. If this is not the case, then normalization will lead to overestimation and thus misrepresentation of the EMG signal with regards to muscular effort [7,9]. Overestimation of normalized EMG signals could theoretically be solved by superimposing electrical stimulation onto the voluntary contraction. However, high-intensity stimulation is not possible for all muscles and is often perceived to be uncomfortable [27]. In addition, after electrical stimulation motor units fire in synchrony, leading to EMG amplitudes (M-waves) that are different from EMG amplitudes in voluntary contractions with non-synchronous motor unit firing [28]. Consequently, normalized values are difficult to interpret. Therefore, this study only included voluntary contractions. In the young cohort, voluntary maximum dynamic contractions elicited higher excitations and were better suited to reduce variance between participants than normalization to MVIC (Figure 2). This is in line with previous research on normalization using dynamic contractions [10].

Normalization to sub-maximal contractions is often recommended for older adults [1]. However, no significant differences in peak excitation were found between MVIC and s-MVDC in the older cohort. This implies that both methods would be equally suitable to estimate maximum voluntary excitation in the elderly. Our data suggest that both methods underestimate true maximum excitation, leading to normalized signals exceeding 100% during the unloaded stepping tasks. The lower between-participant variance generally found in EMG when normalized to s-MVDC (Figure 2) for all three muscles does point towards s-MVDC as the best normalization method for the elderly cohort, with exception of gluteus medius during lateral stepping. This is in partial accordance with a study in osteoarthritis patients by French et al. [29], who stated that in gluteus medius, MVIC is deemed more reliable (lower within-participant variance) than dynamic normalization, but the latter is still recommended to reduce between-participant variance. Greater variance in normalized amplitudes with MVIC, combined with amplitudes exceeding 100%, indicate a lack of validity of the MVIC normalization [29]. The different testing positions for dynamic and isometric contractions did not appear to have any effect on maximum excitation of the gluteus medius in this age group.

The skewed differences found between maximum excitations obtained from isometric versus dynamic contractions in each age group prompted the question; is there an interaction effect of age and contraction mode on maximum voluntary excitation? Age-related differences in maximum excitation may in part be accounted for by differences in thickness of subcutaneous fat layers and skin impedance [3]. These confounding factors are the reason why signal normalization is essential when comparing between age groups. Nevertheless, age-related confounders would be expected to have an equal impact on maximum voluntary excitation regardless of the contraction mode. However, two-way ANOVA exploring the interaction effect of age x contraction mode, and thus independent of age-related confounders, showed that the difference in maximum voluntary excitation between isometric and dynamic contractions in vastus lateralis was age-dependent. This indicates that, even when the same contraction mode is applied to obtain maximum voluntary excitation for normalization, caution should be taken when comparing normalized EMG between different age groups.

This age-dependent difference in magnitude of maximum voluntary excitation could be attributable to other physiological factors than skin impedance and sub-cutaneous fat. For example, magnitude of excitation depends on both the number of activated motor units (recruitment) and motor unit firing rates (rate coding) [14]. Recruitment is generally diminished with age due to a decline in the number of motor units through the process of sarcopenia [30]. Additionally, motor unit firing rates decline with age [31] due to increased irregularity, likely caused by denervation of the muscle fibers [32]. The decrease of motor unit firing rates in particular might explain why, in contrast with the young cohort, no differences were found in maximum voluntary excitation between MVIC and s-MVDC in the older cohort. In a study of motor unit firing rates of the soleus muscle of young adults, Kallio et al. [33] found that concentric dynamic contractions incited higher firing rates and thus higher muscle activity than isometric contractions at the same relative intensities. In older adults, the reduced firing rate capacity would have a relatively large impact on maximum voluntary excitation obtained during dynamic compared to isometric contractions, leading to more equal maximum voluntary excitations obtained from both conditions.

To summarize, this study shows that differences in maximum voluntary excitation between isometric and dynamic contraction modes are age-dependent and therefore, caution should be used when comparing signals obtained from different normalization methods between age groups. MVDCs elicited higher voluntary excitation than MVICs and s-MVDCs in young women. This indicates MVDC as a more suitable normalization method to reduce between-participant variance and allow more accurate assessment of individual muscle contributions and force estimations during dynamic activities. In contrast, no differences were found between s-MVDC and MVIC in older women. The

generally lower amount of signals exceeding 100% and lower between-participant variance of the normalized EMG signals point towards s-MVDC as the most suitable normalization method overall.

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Section 2.1. Electromyography as a tool to assess training potential for muscle mass and strength during weight bearing exercise

Paper 2: Weight bearing exercise can elicit similar peak muscle activation as medium-high intensity resistance exercise in elderly women

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Abstract

Purpose: To assess whether stepping-based weight bearing exercise (WBE) can elicit peak activation of upper leg muscles similar to resistance exercise (RE) at an intensity required to induce strength gains in elderly women. **Methods:** Muscular activation of several upper leg muscles was measured during RE and WBE in a cohort of 19 healthy elderly women ($69.3y \pm 3.4$). WBE consisted of forward and lateral stepping with step heights of 10, 20 and 30 cm. Muscular activation was compared to 60% of one-repetition maximum (1-RM) of congruent RE. **Results:** Peak activation during WBE was higher than RE at 60% 1-RM during forward and lateral stepping in vastus lateralis starting at 20 cm ($p = 0.049$ and $p = 0.001$), and biceps femoris at 30 cm step height ($p = 0.024$ and $p = 0.030$). Gluteus maximus peak activation matched RE at 60% 1-RM at 20 and 30 cm step height regardless of step direction ($p \geq 0.077$). Peak activation of the rectus femoris and gluteus medius matched RE activation at 60% 1-RM during lateral stepping at 30 cm ($p = 0.355$ and $p = 0.243$ respectively) but not during forward stepping. WBE did not induce similar activation as RE in the semitendinosus. **Conclusion:** In WBE, most upper leg muscles were recruited at an equal or higher intensity than in RE at 60% 1-RM. Lateral stepping at 30 cm step height showed the highest training potential of all WBE's applied.

Introduction

Sarcopenia is defined as the age-related loss of muscle mass and strength [1] and is one of the leading causes of falls [2] and functional impairment in elderly [3,4]. However, engaging in physical activity can ameliorate the debilitating effects of sarcopenia on functional performance and mobility [5]. Even though muscle mass and strength will inevitably decline over time, muscle plasticity is rather well preserved [3,5,6]. This ability has been demonstrated in ages ranging up to 85 [3,5,7]. Consequently, over the past decade, a plethora of exercise types have been suggested to preserve functional performance in elderly. Among these, resistance exercise (RE) has generally been indicated as the most effective way to induce gains in muscle mass and strength [8,9].

Muscle strength is a strong predictor of functional performance in elderly [2,10] and several studies have shown that strength gains from RE can translate into functional improvements [3,11]. However, Bean et al. (2009) found that functional improvements were only achieved in a subset of studies with appropriate RE task-specificity, but not in those studies that lacked RE task-specificity, indicating that strength is just one of the determinants of functional ability and balance performance. [12–14]. On a motivational level, RE participation in elderly appears to be limited. For example, data from the 2015 National Health Interview Survey (USA) show that only 15.2% of females between 65 and 74 years old met the federal physical activity guidelines when resistance training was taken into

account [15]. In addition, van Roie et al. (2015) have found that it is difficult to maintain exercise adherence to RE in this population. With limited participation and adherence, it is questionable whether RE is viable as a long-term training method for elderly.

Therefore, several researchers have recently directed their focus at more functional training modalities, stating that exercise protocols aiming to combat functional decline in elderly cannot be based solely on open kinetic chain RE. Alternatively, closed kinetic chain RE's such as the leg press appear to be more functional since they involve multi-joint movement and are considered to be safer than open kinetic chain RE [17,18]. However, training modalities to improve performance of everyday tasks and to prevent falls should also focus on functional parameters like balance maintenance and coordination [13]. A shift towards more functional training is supported by findings that neuromuscular adaptations in elderly appear to be highly task-specific [14,19]. In fact, several studies have demonstrated the efficacy of task-specific training for elderly [11,14,20].

One type of exercise that incorporates essential functional components for performance of everyday tasks, such as balance performance and muscular coordination, is weight bearing exercise (WBE). WBE is characterized by a certain degree of vertical impact relatable to activities of daily life, like normal gait, stair-navigation, stepping and jumping. Due to its large degree of task-specificity and incorporation of balance maintenance, stepping-based WBE could serve as a useful training modality to improve functional ability and strength. In a systematic review on fall prevention in elderly, Sherrington et al. state that 'exercise must provide a moderate or high challenge to balance' by reducing the base of support, involving movement of the center of gravity and reducing the need for upper limb support [9]. Stepping exercise incorporates all three of these balance challenging elements and may therefore help when training to prevent falling incidents.

Ideally, exercises that aim to improve functional performance and decrease falling incidents in elderly should incorporate both strengthening and task-specific components to achieve optimal effectiveness [21]. It is conceivable that WBE may also lead to muscle strength gains, but unfortunately it remains unknown whether stepping exercise can provide a sufficient training stimulus, because little research has been done to compare WBE with RE's known to improve muscle strength. Due to the mechanically complex nature of WBE [22], the mechanical indeterminacy of muscle-joint-systems and the inability to measure muscle forces without the use of invasive procedures it is hard to compare these exercise types based on muscle output [23]. Alternatively, muscle activation as measured with surface electromyography (sEMG) can provide some fundamental knowledge on the potential training stimulus that WBE can provide compared to RE.

The current study aimed to compare muscle activation of several major upper leg muscles of elderly women during WBE, and RE at 60% of one-repetition maximum (1-RM). This intensity of 60%

of 1-RM for RE was selected as a reference since it is established as the threshold for strength gains in untrained adults by the American College of Sports Medicine [24]. By establishing the relative activation during each WBE to activation obtained during a maximal contraction, the strengthening potential for each muscle can be inferred [25]. The definition of 60% 1-RM as the critical threshold for strength gains is further supported by a review from Macadam, Cronin and Contreras (2015) and meta-analysis by Schoenfeld et al. (2013). For elderly this threshold is less clearly defined. According to recent research the relative threshold for muscular gains is likely lower for older adults than young adults [28–30]. However, in the absence of a clearly defined threshold for strength gains in elderly we maintained the established peak activation of 60% 1-RM as the reference baseline.

The main goals were (1) to determine whether WBE can elicit peak activation levels sufficient to surpass the threshold for strength gains in this population and (2) how training characteristics, such as step height and step direction, affect peak activation levels. We hypothesized that stepping-based WBE at step heights of 20 and 30 cm could elicit peak muscular activation similar to, or higher than RE at 60% of a 1-RM. Additionally, we assessed the timing of peak activation for each muscle and made additional comparisons with results from closed kinetic chain resistance exercise to support our findings.

Materials and methods

Subjects

Twenty-two healthy, community-dwelling elderly women were recruited through posters at various social activities for elderly in Leuven (Belgium). Exclusion criteria, stated on the recruitment material and confirmed by a questionnaire, were diagnosed osteoarthritis of the lower limbs, hip, knee or ankle prosthetics, a history of mental disorders, balance disorders, brain injuries, and recurring dizziness. Three participants dropped out between the familiarization and testing session. One sustained a sprained ankle in the week following familiarization and two did not wish to disclose their reason for dropping out. The average age of the remaining nineteen subjects was 69.1 years (± 3.1). This study was approved by the Human Ethics Committee of KU Leuven in accordance with the Declaration of Helsinki. All subjects provided signed informed consent prior to participation.

Familiarization and 1-RM testing

A flowchart of the study protocol is provided in Figure 1. All subjects attended an individual familiarization session, during which they performed all RE's at least three times at low intensity. After familiarization, individual 1-RM for each RE was estimated in accordance with methods employed by

Brzycki (1993) where five-repetition maximum (86% 1-RM) was the minimum intensity used for estimation. Estimation of 1-RM was chosen since some population groups like sedentary elderly might experience difficulty to maximally exert themselves during direct 1-RM measurements [32]. Based on the estimated 1-RM, the external loads corresponding with the predetermined resistance levels (40, 60 and 80% respectively) for each RE were calculated. Familiarization occurred at least one week prior to testing to avoid any effects of fatigue.

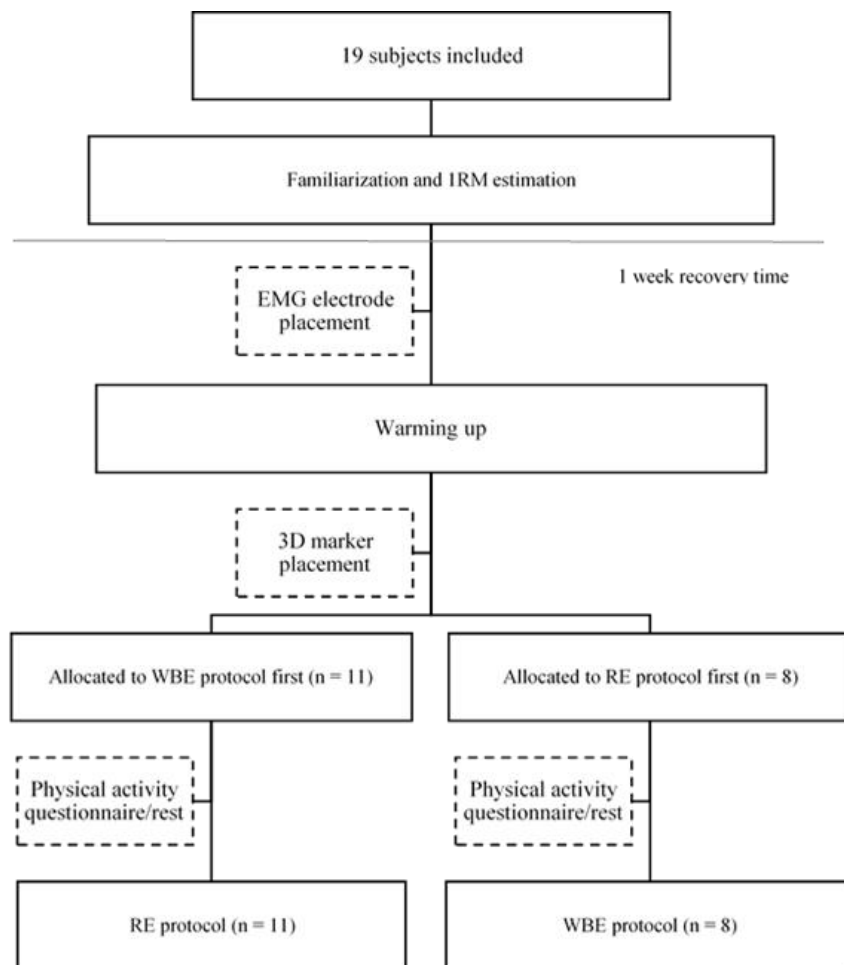


Figure 1: Flowchart of familiarization and testing procedures

Weight bearing and resistance exercise

On the testing day, the subjects were fitted with electrodes on the dominant leg to record sEMG. Left-right leg dominance was established by asking the participants with which foot they would kick a ball. sEMG was recorded from the vastus lateralis (VL), rectus femoris (RF), biceps femoris (BF), semitendinosus (ST), gluteus maximus (GMAX) and gluteus medius (GMED). Before electrode placement the skin was shaved and thoroughly rubbed with an alcohol swab. Electrodes (Ambu®

BlueSensor P Ag/Ag-Cl electrodes, Ballerup, DK) were placed on the belly of the muscles with an inter-electrode distance of 10mm. Subjects then performed a warm-up of 5 minutes cycling on a cycle ergometer at 70-80 rpm at a preferred resistance. The subjects were fitted with 50 retro-reflective markers [33] in order to record kinematics during the dynamic trials with 3D motion capturing (Vicon®, Oxford Metrics, Oxford, UK). Subjects were randomly assigned to perform either WBE or RE first, followed by RE and WBE respectively. The WBE protocol consisted of forward stepping (Fstep) and lateral stepping (Lstep) onto and off wooden blocks with heights of 10 cm, 20 cm and 30 cm respectively. For safety reasons, subjects were allowed to place their hand on a support bar during lateral stepping, without gripping the bar to avoid any force being applied by the hand during ascent. Every trial was performed twice to ensure at least one trial with proper recording of the EMG signals. The RE protocol consisted of five open kinetic chain exercises and one closed kinetic chain exercise. The open kinetic chain exercises included a seated knee extension, knee flexion in prone position, standing hip extension, standing hip flexion and standing hip abduction performed with a cable jungle (Technogym®, Gambettola, IT), adapted to simulate RE in a common gym setting. A seated unilateral leg press was included as a closed kinetic chain exercise. During the RE trials subjects performed three repetitions at each intensity (40, 60 and 80% of 1-RM respectively) to ensure recording of at least one full cycle from lifting the weight stack to returning the weight stack to starting position. Both RE and WBE were performed at a controlled speed guided by verbal feedback (one second concentric and one second eccentric contraction for RE and one second ascent for WBE).

Data collection

All measurements were performed at the Movement and posture Analysis Laboratory Leuven (MALL). Muscle activation was measured with sEMG through a telemetric system (Aurion®, ZeroWire, Milan, IT) at a sampling frequency of 1000 samples/s. Kinematics were recorded with a 3D motion capturing system (10-15 MX camera system; Vicon®, Oxford Metrics, Oxford, UK) sampled at 100 samples/s to establish start and end of each exercise. The raw sEMG signals were high-pass filtered with a 1st order Butterworth filter with a cut-off at 20Hz [23,34], full-wave rectified and smoothed with a 0.1-s moving average. The resulting signals were then normalized to the maximal dynamic output obtained during the muscle specific RE [35] which, due to difficulties of elderly to perform maximal dynamic contractions [36], was recorded at an intensity of 80% 1-RM [23], before establishing peak activation per trial. Normalization to a dynamic maximum (1-RM) was chosen over normalization to an isometric maximal voluntary contraction (iMVC) since iMVC-normalized data resulted in higher inter-subject variation, which was in line with findings by Burden (2010). For the WBE trials, the time-

normalized sEMG curves were plotted against the vertical displacement of the pelvis (represented by a marker on the sacrum) in order to detect during which phase of stepping peak activation occurred in each muscle.

Baseline determination

To provide a meaningful assessment of WBE as a training modality we employed a comparison with the American College of Sports Medicine-established threshold for muscle strength gains in RE for untrained adults, which is $\geq 60\%$ of 1-RM [24,27].

Statistical analysis

All processing was performed with MATLAB R2014b (MathWorks®, Natick, USA). Statistical analysis was performed with SPSS (IBM® SPSS v23 Statistics for Windows, Armonk, USA). The data was tested for normality with a Kolmogorov-Smirnov test. Since the assumption of normality was violated, overall significance of differences between each exercise, intensity and the reference exercise at baseline (60% 1-RM) were determined by means of a Friedman test. If an overall significant difference ($P < 0.05$) was found, a Wilcoxon signed rank test was performed to determine differences in peak sEMG of the individual muscles between each WBE and the baseline. Comparisons were made between each exercise intensity and the relevant baseline RE for that muscle (knee extension for VL and RF, knee flexion for BF and ST, hip extension for GMAX and hip abduction for GMED). Additional comparisons were made between corresponding intensities of each open kinetic chain RE and leg press.

Results

Only data from the ascent phase of stepping was analyzed since none of the recorded sEMG signals during descent were able to match or surpass those obtained during RE at 60% 1-RM. Positive dose-response relationships were found between exercise intensities (step height in WBE and percentage of 1-RM in RE) and peak sEMG amplitude for each muscle (Figure 2). Below we report muscular activation during WBE (Fstep and Lstep) and leg press, in comparison to the baseline of the most relevant RE, separately for each muscle group. An overview of the exercises that showed similar or significantly higher peak activation than the baseline can be found in Table 1.

Quadriceps

For the VL, the baseline RE was knee extension. Fstep at 10 cm elicited a significantly lower maximal activation than the baseline ($p = 0.035$), while Fstep at 20 and 30 cm elicited significantly higher activation levels ($p = 0.049$ and $p = 0.002$ respectively) than the baseline. Lstep at 10 cm step height showed no significant difference with the baseline ($p = 0.723$) and at 20 and 30 cm heights, significantly higher activation was recorded ($p = 0.001$ for both). When each intensity of the leg press was compared to the corresponding intensity of knee extension, a significant difference was found between both exercises at 40% 1-RM ($p = 0.013$) but not at 60 and 80% 1-RM ($p > 0.05$ for both). For the RF, knee extension was also used as the baseline RE. Forward stepping elicited significantly lower activation of the RF than the baseline at all step heights ($p < 0.001$ for 10 and 20 cm and $p = 0.024$ for 30 cm). Lateral stepping elicited higher activation than forward stepping at the same step heights. However, 10 and 20 cm step height elicited lower activation than the baseline ($p < 0.001$ and $p = 0.044$ respectively). Only lateral stepping at 30 cm elicited similar activation to the baseline ($p = 0.355$). Comparisons between the corresponding intensities of leg press and knee extension also showed consistently higher activation of the RF during knee extension ($p < 0.01$).

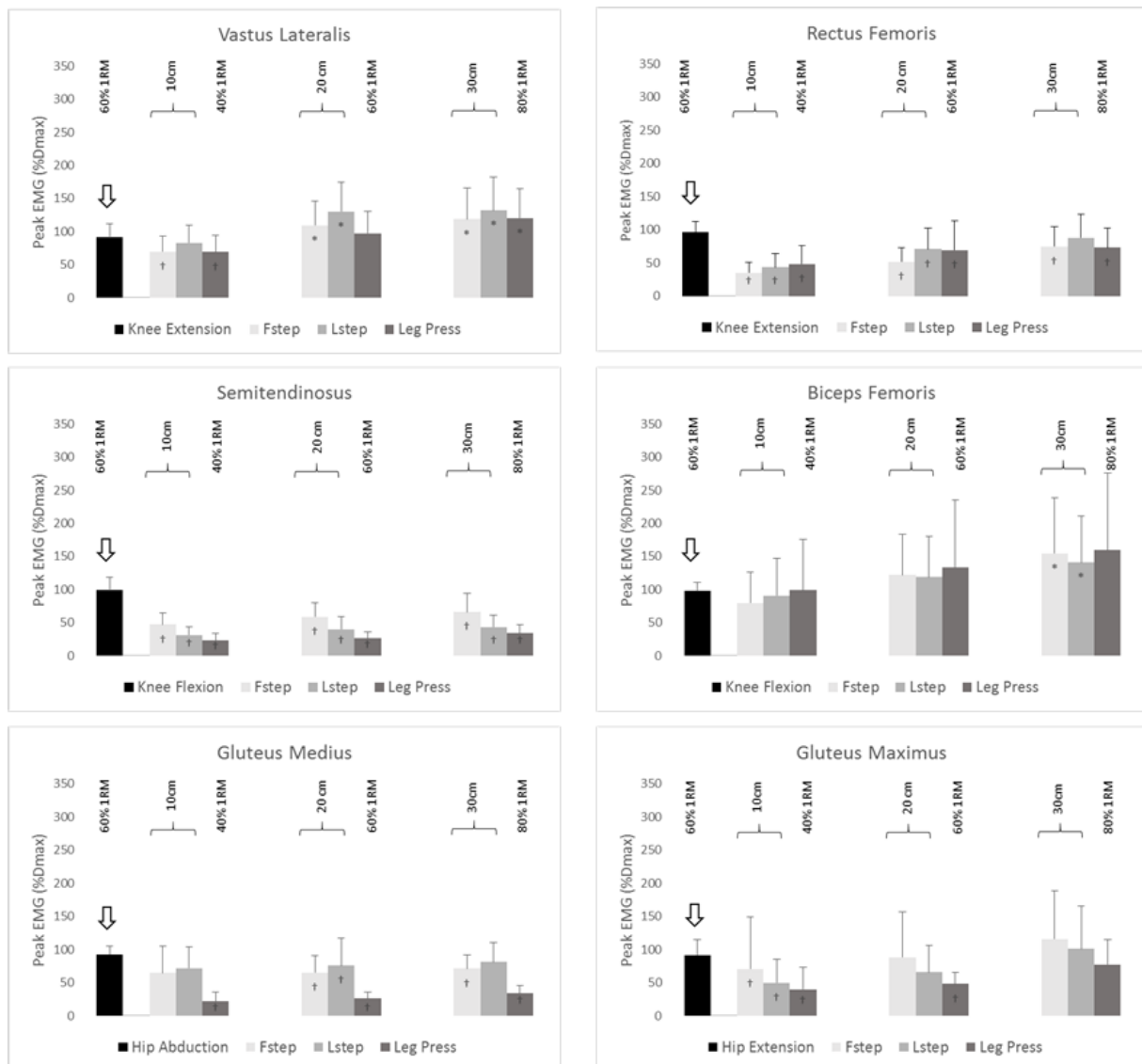


Figure 2: peak sEMG amplitudes during Fstep, Lstep and Leg Press at 3 different intensities compared to baseline activation (60% 1-RM) of the congruent RE (knee extension for quadriceps, knee flexion for hamstrings, hip abduction for gluteus medius and hip extension for gluteus maximus) indicated by ↓, † = significantly lower activation. * = significantly higher activation.

Table 1: maximal amplitude of VL, RF, BF, ST, GMAX and GMED activation at different intensities of WBE and RE. Intensity levels respectively indicate 10, 20 or 30cm step height for WBE and 40, 60 or 80% of 1RM for RE. Underscored figures indicate reference baseline of 60% 1-RM. Bold figures indicate WBE and leg press exercises that incited equal or significantly higher activation compared to reference baseline.

Trial	Mean peak (% DMAX)		
Intensity	1	2	3
VL			
Knee extension	83.7±20.6	<u>91.4±20.8</u>	100±0
Leg press	69.5±25.0	97.6±32.7	120.4±44.7
Forward step	69.9±23.2	109.6±36.8	118.7±47.6
Lateral step	83.1±26.3	130.5±43.6	132.2±49.7
RF			
Knee extension	75.9±18.7	<u>96.2±16.3</u>	100±0
Leg press	48.2±28.5	69.4±44.1	73.0±29.9
Forward step	35.4±15.7	51.4±21.1	74.8±30.1
Lateral step	43.4±20.4	70.8±31.5	88.2±35.0
ST			
Knee flexion	88.1±16.3	<u>99.0±19.4</u>	100±0
Leg press	23.5±10.0	26.6±9.1	34.2±13.3
Forward step	47.4±17.5	59.0±21.4	66.3±27.6
Lateral step	31.3±12.1	40.1±19.0	43.6±17.7
BF			
Knee flexion	93.0±14.6	<u>97.9±12.6</u>	100±0
Leg press	99.3±76.1	133.4±102.0	159.4±65.1
Forward step	80.1±46.2	122.1±61.5	154.5±84.3
Lateral step	90.7±56.2	119.0±61.2	141.1±69.5
GMAX			
Hip extension	80.7±17.8	<u>91.4±23.1</u>	100±0
Leg press	39.8±33.8	47.8±17.7	77.4±37.4
Forward step	70.6±78.2	65.3±69.0	115.8±72.5
Lateral step	49.9±35.4	65.5±40.3	101.1±64.3

<i>GMED</i>			
Hip abduction	82.6±13.7	<u>92.5±12.2</u>	100±0
Leg press	21.7±14.4	26.0±9.8	33.6±12.5
Forward step	64.3±40.2	65.3±25.9	71.1±20.5
Lateral step	71.9±31.4	75.8±40.7	81.2±29.7

Hamstrings

For both hamstrings, the baseline exercise was knee flexion. In the ST, none of the stepping exercises or leg press intensities elicited similar or higher activation than the baseline ($p < 0.001$). However, in the BF all stepping exercises produced similar or higher activation than the baseline. Both forward and lateral stepping at 10 and 20 cm elicited similar peak activation to knee flexion ($p > 0.05$ for all). Both stepping directions at 30 cm step height elicited significantly higher activation ($p = 0.024$ for Fstep and $p = 0.030$ for Lstep). All leg press exercises resulted in similar activity as their corresponding knee flexion intensity ($p > 0.05$).

Gluteus maximus

For GMAX the baseline exercise was hip extension. A step height of 10 cm elicited significantly lower activation than the baseline during forward and lateral stepping ($p = 0.040$ for Fstep and $p = 0.004$ for Lstep). However, similar activation to the baseline was elicited at step heights of 20 and 30 cm ($p > 0.05$ for both stepping directions). When compared to their corresponding hip extension intensity, all leg press intensities resulted in significantly lower activation ($p < 0.05$).

Gluteus medius

The baseline exercise for the GMED was hip abduction. Fstep at 10 cm showed similar activation to the baseline ($p = 0.077$), however, Fstep at 20 and 30 cm both elicited significantly lower activation ($p = 0.004$ and $p = 0.024$ respectively). Lstep at 10 cm and 30 cm showed similar activation to the baseline ($p = 0.070$ and $p = 0.243$ respectively), while Lstep at 20 cm showed significantly lower activation ($p = 0.044$). All leg press intensities produced significantly lower activation than their corresponding hip abduction intensities ($p < 0.001$ for all intensities).

Timing of peak activation

Figure 3 shows the muscular activation patterns of one representative subject during ascent and descent for Fstep and ascent for Lstep at 30 cm step height. Peak activation occurs during the ascent phase of both stepping directions for all muscles except the ST. The ST shows clear peak activation during the final phase of descent during forward stepping and several peaks over the whole step cycle during lateral stepping with the maximal peak occurring during the final phase of double support. Because lateral stepping is a less common task during activities of daily life, lateral stepping ascent and descent were recorded separately to allow for more standardized trial execution. Peak activation during descent did not surpass activation obtained during ascent and was therefore left out of further analyses.

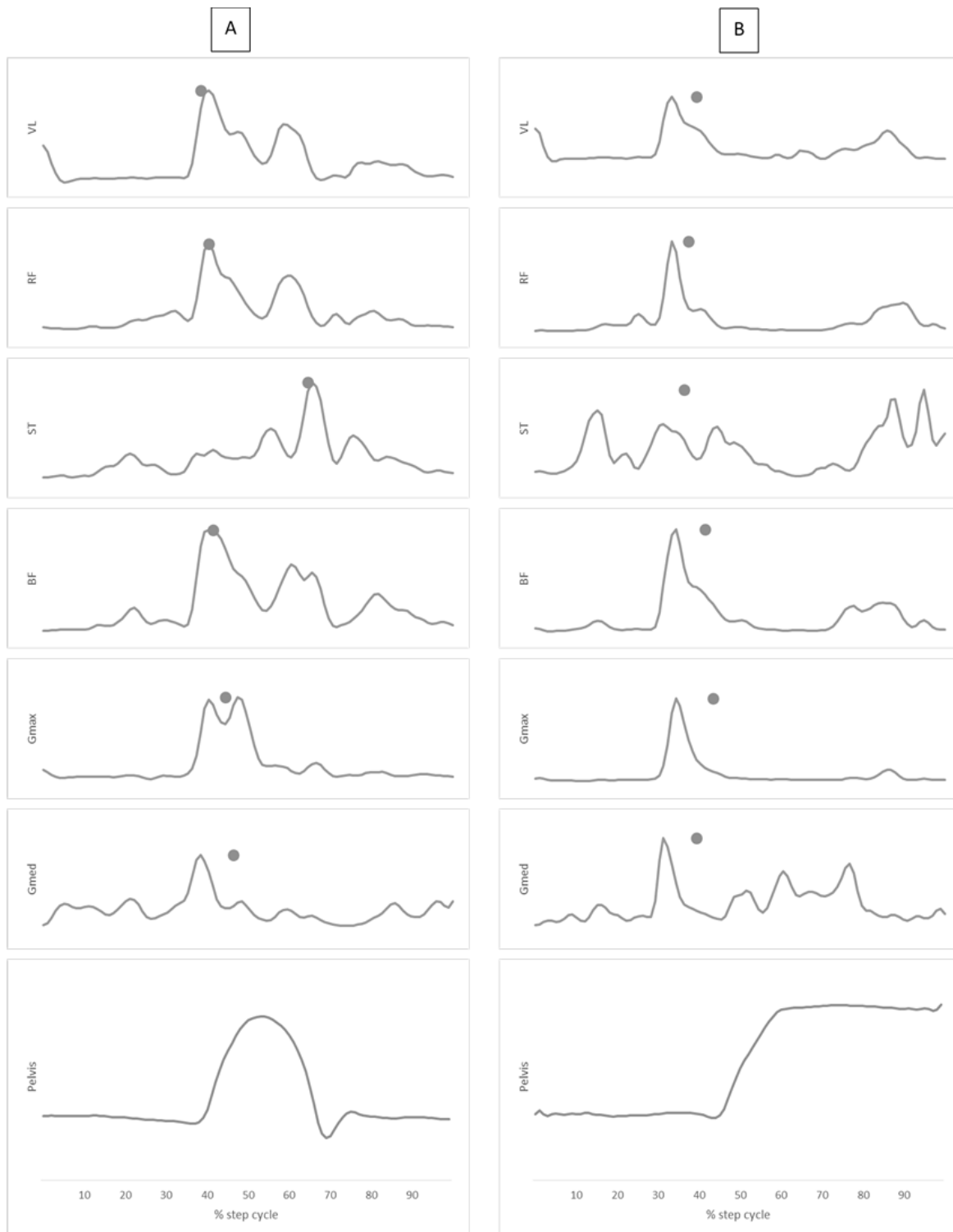


Figure 3: EMG output of VL, RF, ST, BF, GMAX and GMED muscles of one representative subject during ascent and descent of Fstep at 30 cm (A) and ascent of Lstep at 30 cm (B). Group average % of step cycle at which peak activation for each muscle occurred is depicted by a dot. Step cycle phases are

depicted by vertical displacement of the pelvis (bottom graphs). A low-pass 3rd order butterworth filter was applied at 3 Hz to smooth the EMG signals.

Discussion

To the authors' knowledge, this is the first study to compare peak muscle activation from various stepping exercise modalities with a reference intensity of RE. While several studies have shown that elderly tend to perform daily life activities at a relatively higher effort than young adults [38,39] and that task-specific training is effective for older adults [11,14,20], little evidence exists to determine which stepping exercise modalities have the most potential to improve muscle strength in this age group. Therefore, the purpose of this comparison was to determine if, with appropriate step height and direction, stepping could elicit peak muscle activation similar to medium-high intensity RE in elderly subjects and which conditions would yield highest activation. Our findings show that, depending on step height and direction, WBE can indeed elicit peak activation similar to -or higher than- RE at 60% 1-RM for all muscles except the ST.

Peak activation in weight bearing and resistance exercise

Although peak activation of the individual muscles during forward and lateral stepping has shown the potential to match and even surpass peak activation during a congruent RE at the threshold intensity of 60% 1-RM (Figure 2), step height and, to a certain extent, step direction had different effects on the individual muscle activation. For this reason the comparisons will be discussed separately per muscle group.

For the quadriceps muscles, the minimal required step height to achieve similar peak activation to the baseline was remarkably different. Lateral stepping at 10 cm was sufficient to elicit activation of the VL similar to the baseline. In the RF however, a minimum step height of 30 cm in lateral direction was required in order to reach peak activation similar to the baseline. Similar peak activation of the VL during corresponding intensities of leg press and knee extension shows that there is no difference between open and closed kinetic chain RE as a training stimulus for the VL. For the RF, none of the leg press intensities was able to elicit peak activation similar to congruent intensities of knee extension. These differences between VL and RF are all in line with results by Stensdotter et al. (2003) which they related to the nature of the RF as a multi-joint muscle and the fact that the RF has relative later onset activation timing compared to the other quadriceps muscles.

For the hamstrings clear differences were found between individual muscles. As opposed to the ST, which did not show activation up to baseline values for any of the WBE's or leg press intensities, the BF could be recruited to the baseline starting at a step height of 10 cm and even showed significantly higher activation than the baseline at 30 cm step height for both forward and lateral directions. The difference in relative peak activation between ST and BF could be attributable to differences in neuromuscular coordination of the hamstrings to achieve the most economic force production during different tasks. Previous research has shown that during high load open kinetic chain exercises like the leg curl, the ST is activated to a much larger extent than the BF [41]. Consequently, the potential for closed kinetic chain exercise to elicit similar peak activation of the ST compared to the baseline is lower than for the BF.

GMAX showed similar recruitment to the baseline from 20 cm step height, regardless of step direction. During stepping the GMAX is mainly responsible for hip extension but also counteracts hip flexion moments induced by the RF when extending the knee during step ascent. This degree of co-activation is not required during isolated hip extension and may therefore account for the similarities in peak activation. Leg press peak activation compared to corresponding resistances of hip extension did not show any significant differences, indicating that closed kinetic chain resistance exercise did not provide an additional benefit over open kinetic chain resistance exercise for the GMAX.

GMED peak activation was relatively low in the forward stepping trials, which are functionally similar to stair climbing [42,43]. Forward stepping at 10 cm and lateral stepping at 10 cm and 30 cm all recruited GMED to a level similar to the baseline. Overall, muscle activation was higher during lateral stepping than forward stepping. This is in line with research by Mercer et al. who found that sEMG activity of the GMED muscles was significantly higher when stepping in lateral direction compared to stepping in a forward direction [44]. Additionally, this study indicates that a step height of 30 cm is preferable to achieve sufficient recruitment. Low peak activation of the GMED during the leg press indicated that, despite being considered an effective way to promote strength training in elderly, the leg press is likely not ideally suited to induce gains in muscle strength of the GMED.

Overall, stepping-based WBE appears to be a viable way for elderly to simultaneously recruit several important upper leg muscles to a level required to improve muscle strength. Lateral stepping at a height of 30 cm yielded the best results as it simultaneously recruited all muscles measured up to –or beyond– their baseline activation, with the exception of the ST. This makes it an even more effective exercise than a leg press at 80% 1-RM, which could only recruit three out of six muscles to baseline activation.

Timing of peak activation

Our results (Figure 3) show that peak activation for most muscles (except ST) occurs during the ascent phase of stepping, regardless of stepping direction. Similar activation patterns for VL and BF in forward stepping were found by Reeves et al. [45], indicating concentric work performed by the quadriceps to lift the body while the hamstrings co-contract to extend the hip and simultaneously stabilize the knee joint. Peak activation of the GMED during the ascent phase of lateral stepping was expected since the GMED is the primary muscle responsible for hip abduction. However, during forward stepping peak activation of the GMED also occurred during the ascent phase which could be attributed to its role in controlling lateral weight shift during step ascent [44].

Clinical implications

These findings indicate the importance of acquiring fundamental knowledge regarding different exercise modalities prior to designing more effective exercise programs for elderly. For example, most studies on the effects of stepping exercise only applied a limited range of step heights, based on commonly encountered step heights [42,43]. The results of this study however, show that this may not provide enough training stimulus for the RF and GMED. For the VL, WBE appears to be an excellent exercise method since a step height of 20 cm is more than sufficient to achieve threshold level activation regardless of stepping direction. For the GMED however, proper step direction and height (lateral at 30 cm) are essential to achieve threshold activation.

Future considerations

There are some limitations to this study that need to be taken into consideration. First, some major leg muscles like the vastus medialis, tibialis anterior and gastrocnemius were not included in the analyses. Previous research by Stensdotter et al. (2003) has shown that activation of the vastus medialis obliquus is higher during closed kinetic chain exercises compared to open kinetic chain exercises, indicating that stepping exercise also has a higher training potential for the vastus medialis obliquus. And while the plantar- and dorsiflexors also play an important role during functional tasks and balance recovery [2], no congruent RE was performed to serve as a reference for comparison.

Second, no assumptions can be made with regard to repetitions required to improve muscle strength. Since fatigue affects the EMG power spectrum [46] and fatigue onset is different in every subject, all exercises were performed with minimal repetitions to minimize possible signal changes which could affect a reliable comparison between each exercise type and intensity. Further research is needed to explore the optimal training volume and further improve the fundamental basis for stepping based WBE in elderly.

Third, during lateral stepping a safety bar was essential to provide subjects with the confidence to perform an unfamiliar movement normally, without fear of falling. Subjects were clearly instructed to only use the bar for tactile feedback and any force applied was visible since the bar could shift slightly. When a shift of the bar was detected or task execution was not adequate, subjects were asked to perform the task again. Only adequately performed tasks were included in the analyses. However, the use of this safety bar may still have influenced muscular activation of the GMED in particular, resulting in a higher variability at step height of 20 cm where not all subjects utilized this safety feature. However, even with the use of a safety bar, lateral stepping at 30 cm could still incite muscular activation to the baseline reference for muscular gains.

Finally, this study was conducted exclusively with elderly females because they are at higher risk for developing functional limitations and falling incidents compared to men due to accelerated muscle loss after menopause [5,8]. In addition, the cohort was quite homogenous due to strict exclusion criteria. For this reason no additional baseline measurements of functional status were recorded to further characterize the cohort. Therefore, caution is advised when extrapolating the results of this study to male or young populations and elderly with physical disability.

Conclusion

Stepping-based WBE appears to be a viable alternative to RE for improving muscle strength, since it shows the capacity to produce peak muscular activation similar to RE at an intensity required to induce hypertrophy and strength gains, while also incorporating relevant task-specific challenges to balance and coordination. However, exercise characteristics such as step height and step direction affect recruitment of individual muscles differentially and need to be taken into account when designing training programs. Lateral stepping at 30 cm step height appears to provide the best training potential for all muscles except the ST. The findings from this study can be used to comprise more evidence-based WBE-based training programs to improve both strength and functional performance in elderly.

Conflicts of interest

The authors declare that they have no conflicts of interest. The results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

Acknowledgements

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Section 2.2. Bench stepping exercise as a way to improve muscle mass, strength and functional ability in older women

Paper 3: Bench stepping with incremental heights improves muscle volume, strength and functional performance in older women

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Abstract

Aim: Task-specific exercises such as bench stepping can improve functional ability and reduce falling incidents in older adults. However, such exercises are often not optimized to improve muscle volume and force-velocity characteristics. This study determined the effects of a 12-week stepping program using incremental step heights (STEEP), on muscle volume, strength, power, functional ability and balance performance in older women.

Methods: Forty-five community-dwelling women ($69y \pm 4$) were randomly assigned to the STEEP group or a non-training CONTROL group. Training intensity was primarily determined by step height, while training volume remained equal. Thigh muscle volume (CT-scan), force-velocity characteristics of the knee extensors (Biodex dynamometer) and functional ability (Short Physical Performance Battery, timed stair ascent, 10-m walk test and countermovement jump height) were determined pre- and post-intervention. In addition, 3D trunk accelerations were recorded at the lower back to assess balance during the Short Physical Performance Battery balance tests.

Results: Two-way ANOVA showed that the STEEP program increased thigh muscle volume, knee extensor isometric peak torque, dynamic peak power, unloaded rate of velocity development and improved performance on all functional tests to a greater extent than CONTROL ($p < .05$), except the countermovement jump. No improvements were found for peak velocity and balance performance ($p > .05$).

Conclusion: Our results indicate that bench step training with incremental step heights simultaneously improves functional ability, thigh muscle volume and force-velocity characteristics of the knee extensors in older women.

Key words: functional training; strength training; balance; sarcopenia; weight bearing exercise; muscle hypertrophy

Introduction

The age-related loss of muscle volume, strength and power is an important predictor for fall risk, loss of mobility and independence in older adults [1,2]. This loss of muscle volume is accelerated after menopause [3], making women particularly susceptible. Moreover, strength and power decrease to a much larger degree than can be explained by the loss of muscle volume alone [4]. Therefore, it is imperative to maintain muscle volume, strength and power for as long as possible. Engaging in physical activity can prevent and even reverse the muscular and functional declines [5]. Currently, most training interventions appear to maintain a dichotomous approach, employing resistance exercise to improve muscle characteristics and task-specific exercise to improve functional performance. However, few studies have explored if exercises can be adapted to target muscle characteristics and functional performance simultaneously.

Resistance exercise is generally considered most effective in improving muscle volume and strength [3,6]. However, improvements in muscle strength through resistance training alone do not necessarily translate to improvements in functional performance [7–9], likely because training adaptations in older adults are highly task-specific to activities of daily life (e.g. stepping and obstacle navigation) [9,10]. On the other hand, training programs based exclusively on functional exercises rarely result in meaningful improvements in muscle volume and strength [9,11]. Therefore, current best practice recommendations include multi-component exercises that target both strength and functional ability [5,6,12].

Unfortunately, combining functional exercise with traditional resistance training is not as simple as it might seem. This is due to high avoidance of machine-based resistance training [13], preference for other forms of physical activity [14] and increased exercise duration, which is an important motivational barrier for exercise participation and adherence in older populations [14,15]. Thus, the challenge in designing training programs for older adults is to prescribe time-efficient programs that improve both strength and functional performance with a low motivational threshold for participation.

Bench stepping may simultaneously target strength and functional performance. It is a low-cost exercise that can be performed in both group and home-based settings, seemingly with little to no supervision (although the latter has not yet been properly substantiated) [16–18]. Bench stepping produces only low to moderate skeletal loading [18], and can be performed up to step heights of 47 cm by older women, without the use of external support [8]. Additionally, the training intensity can easily be modified by altering step height [18]. In a non-fatigued state, a minimum step height of 20 to

30 cm was required to achieve electromyography (EMG) amplitudes comparable to resistance exercise at 60% of one-repetition maximum (1-RM) [19], which is the recommended training load for strength gains in untrained adults defined by the American College of Sports Medicine [20]. Additionally, lateral stepping with a minimum step height of 30 cm is required to sufficiently activate the hip abductors [19], which is particularly relevant for fall prevention [7]. Based on these findings, we designed an optimized training program dubbed the ‘Strength Training for Elderly through Elevated stePping’ (STEEP) program, a 12-week task-specific strength training program for older women using incremental step heights exceeding ~18-22 cm step heights which are most common in daily life.

The primary aim of this study was to examine the effects of the STEEP program on muscle volume, force-velocity characteristics, functional performance and balance in older women. Additionally, adherence was tracked and motivation questionnaires were administered in the intervention group to assess the likelihood of long-term training adherence after cessation of the intervention. We hypothesized that thigh muscle volume, knee extensor strength and power, functional performance and balance would be improved. Additionally, we hypothesized that feelings towards the training program would be positive and that perceived enjoyment, feasibility and effectiveness would be high when subjectively compared to traditional resistance exercise.

2. Materials and methods

2.1. Participants

Forty-five sedentary community-dwelling women aged 65y and older ($69y \pm 4$) were recruited through advertisements around Leuven, Belgium. Exclusion criteria included participation in a structured training program in the previous 12 months, cardiovascular disease, lower limb prosthetics, arthrosis of the hip or knee, and neurological disease. Participants were assigned to the training group (STEEP; $n = 24$) or the control group (CONTROL; $n = 21$) through a computer-generated randomization scheme, blocked in groups of four, prior to the initial tests. This study was approved by the Human Ethics Committee of KU Leuven, in accordance with the Declaration of Helsinki and registered with the Clinical Trial Center UZ Leuven (S60533). All participants provided signed informed consent before participation.

2.2. Training protocol

The CONTROL group did not participate in training and was asked to maintain their habitual physical activity. The training program performed by the STEEP group is reported below following the

Consensus on Exercise Reporting Template (CERT, see appendix 2 for checklist) [21]. Training in the STEEP group consisted of 40 minutes of bench stepping exercise using modular height-adjustable stepping benches, performed 3 times per week for 12 weeks. As previously stated, in a non-fatiguing protocol, EMG amplitudes at step heights of 20 to 30 cm were found to be similar to resistance exercise at 60% of 1-RM [19]. However, no guidelines are available with regard to the number of bench-stepping repetitions required to achieve hypertrophy and strength gains. Therefore, we selected the number of repetitions based on previous studies using multi-joint resistance exercises such as the leg press. These found that the number of repetitions to achieve momentary muscle fatigue (failure) on a leg press at 60% 1-RM ranged between 36 and 38 [22,23]. To avoid exceeding this indicated maximum threshold (which may lead to fatigue-related incidents), and to facilitate musical cueing, the number of repetitions per set was fixed to 32. By fixing the number of repetitions for all subjects and intensities, we could also avoid differences in training volume. During the first two weeks of training, individual entry levels (level 1, 3 or 5; Table 1) were determined by assessing the maximum step height at which the participants could complete all sets at the preset pace (~30 steps/min) in both directions. All training sessions were conducted in groups of 8-9 participants by a certified professional fitness instructor in a dedicated fitness room at the faculty of movement and rehabilitation sciences of KU Leuven. Adherence to the training protocol was ensured by the instructor and recorded using a tick list.

Table 1: Overview of the STEEP program.

		Step height Fstep (cm)	Step height Lstep (cm)	Body mass Fstep (%)	Body mass Lstep (%)
Level 1	Week 1	18	18		
	Week 2	18	18		
Level 2	Week 1	24	18		
	Week 2	24	18		
Level 3	Week 1	24	24		
	Week 2	24	24		
Level 4	Week 1	30	24		
	Week 2	30	24		
Level 5	Week 1	30	30		
	Week 2	30	30		
Level 6	Week 1	36	30		
	Week 2	36	30		
Level 7	Week 1	36	36		
	Week 2	36	36		
Level 8	Week 1	36	36	5	
	Week 2	36	36	5	
Level 9	Week 1	36	36	5	5
	Week 2	36	36	5	5
Level 10	Week 1	36	36	10	5
	Week 2	36	36	10	5

Each level encompasses two weeks of training. During week 1 and 2 participants were assigned to their respective baseline level (1, 3 or 5) and provided with the corresponding progression program. Participants automatically progressed to the next level every time they completed 2 weeks of the previous level. For participants starting at level 5, weighted vests with 5-10% body mass were added to

prevent a ceiling effect after achieving the maximum step height of 36 cm. Participants performed 2 x 32 repetitions of stepping in forward direction (Fstep), one set for the right and one set for the left leg. This sequence was repeated in lateral direction (Lstep). After a short break, an identical second set was performed. Each session started with a low-intensity warming-up without using stepping benches and ended with a cooling-down that consisted mainly of stretching exercises.

By assigning individual entry levels, no adjustments were required for differences in training progression due to baseline functional ability or anthropometrics. Initial progression was solely determined by step height. Step height increments were set at 6 cm, starting at 18 cm. The maximum step height was set at 36 cm. If participants progressed past 36 cm step height for both forward and lateral direction, intensity was further increased using weighted vests with 5% or 10% body mass to ensure that a systematic increase in training intensity could be maintained [17].

2.3. Outcome measures

2.3.1. Participant characteristics

Participant characteristics were recorded during the pre-tests. Habitual physical activity (PA) was determined using the Godin Leisure-Time Exercise Questionnaire [24]. Handgrip strength was recorded using a Jamar handheld dynamometer (Sammons Preston Inc., Bolingbrook, IL, USA). Three measurements were obtained from the dominant hand and the highest value (in kg) was used to indicate maximum grip strength. Test-retest reliability for handgrip strength testing in older adults is well established with an intra-class correlation coefficient (ICC) of .91 to .95 for the right and left hand respectively [25].

2.3.2. Muscle volume

Muscle volume of both legs was obtained within a week pre- and post-intervention using computerized tomography (CT; Somatom Force®, Siemens Medical Solutions, Erlangen, DE). All scans were performed at the same time of day and participants were instructed to lay on the scanning bed for 5 minutes in supine position prior to the scan. Four 5 mm axial slices were obtained at the midpoint of the distance between the medial edge of the trochanter and the intercondyloid fossa of the femur. These slices were combined and total muscle volume (in cm³) was determined with custom software developed at the university hospital using standard Hounsfield Units for skeletal muscle (0–100). Test-

retest reliability evaluated for a similar approach in our lab showed an ICC of .99 and a coefficient of variation (CV%) of 1.3 [26].

2.3.3. Force-velocity characteristics

Torque and velocity of the knee extensors were obtained using a Biodex System 4 Pro[®] isokinetic dynamometer (Biodex Medical Systems, Shirley, USA; Figure 1), in accordance with procedures used in previous studies [4,27].



Figure 1: Setup of the isokinetic dynamometer (top left). The timed stair ascent task with lower back-mounted accelerometer (top right). Impression of a training session in week 10 (bottom).

Testing was performed unilaterally on the dominant side. The range of motion was set between 90° to 160° (full knee extension corresponded to 180°). Isometric strength was assessed by measuring peak torque (in Nm) at knee angles of 120° ($pT_{\text{isom}120}$) and 90° ($pT_{\text{isom}90}$). At both angles, participants performed four repetitions of 5 seconds maximum voluntary contraction, separated by 20 s rest periods. Peak power (pP) and peak velocity (pV) were measured using isotonic contractions. Four ballistic knee extensions were performed against constant resistances. Starting at 90°, participants were instructed to extend their knee four times as fast as possible to 160°. Resistance was consecutively set at 40%, 20%, 0% and 60% of $pT_{\text{isom}90}$. For each resistance, the trials that produced the highest peak power (pP in Nm/s) were used for comparisons of both pP and pV. Additionally, the rate of velocity development (RVD in °/s²) at each resistance was calculated [28]. Test-retest reliability in our lab shows an ICC ranging from .94 to .97 and CV% of 7.8 for the isometric tests [26,27]. Reliability for pP, pV and RVD obtained from isotonic tests was also excellent with an ICC ranging from .85 to .98 for and CV% ranging from 3 to 9 [28].

2.3.4. Functional and balance performance

Functional and balance performance were assessed using an extended version of the Short Physical Performance Battery (SPPB) [29]. Each of the balance tests (side-by-side, semi-tandem and tandem stance) was recorded three times for 30 seconds instead of 10 seconds to allow more accurate assessment of balance performance. SPPB scores were calculated using the first 10 seconds of each trial. In addition to the 5x sit-to-stand test (5xSTS), the functional test battery included a timed 10-meter walk test at maximum walking speed (10MW) and a timed 12-step stair ascent (SA). Each functional test was performed twice and the best performance was used for data analysis. A counter-movement jump (CMJ) was used as an indicator of explosive lower limb muscle power. CMJ height was estimated based on flight time recorded from three separate jumps using a contact mat [30]. During all functional tests kinematic data were collected at the lower back using 3D accelerometry (DynaPort MoveTest®, McRoberts, The Hague, NL; Figure 1). Reliability for SPPB in older adults, instrumented STS in a geriatric population, maximum walking speed, and CMJ in older females was demonstrated in previous studies [30–34]. Reliability of instrumented SA in our lab was excellent, with an ICC of .93 and CV% of 4. To assess balance performance during the static tests of the SPPB, medio-lateral balance performance was assessed using the root mean square of the displacement (mm). Overall balance performance was assessed using the total length of the sway path divided by duration of the measurement (mm/s). Using accelerometry at the lower back, rather than center of pressure

measurements, provided us with a way to measure postural sway directly by estimating acceleration of the center of gravity, which is the controlled variable in balance tasks [35], and has been shown to have good reliability [36].

2.3.5. Motivation questionnaires

Custom questionnaires (supplemental material) were completed by the STEEP group during weeks 1, 6 and 12 of the training program. These questionnaires included five questions that assessed feelings related to exercise on a 11-point Likert scale (e.g. 0 = totally disagree, 10 = totally agree)[14]. The internal consistency of these questions was checked with Cronbach's α , where question 3 was inversely coded because of a negative scale. Cronbach's α was 0.64 when all 5 questions were included. However, by removing question 3, Cronbach's α improved to an acceptable value of 0.75, consistent with analyses by Van Roie et al. [14]. Question 3 was therefore removed from this item and treated as a separate item 'relief'. Three additional questions were included to assess the likelihood of training adherence to the STEEP program compared to resistance training. These three items ('enjoyability', 'feasibility' and 'effectiveness') were analyzed separately.

2.3.6. Statistical analyses

Sample sizes were calculated based on the effect size on pT_{isom90} from a previous study using resistance exercise (partial η squared = .287)[37]. A total of 38 participants was required to detect a similar effect size with a power of 90% on a two-sided test with $\alpha=.05$. Statistical analyses were performed with SPSS (IBM® SPSS v23 Statistics for Windows, Armonk, USA). Data were tested for normality with a Kolmogorov-Smirnov test. Depending on the normality of the data, baseline differences between groups were analyzed using either independent samples T-tests or Mann-Whitney U tests. In order to check for group x time interaction effects, non-normal data were first log-transformed and all data were subsequently analyzed using a mixed ANOVA design with time as within-subjects factor and group as between-subjects factor. If a significant F -value was found, within-group changes were analyzed using paired samples T-tests. Scores on the motivation questionnaires obtained from the STEEP group were analyzed using a Kendall's W test.

3. Results

3.1. Baseline participant characteristics and adherence

No significant differences in participants' characteristics were found between groups at baseline ($p > .05$; Table 2). Attendance of the training sessions was 90% and all participants were able to complete their assigned progression program. Two participants dropped out between the pre- and post-tests. One participant from the STEEP group dropped out because of excessive sweating, and one from the CONTROL group due to an unscheduled medical procedure (Figure 2). Even though participants with osteoarthritis were excluded from the study, three participants initially reported light knee pain when stepping at heights exceeding 18 cm. However, after receiving instructions on proper foot placement, these participants indicated no more pain during subsequent training sessions. No further negative effects were reported.

Table 2: Participant characteristics of the STEEP and CONTROL group, mean difference (95% confidence interval; CI), significance of difference and effect sizes at baseline.

	STEEP	CONTROL	mean difference (95% CI)	<i>p</i>	Effect size (Cohen's <i>d</i>)
Age (y)	69 ± 4	69 ± 4	0.03 (-2.33 to 2.39)	0.98	0.02
Body mass (kg)	72 ± 14	66 ± 11	6.67 (-0.34 to 13.68)	0.06	0.51
Height (cm)	164 ± 6	162 ± 5	2.52 (-0.88 to 5.91)	0.14	0.36
BMI (kg/m²)	26.77 ± 4.70	25.09 ± 3.36	1.79 (-0.67 to 4.25)	0.15	0.41
Leisure time PA-score	24.52 ± 24.81	22.80 ± 14.53	1.26 (-11.00 to 13.51)	0.84	0.08
Handgrip strength (kg)	28.22 ± 4.77	29.00 ± 5.71	-0.53 (-3.76 to 2.69)	0.74	0.15
Left/Right dominance	1/23	1/20			

3.2. Muscle volume

A significant group x time interaction effect was found for relative change of muscle volume. Muscle volume increased significantly in the STEEP group (2.8% for the right leg and 2.6% for the left leg). No significant differences were detected in the CONTROL group (Table 3).

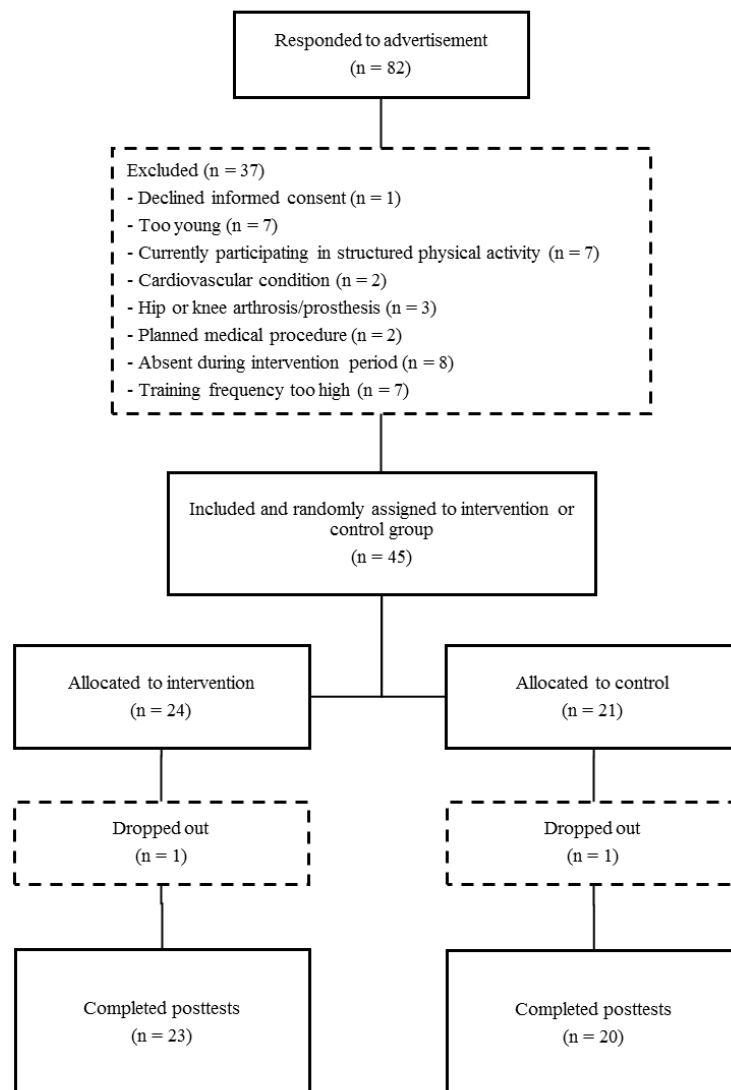


Figure 2: CONSORT diagram.

Section 2.2. Bench stepping exercise as a way to counteract sarcopenia and functional decline in older women

						Between-group difference (95% CI)	Between-group difference for change over time ^a	
							significance (p value)	effect size (η _p ²)
		STEEP	%Δ	CONTROL	%Δ			
CT-scans								
MV right (cm ³)	Pre	193.0 ± 29.2		202.3 ± 32.7		-4.54		
	Post	199.1 ± 28.1	2.8 ± 4.1**	200.1 ± 31.5	-1.0 ± 2.9	(-23.39 to 14.32)	0.002	0.214
MV left (cm ³)	Pre	190.8 ± 31.0		199.8 ± 30.4		-4.13		
	Post	196.7 ± 29.5	2.6 ± 3.9**	197.4 ± 27.7	-1.0 ± 3.8	(-22.61 to 14.35)	0.005	0.181
Isometric tests								
pT at 120° (Nm) ^b	Pre	96.3 ± 21.1		112.4 ± 14.5		-7.45		
	Post	110.0 ± 24.2	15.7 ± 20.7**	108.8 ± 19.1	-2.7 ± 16.1	(-18.93 to 4.04)	0.002	0.204
pT 90° (Nm)	Pre	125.5 ± 27.5		142.2 ± 29.0		-4.96		
	Post	137.2 ± 30.8	9.6 ± 10.7**	130.4 ± 38.1	-7.8 ± 21.1	(-23.11 to 13.19)	0.001	0.227
Isotonic test at 0% load								
pV (°/s)	Pre	365.6 ± 24.8		374.3 ± 17.8		-5.80		
	Post	372.4 ± 16.5	2.4 ± 7.4	375.7 ± 16.4	0.4 ± 1.9	(-16.48 to 4.89)	0.301	0.027
RVD (°/s ²) ^b	Pre	1515.4 ± 396.7		1548.4 ± 279.1		46.95		
	Post	1704.4 ± 284.3	18.3 ± 30.1**	1577.6 ± 270.0	2.9 ± 14.3	(-142.18 to 236.08)	0.037	0.109
pP (Nm/s)	Pre	6.4 ± 0.4		6.5 ± 0.3		-0.10		
	Post	6.5 ± 0.3	2.4 ± 7.4	6.6 ± 0.3	0.4 ± 1.9	(-0.29 to 0.09)	0.299	0.027
Isotonic test at 20% load								
pV (°/s)	Pre	304.2 ± 21.5		303.1 ± 18.4		0.79		
	Post	307.1 ± 19.5	1.4 ± 6.0	307.3 ± 23.7	1.4 ± 5.1	(-11.18 to 12.76)	0.888	0.001
RVD (°/s ²)	Pre	1127.1 ± 238.9		1172.5 ± 139.6		-14.69		
	Post	1198.2 ± 167.6	7.7 ± 18.5	1179.9 ± 186.0	0.5 ± 9.0	(-124.29 to 94.91)	0.277	0.030
pP (Nm/s)	Pre	128.1 ± 28.2		143.4 ± 30.6		-7.52		
	Post	140.3± 31.3	11.2 ± 12.4**	141.3 ± 29.3	-1.1 ± 5.4	(-25.88 to 10.83)	<0.001	0.345
Isotonic test at 40% load								
pV (°/s) ^b	Pre	213.6 ± 27.8		206.2 ± 27.7		6.44		
	Post	216.7 ± 36.5	3.8 ± 12.3	215.3 ± 35.6	4.5 ± 11.6	(-11.21 to 24.10)	0.864	0.001
RVD (°/s ²)	Pre	811.4 ± 165.7		810.9 ± 123.9		-3.58		
	Post	853.5 ± 95.6	9.6 ± 28.1	861.2 ± 146.4	6.9 ± 14.6	(-79.63 to 72.48)	0.837	0.001
pP (Nm/s)	Pre	180.6 ± 45.3		193.1 ± 41.6		-6.65		
	Post	195.0 ± 47.6	12.5 ± 14.6**	200.6 ± 40.0	4.5 ± 7.5	(-32.54 to 19.25)	0.045	0.097
Isotonic test at 60% load								
pV (°/s)	Pre	137.8 ± 30.9		127.8 ± 22.6		9.85		
	Post	146.5 ± 30.1	8.2 ± 22.9	131.2 ± 33.3	7.1 ± 19.3	(-6.18 to 25.88)	0.986	<0.001
RVD (°/s ²)	Pre	547.5 ± 203.8		500.4 ± 180.1		26.41		
	Post	569.1 ± 142.4	18.3 ± 45.9	553.0 ± 209.2	18.8 ± 67.1	(-82.29 to 135.11)	0.662	0.005
pP (Nm/s) ^b	Pre	176.2 ± 54.6		180.9 ± 38.1		3.56		
	Post	200.1 ± 50.3	17.2 ± 23.6**	191.2 ± 50.4	3.6 ± 12.6	(-26.53 to 33.65)	0.029	0.117
Functional performance tests								
SPPB ^b	Pre	11.3 ± 1.0		11.9 ± 0.4		-0.26		
	Post	11.78 ± 0.7	4.6 ± 6.6**	11.8 ± 0.4	-0.8 ± 3.8	(-0.64 to 0.13)	0.002	0.209
5xSTS (s) ^b	Pre	11.0 ± 2.4		10.4 ± 1.3		-0.03		
	Post	9.8 ± 2.4	-9.4 ± 12.4**	10.3 ± 1.1	-0.2 ± 10.2	(-1.16 to 1.10)	0.007	0.162

10m walk (s)	Pre	6.3 ± 1.0		5.9 ± 0.7		0.25		
	Post	5.7 ± 0.9	-9.1 ± 11.3**	5.7 ± 0.9	-4.5 ± 7.6	(-0.27 to 0.77)	0.038	0.100
Stair ascent (s) ^b	Pre	5.0 ± 1.0		4.3 ± 0.9		0.45		
	Post	4.6 ± 0.9	-7.9 ± 9.9**	4.4 ± 1.0	1.9 ± 12.2	(-0.12 to 1.03)	0.004	0.182
CMJ (mm)	Pre	115.7 ± 34.8		133.2 ± 23.8		-14.43		
	Post	124.7 ± 30.2	12.0 ± 19.7	136.1 ± 27.3	2.8 ± 13.7	(-32.18 to 3.31)	0.280	0.029

*Table 3: Mean and standard deviation of muscle volume and force-velocity characteristics of the knee extensors pre- and post-intervention with % change, mean difference (95% confidence interval; CI), significance of difference and effect sizes. ^a group-by-time interaction from mixed ANOVA. ^b statistical analyses performed using log-transformed data, reported means and mean differences from non-transformed data. ** Significant within-group difference ($p < 0.01$).*

3.3. Force-velocity characteristics

Dynamometry data from five participants were excluded from the analyses. This included data from all isotonic contractions of two participants from both groups due to incorrect task execution during either pre- or post-measurements (e.g. incomplete range of motion). Isotonic contractions at 60% pT of one participant from the CONTROL group were removed, because the participant was unable to move the lever arm at this resistance. Significant main effects were found with improvements in the STEEP group, compared to the CONTROL group, for $pT_{\text{isom}120}$, $pT_{\text{isom}90}$, pP at 20%, 40%, and 60% of $pT_{\text{isom}90}$, and RVD during unloaded isotonic contraction ($p \leq 0.01$ for within-group effects in STEEP; Table 3). No improvements were found for pV at any of the applied resistances in either group ($p > 0.05$).

3.4. Functional and balance performance

SPPB scores were all above 9, indicating that none of the participants showed impaired functional ability. The SPPB scores improved significantly in the STEEP group compared to the CONTROL group ($p = 0.004$ within-group effect in STEEP; Table 3). However, this change was less than one point and therefore not clinically meaningful [38]. A significant group x time interaction effect was found for functional performance. Functional performance improved in the STEEP group, indicated by decreases in 5xSTS duration, 10MW duration and SA duration ($p < 0.01$). No differences were found in the CONTROL group ($p > 0.05$). In contrast, no interaction effects were found between groups for CMJ height or postural sway during any of the balance tests ($p \geq 0.05$).

3.5. Motivation questionnaires

Scoring on all items indicated a strong positive perception of the training program (scores above 8), with a further significant increase during the training period ($p=.015$; Table 4). The participants indicated to feel slightly relieved after finishing the training sessions (scores below 5), with no changes over time ($p=.099$). For the items comparing STEEP with resistance exercise, scores indicated a more positive perception towards the STEEP program for enjoyability, feasibility and effectiveness (all scores above 5), which showed no change over the course of the program ($p>.05$).

Table 4: Mean $\pm$ standard deviation and significance of time effect on scores from the motivation questionnaires.

	Week 1	Week 6	Week 12	p -value	Effect size (Kendall's W)
<i>Positive feelings related to exercise</i>	8.73 $\pm$ 1.12	9.24 $\pm$ 0.78	9.35 $\pm$ 0.66	0.015*	0.196
<i>Relief</i>	4.55 $\pm$ 3.14	4.65 $\pm$ 2.77	3.91 $\pm$ 2.91	0.099	0.116
<i>Enjoyability</i>	8.32 $\pm$ 2.03	7.95 $\pm$ 1.91	8.64 $\pm$ 1.89	0.850	0.013
<i>Feasibility</i>	7.11 $\pm$ 1.70	6.90 $\pm$ 7.87	6.73 $\pm$ 2.69	0.643	0.028
<i>Effectiveness</i>	6.45 $\pm$ 1.96	6.65 $\pm$ 1.90	7.05 $\pm$ 2.06	0.334	0.067

Scores were rated on a 11-point Likert scale (ranging from 0 = 'Strongly disagree', to 10 = 'Strongly agree'). p -values and effect size were obtained using Kendall's W test. * indicates a significant time effect ($p < 0.05$).

4. Discussion

To our knowledge, this is the first intervention study to assess bench stepping with incremental step heights as a functional training to improve muscle volume, strength and power in older women. Our main finding is that the STEEP program improved functional performance, muscle volume and force/velocity characteristics of the knee extensors. Additionally, reported feelings related to the bench stepping exercises were very positive.

The functional improvements found in our study are in line with a study by Hallage et al. [39]. The same study reported improvements in lower body strength even though they employed bench stepping at regular heights only and did not specifically design their program to achieve strength gains, as indicated by the defined target intensity of 50-70% of the heart rate reserve rather than maintaining the threshold of 60% 1-RM [19,39]. However, they only estimated overall strength using a chair-stand test. Other functional training studies (including stair climbing) that found improvements in functional performance, and used isokinetic dynamometers to directly measure isometric and dynamic strength, did not find consistent improvements in knee extension or leg press strength [9,40]. This is likely attributable to the sub-optimal training stimulus for hypertrophy and strength gains provided by stepping at regular step heights [19]. Initially, some subjects reported light knee pain during the exercises when progressing to step heights exceeding 18 cm. This was likely attributable to altered foot progression angles indicating toe-out during step ascent, increasing the knee adduction moment [41]. This was remedied by providing instructions on correct (straight) foot placement.

Our expectation that training with step heights exceeding those regularly encountered in daily life causes improvements in muscle volume, strength and power of the knee extensors was confirmed. Muscle volume increased 2.8% in the STEEP group, comparable to improvements of 3.2% after 12 weeks of high-intensity resistance exercise (80% 1-RM) in a cohort of older men and women [37]. Although improvements in muscle volume are usually correlated with improvements in muscle strength, no causal relationship has been established in previous studies [42]. Nevertheless, improvements in muscle volume can be indicative of the number of muscle fibers in parallel and the presence of larger and more powerful type II muscle fibers [43,44], providing a buffer against further age-related decreases in strength. Increased muscle volume also acts as a buffer for increased amino acid demands imposed by injuries and disease and is inversely associated with insulin resistance [45,46].

Muscle strength is a good predictor of functional ability and falls and previous research has shown that improvements in muscle strength of the lower limbs decreases the risk of falling by improving moment generation after tripping [1,5,47]. The knee extensor muscles in particular play a crucial role during dynamic tasks such as walking, stair negotiation, rising from a chair, and balance control [48–52]. The average relative increase of muscle strength in the STEEP group (15.7% for pT_{isom120} and 9.6% for pT_{isom90}) appeared to be higher than previously reported improvements with resistance exercise (11.8% and 5.5% respectively), and showed consistent and large effect sizes (Cohen's d ; 0.92 for pT_{isom120} and 0.90 for pT_{isom90} versus very large effect size of 1.60 for pT_{isom120} and small effect size of 0.45 for pT_{isom90} found by Van Roie et al.) [37,53]. However, we have to note that

the study by Van Roie et al. included both male and female participants, which might have led to higher variability in isometric strength performance, consequently reducing the effect size.

pP, which may be an even stronger predictor of functional ability and falls than strength [54,55], was significantly improved in the STEEP group, while pV was not. This indicates that the improvements in pP are mainly attributable to improvements of the force produced, rather than the velocity attained. As with resistance exercise, the improvements of strength and power found in this study are most likely mediated by both muscular and neural adaptations [9,43,44,56]. The lack of improvement of pV is not surprising since the STEEP program did not incorporate explosive or ballistic contractions [54]. However, it is worth noting that pV was maintained in the STEEP group despite an increase of the absolute external resistance between the pre- and post-tests (applied relative external load was based on pT_{isom90} obtained during the same session). This indicates that the ability to generate force was improved without decreasing contraction speed, which is confirmed by the fact that RVD did not change in the loaded conditions. Additionally, the improvement in RVD during unloaded contractions indicates that potential improvements in RVD in the loaded conditions may have been negated by the increased absolute load during the isotonic contractions. Remarkably, the gains in power in the STEEP group were not reflected by a significant gain in CMJ height compared to the control group, even though previous research has shown a strong correlation between these outcome measures [57]. However, closer inspection of the data revealed that the STEEP group did show an average increase of 12% in CMJ height as opposed to 2.8% in the CONTROL group. The absence of statistical significance could be attributed to the presence of two outliers; one participant in the STEEP group showed a reduced CMJ height of -32.9% whereas one participant in the CONTROL group showed an increase of 41.7%. Although these relative differences were large compared to the standard deviations, we took a conservative approach by not removing them from the analyses because performance of both participants was found to be consistent within all three trials for both pre- and post-tests. However, removing the data from these subjects did result in a significant group x time interaction effect ($p=.007$), indicating a significant improvement in the STEEP group compared to the CONTROL group. The results of the CMJ may also have been affected by a difference in baseline performance between groups, which was bigger than the change score within the training group. To control for this, we performed an additional analysis of covariance (ANCOVA) on the change scores using the baseline as a covariate (data not shown) [58]. However, these analyses showed similar results to the two-way ANOVA.

Stepping in lateral direction was incorporated to improve balance performance. Previous research has shown that, given the appropriate step height, lateral stepping elicits similar EMG

amplitudes in the gluteus medius as hip abduction exercises at intensities recommended by the American College of Sports Medicine to improve muscle volume and strength [19,20], and that there is a relationship between rate of force development of gluteus medius and mediolateral stability in older adults [7]. However, in contrast with the improvements found in muscle volume, strength and power, postural sway during the balance tasks of the SPPB was not improved. This lack of improvement in balance performance is likely attributable to the fact that balance performance at baseline was already high (indicated by high SPPB scores), causing a ceiling effect. Consequently, more challenging balance tasks might be needed to reveal training-induced improvements in balance performance and fall recovery [59].

Motivation questionnaires were administered to provide an indication on the likelihood of long-term training adherence and possible motivational thresholds. The high scores on feelings related to the exercises (items 1-5 of the questionnaire) indicate that the STEEP program did not present any motivational thresholds for training participation in this cohort, which is confirmed by higher adherence compared to previous studies [60], and the low drop-out rate. Most of the participants indicated that they had never participated in resistance training and did not intend to in the future. This meant that they could not judge differences in enjoyability, intensity and effectiveness (items 6-8 of the questionnaire) based on prior experience and might have an unfounded negative predisposition towards resistance exercise. Thus, caution should be taken when interpreting the results from these items. Nevertheless, we included these items to provide some indication about the likelihood that bench stepping, even at higher step increments, would suffer from evasion rates that are comparable to those reported for machine-based resistance exercise [13]. We also need to take into account that these positive scores could be affected by self-selection and social desirability [14]. Regardless, this still provides a good indication of possible subjective thresholds. Combined with the previously reported high long-term adherence rates of group-based training [60], low costs and high accessibility of bench stepping, these results indicate a high likelihood of long-term training adherence to the STEEP program.

Finally, we have to acknowledge some limitations of this study. First, although the training-based improvements in muscle volume, strength and power found in this study appear to be considerable, it is difficult to define their clinical impact. For example, this is possible for the SPPB, because it is specifically designed as a tool to detect (risk of) disability with clearly defined cut-off points for diagnostic purposes. However, if we compare the improvements found with the expected relative losses associated with a sedentary lifestyle in older adults, 12 weeks of bench-stepping with incremental heights would compensate for an annual loss of muscle volume (1-2%) [61]. Furthermore,

the improvements in strength and power far exceed their estimated annual losses of 3% [62] and 3-4% [63] respectively.

Second, the results of this study cannot be generalized to frail older adults. Our primary aim was to investigate whether the STEEP program could be implemented as an effective prevention training program for older women who are not yet at risk. However, the significant improvements found indicate that it may be worthwhile to explore the feasibility and effectiveness of the STEEP program in frail older adults with an increased risk of falls or loss of mobility. Safely elevating the center of mass with single leg support may be challenging or unsafe for these populations. However, safety bars [16,19] and adjustments of training progression to ensure individual maximum functional capacity is not exceeded, can make bench stepping a safe and suitable exercise modality for frail older adults.

In conclusion, this study showed that bench stepping, with incremental step heights in both forward and lateral direction, improves functional performance but also increases muscle volume, strength and power of the knee extensors. By simultaneously modifying multiple risk factors for falls and functional decline, the STEEP program provides an effective, time-efficient and low-threshold exercise program for older women.

Conflict of Interest

The authors have no conflicts of interest to declare.

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Appendix A

Supplementary material: English translation of the motivation questionnaire.

Appendix A: English translation of the motivation questionnaire.

What feelings did you experience during the exercises you just performed?

Below each question you can indicate to what degree the provided statement applies to you on a scale from 0 to 10 by circling the appropriate number.

1. How enjoyable were the exercises while performing them?

10	very enjoyable
9	
8	enjoyable
7	
6	rather enjoyable
5	neutral
4	rather unenjoyable
3	
2	unenjoyable
1	
0	very unenjoyable

2. How proud are you of performing these exercises?

10	very proud
9	
8	proud
7	
6	rather proud
5	neutral
4	rather unproud
3	
2	unproud
1	
0	very unproud

3. How relieved are you that these exercises are over?

10	very relieved
9	
8	relieved
7	
6	rather relieved
5	neutral
4	rather unrelieved
3	
2	unrelieved
1	
0	very unrelieved

4. How confident are you that you will be able to perform these exercises next time?

10	very confident
9	
8	confident
7	
6	rather confident
5	neutral
4	rather unconfident
3	
2	unconfident
1	
0	very unconfident

5. How motivated are you to perform these exercises next time?

10	very motivated
9	
8	motivated
7	
6	rather motivated
5	neutral
4	rather unmotivated
3	
2	unmotivated
1	
0	very unmotivated

6. To what extent do you agree with the following statement: “Performing these exercises seems more enjoyable than strength training with resistance training devices.”

10	totally agree
9	
8	agree
7	
6	somewhat agree
5	neutral
4	somewhat disagree
3	
2	disagree
1	
0	totally disagree

- 7. To what extent do you agree with the following statement: “Performing these exercises seems less physically straining than strength training with resistance training devices.”**

10	totally agree
9	
8	agree
7	
6	somewhat agree
5	neutral
4	somewhat disagree
3	
2	disagree
1	
0	totally disagree

- 8. To what extent do you agree with the following statement: “Performing these exercises seems more effective to improve strength than strength training with resistance training devices.”**

10	totally agree
9	
8	agree
7	
6	somewhat agree
5	neutral
4	somewhat disagree
3	
2	disagree
1	
0	totally disagree

Section 2.3. Neuro-motor strategies for step ascent in older women

Paper 4: Age-related differences in muscle synergy organization during step ascent across step heights and directions

Submitted as:

Remco J. Baggen, Jaap H. Van Dieën, Evelien Van Roie, Sabine M. Verschueren, Georgios Giarmatzis, Christophe Delecluse, Nadia Dominici. Age-related differences in muscle synergy organization during step ascent across step heights and directions. *In preparation*.

Abstract

Purpose: Older adults modulate their motor strategies to enable them to operate within their maximum capacity when ascending steps. This study used muscle synergy analysis to explore age-related differences in dynamic motor control when ascending steps of different heights.

Methods: Fifteen older women ($67.0y \pm 2.5$) and ten young women ($22.5y \pm 1.6$) performed stepping in forward and lateral directions at step heights of 10, 20 and 30 cm. Surface electromyography (EMG) was obtained from 10 lower limb and torso muscles. Non-negative matrix factorization was used to identify sets of (n) synergies and variance accounted for (VAF) by the detected number of synergies was compared to assess complexity of motor control. Correlation coefficients between muscle weightings and variability of the temporal activation patterns were calculated to compare synergy structures.

Results: Four synergies accounted for >85% VAF across age groups and stepping conditions. Two-way ANOVA (age x step height) of VAF obtained from $n = 4$ synergies revealed that step height and age significantly decreased VAF, indicating increased synergy complexity during forward stepping but not lateral stepping. No age x step height interaction effects were found for either stepping direction. Higher hamstring co-contraction was found in older women compared to young during forward stepping. For lateral stepping, young women showed lower similarity of synergy weightings between step heights compared to older women.

Conclusions: Motor control of young and community-dwelling older women could not be differentiated based on the number of synergies extracted. However, additional analyses of synergy complexity, such as VAF by the given number of synergies, and synergy structure revealed age- and step-height related differences. These results show that synergy analyses of more challenging functional tasks such as step ascent with increased height can detect subtle differences in muscle synergy organization and recruitment patterns between age groups.

Introduction

Previous studies have found that low-dimensional sets of motor modules, also known as muscle synergies, can be used to reconstruct muscle activation responses during various motor tasks [1–4]. These synergies are composed of groups of muscles that are assumed to be activated by a single neural command [5]. It is thought that the central nervous system employs this modular organization to reduce the large number of degrees of freedom inherent to the redundancy of the human musculoskeletal system [6] and to allow for flexible but accurate response selection during motor tasks [7]. However, some researchers have argued that modular recruitment of muscles, rather than reflecting neural control strategies employed by the central nervous system, could merely be an effect of task constraints or optimized performance criteria [5]. Regardless of the mechanisms underlying modular organization of muscle activation, extracting muscle synergies from electromyographic (EMG) signals can provide important insights about motor ability and employed motor strategies to perform functional tasks [8]. Additionally, by reducing large and often highly variable EMG datasets, muscle synergy analysis can improve clinical usefulness [8] and allow for direct biofeedback for rehabilitation and prevention training purposes [9].

Muscle synergy analysis has frequently been used to explore neuromuscular changes in pathologies that affect mobility such as stroke and cerebral palsy [10,11]. However, few studies have investigated the effects of more subtle age-related changes on synergy recruitment [12]. Although the age-related deterioration of muscle mass and strength, also known as sarcopenia [13], occurs gradually, the related neuro-muscular changes can have a major impact on fall risk, mobility and independence in older adults [14–16]. Older women are particularly at risk for falls and fall-related injuries such as hip fractures [17,18]. Therefore, it is imperative to find sensitive tools to detect early onset neuro-muscular deterioration in older adults. However, in community-dwelling older adults, pre-clinical changes in neuro-motor control may go undetected when performing everyday tasks [12]. Higher intensity dynamic tasks could reveal age-related changes in synergy recruitment that would not be detectable otherwise. For example, previous studies exploring age-related differences during gait found that walking with at a higher than preferred cadence revealed small differences of synergy recruitment in older but not in young adults [19,20]. Furthermore, Routson et al. showed alterations in temporal activation patterns of healthy adults in response to increased challenges during gait such as changes in speed, cadence, step length, and step height [21]. Functional exercises such as bench-stepping with increased step height have been shown to elicit higher muscular activation and improve functional ability in older women [22,23]. However, the neuromechanics behind stepping performance

and the impact of normal aging on muscle synergy recruitment during step ascent have not yet been thoroughly explored.

In a previous study, we found that peak activation of several major lower limb muscles occurred during the ascent phase of stepping and that there is a positive dose-response relationship between step height and peak muscle activation. However, the increase in peak activation was accompanied by increased between-subject variance [22]. The congruent increase in between-subject variance could be attributable to a tendency of older adults to modulate their motor strategies, in order to operate within their maximum capacity when ascending steps [24,25]. Other age-related changes such as increased antagonist co-contraction are thought to help maintain postural control during dynamic tasks [26–29]. Muscle synergy analysis can potentially provide a useful way to assess if, and how, older adults modulate motor strategies depending on different challenges imposed during bench-stepping such as increased step height and different step directions. For example, based on a previous study including older adults with and without a history of falls [12], major age-related changes in neuro-motor control could be indicated by a decreased number of extracted synergies. In pre-clinical older adults, these changes might be more subtle, requiring additional analyses of neuro-motor control complexity (indicated by decreased variance accounted for given a fixed number of synergies [10]) and synergy organization.

The purpose of this study was to analyze muscle synergy recruitment during step ascent in forward and lateral directions and with incremental step heights, to provide information on complexity of neuro-motor control. We hypothesized that less synergies would be needed to accurately describe muscle activation in older women compared to young and that, for a given number of synergies, variance accounted for would be lower in older compared to young women. Finally, we hypothesized that synergy organization would be altered, and that synergy recruitment patterns would be more variable in older compared to young women.

Methods

Participants

Eleven older women ($67.0 \text{ y} \pm 2.5$) and ten young women ($22.5 \text{ y} \pm 1.6$) were recruited for this study. Potential participants were excluded if they suffered from neurological or motor disorders, impaired balance control or if they had been involved in a structured training program in the last 6 months prior to participation in the study. All participants signed informed consent prior to

participation in the study. This study was approved by the Human Ethics Committee of KU Leuven in accordance with the Declaration of Helsinki.

Experimental protocol

Participants performed a series of stepping tasks consisting of three repetitions of stepping onto, and over a wooden block in forward direction (Fstep) and stepping onto, and off a wooden block in lateral direction (Lstep). Task intensity was determined by the height of the block (10, 20 and 30 cm) [22]. Every repetition was performed with the dominant leg first. Left-right dominance was determined during familiarization by noting with which foot participants preferred to take the first step. As a control question, participants were asked with which foot they would prefer to kick a ball [30]. Step ascent in both forward and lateral directions was assessed because it requires simultaneous coordination of the hip, knee and ankle musculature and shows close functional resemblance to stair-climbing [30], which is an activity of daily life associated with high fall risk in older adults [31]. The speed of task execution was controlled by a metronome at 1 second for ascent, 1 second mid-stance and 1 second descent to avoid differences in muscle activation due to explosive movements.

Kinematics

Kinematics were recorded using 3D motion capturing (Vicon®, Oxford Metrics, Oxford, UK). Reflective markers were placed on the heels and the sacrum. Only data from the ascent phase were used for analysis. Based on the kinematic data, the start of the ascent phase was defined at 200 ms prior to initial vertical displacement of the heel marker beyond 2x the standard deviation obtained during normal stance. The end of the ascent phase was defined at 500 ms after maximum knee extension, defined as the maximum relative distance between heel and sacrum.

Electromyography recording

Muscular activation was collected unilaterally from ten lower limb and trunk muscles on the dominant side using surface electromyography (EMG) (Aurion®, ZeroWire, Milan, IT) sampled at 1000 samples/s. EMG was recorded from the tibialis anterior (TA), the lateral head of the gastrocnemius (GL), soleus (SOL), vastus lateralis (VL), rectus femoris (RF), biceps femoris (BF), semitendinosus (ST), gluteus maximus (GMAX), gluteus medius (GMED) and the erector spinae (ERS). The skin was shaved and thoroughly rubbed with an alcohol swab to ensure optimal conductivity. Bi-polar Ag/Ag-Cl electrodes (Ambu® BlueSensor P, Ballerup, DK) were then placed on the belly of the muscles with an

inter-electrode distance of 25 mm. Kinematics were recorded with a 3D motion capturing system (10-15 MX camera system, Vicon®, Oxford Metrics, Oxford, UK) sampled at 100 samples/s.

Synergy extraction and data analyses

All EMG and kinematic data were processed using custom MATLAB scripts (MATLAB R2014b, MathWorks®, Natick, USA). The EMG signals were high-pass filtered with a 1st order Butterworth filter with a cut-off at 20Hz, full-wave rectified and smoothed with a 0.1-s moving average window [22,32]. EMG signals from Fstep and Lstep were normalized to the respective maximum activation obtained over all trials performed in the congruent direction so that activation could not exceed 100% [9,11]. The EMG signals were time-synchronized with the kinematically defined start and end points and subsequently normalized over time to define 0-100% of the step cycle. Finally, EMG signals for individual subjects were averaged over the three trials performed in each condition.

Muscle synergies were extracted from the individual EMG data matrix using non-negative matrix factorization (NNMF). NNMF calculates muscle synergies (W) and their relative temporal activation patterns (C), resulting in muscle activations being represented as $W \times C + e$. W represents the relative weight of each muscle per synergy and is constructed as an $m \times n$ matrix where m is the total number of muscles and n is the selected number of synergies. C represents the temporal activation patterns and is constructed as an $n \times t$ matrix where t represents the number of data points over normalized time (100 per individual trial) and e is the residual error matrix [33,34]. The algorithm was repeated 1000 times for each subject to avoid local minima. The appropriate number of synergies for the group-averaged EMG was defined using two criteria. First, using an iterative process where the number of synergies varied between 1 and 10, the minimum number of synergies was selected based on the number required to reach $\geq 85\%$ of variance accounted for (VAF). As an additional criterion, adding a synergy could not add more than 6% to the VAF [3,35]. VAF was defined as the uncentered Pearson correlation coefficient between $W \times C$ and the EMG amplitude time series. Individual synergies obtained from different subjects were pooled and matched based on the correlation of their structure (muscle weightings in each synergy of W) using a cluster analysis algorithm [36]. If a synergy showed equal correlation to more clusters, that synergy remained in the pool it was initially assigned to. Each synergy of W and C was subsequently averaged over all participants in that age group. For comparisons between age groups, the group-averaged synergies were also matched based in their structure using cluster analysis. To assess if age or step height affected motor strategy modulation between groups,

we computed the inter-synergy activation pattern variability, with a fixed number ($n=4$) synergies as the average standard deviation of the synergy activation patterns.

Statistical analyses

Statistical analysis was performed with SPSS (IBM® SPSS v23 Statistics for Windows, Armonk, USA). Two-way repeated measures ANOVA (age x synergy number) for VAF was used to assess the interaction effect of age and selected number (n) synergies on VAF [11]. In addition, two-way repeated measures ANOVA (age x step height) was used to assess the interaction effect of age and step height on synergy complexity, which was defined as VAF obtained with n synergies [10] fixed to four. Sphericity was checked using Mauchly's test for sphericity. Post-hoc tests for age were performed accordingly using independent samples t-tests and using related-samples t-tests for step height and synergy number. α was set to 0.05 for all statistical tests.

Similarity of muscle synergies (based on muscle weightings, W) was quantified based on Pearson's correlation coefficients where $r > 0.7$ represented significant similarity and $r > 0.45$ represented marginal similarity [3,37]. Correlated synergies within age group between step heights, and between age groups for each step height, were considered to be shared synergies, while non-correlated synergies were considered task-specific or age-related synergies [37]. Differences in muscle contributions to each synergy (W) between age groups were checked using Mann-Whitney U tests.

Results

Kinematic data from the heel and pelvic markers showed high similarity ($r > 0.9$) in averaged vertical displacement over time between young and older women for all step heights. An example of the averaged vertical displacement patterns and standard deviations at 30 cm step height is provided in Figure 1.

Two-way ANOVA (age x synergy number) for VAF revealed significant main effects of synergy number for all step directions and heights ($p < 0.001$), but no interaction effects with age ($p \geq 0.05$). A significant main effect of age ($p = 0.028$) was detected only for lateral stepping at 30cm. For the group-averaged data, four muscle synergies were required to achieve a threshold level of 85% VAF from reconstructed signals across both age groups, step directions and step heights (Figure 2). The addition of a fifth synergy did not result in $> 6\%$ VAF in any of these conditions. Four synergies accounted for 91.5%, 89.6% and 89.5% of variance during Fstep in young women and 88.5%, 87.3% and 87.4% in older women for step heights of 10, 20 and 30 cm respectively. VAF by four synergies during Lstep was

89.6%, 88.6% and 89.3% in young women and 88.2%, 88.0% and 86.7% in older women for step heights of 10, 20 and 30 cm respectively. Two-way ANOVA (age x step height) on VAF obtained from $n = 4$ synergies revealed a significant main effect of step height in forward direction ($p = 0.002$), but not in lateral direction ($p = 0.187$). No significant age x step height interaction effect was found for either step direction ($p > 0.05$). A significant age effect was found for forward stepping ($p = 0.026$) but not for lateral stepping ($p = 0.138$). Additional post-hoc tests for forward stepping revealed a significant difference between step heights of 10 cm versus 20 and 30 cm ($p = 0.009$ and 0.014 respectively) but not between 20 and 30 cm ($p > 0.05$).

Comparisons between muscle weightings (Table 1, Figures 3 and 4) showed that synergy 2 and 4 had high inter-step height similarity for both age groups and step directions. Synergy 4 also appeared to be highly similar between age groups. In synergy 2, a shift in quadriceps/hamstring co-activation appeared to be the main contributor to reduced similarity between age groups. This shift was characterized by significantly decreased quadriceps contribution for most stepping conditions in older women, whereas contribution of the hamstrings was significantly increased. Composition of synergy 3 appeared to be the most variable. Whereas Fstep showed more correlated synergy organization within and between age groups, Lstep resulted in lower correlations between step heights for the young group when compared to the older group. Analyses of the temporal activation patterns associated with the extracted muscle weightings (Figures 3 and 4) and the average standard deviation of these temporal activation patterns (Figure 5) showed that the variability of activation during Fstep was higher and increased more strongly with step height for the older women compared to young. Similar results were found for synergy 2 and 4 during Lstep. However, in the young group, variability of the temporal activation patterns from synergies 1 and 3 increased significantly between step heights of 20 and 30 cm.

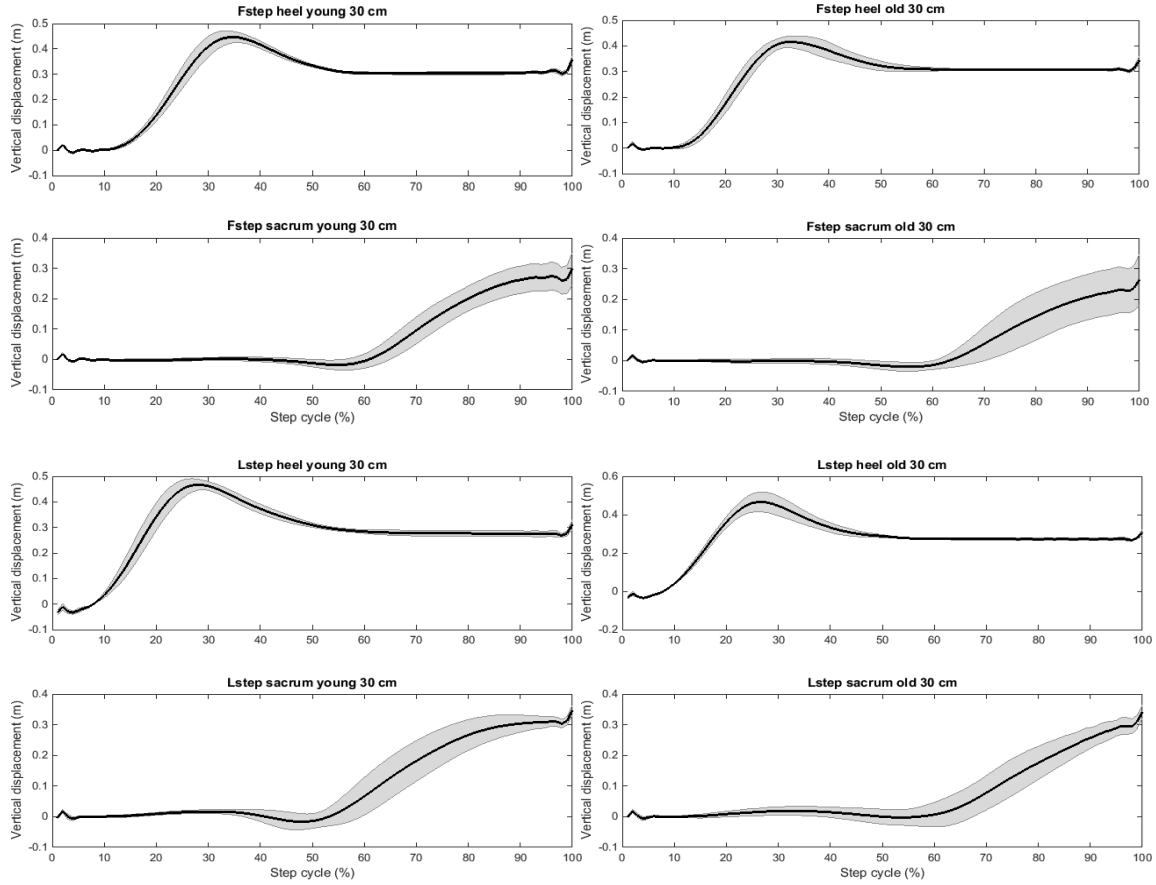


Figure 1: Averaged vertical displacement of the heel and sacrum in young (left column) and older women (right column) at 30 cm step height in forward direction (Fstep) and lateral direction (Lstep).

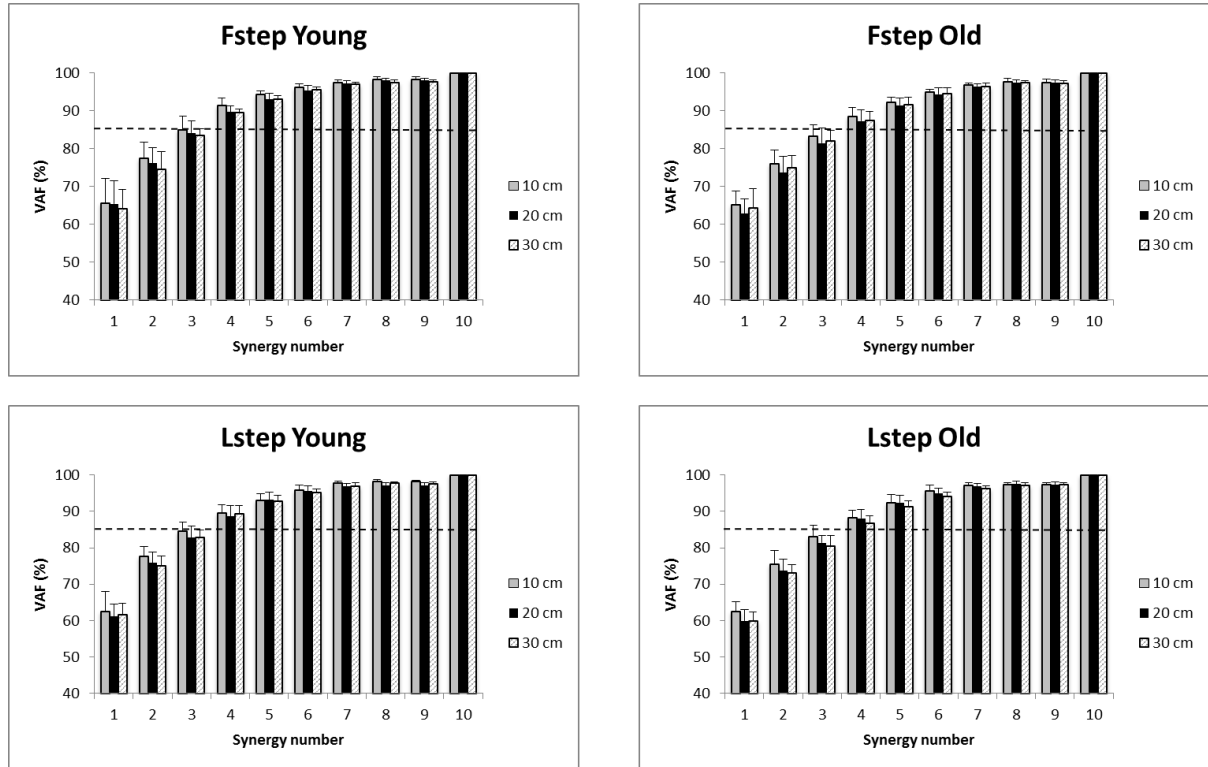


Figure 2: Averaged variance accounted for (VAF) by number of extracted synergies at step heights of 10, 20 and 30 cm in forward (Fstep) and lateral (Lstep) stepping directions for young and older women. The appropriate number of synergies was defined as the least number of synergies required to reach >85% VAF (indicated by dashed lines), and where addition of a synergy did not increase VAF >6%.

Table 1: Similarity index (Pearson's r) of synergy weightings, across step heights for each age group and across age groups for each step height. Results are displayed separately for forward stepping (Fstep) and lateral stepping (Lstep). * = marginal similarity ($r > 0.45$), and ** = significant similarity ($r > 0.7$).

	Young women			Older women			Young vs. Older women		
	10 cm	20 cm	10 cm	10 cm	20 cm	10 cm			
	vs.	vs.	vs.	vs.	vs.	vs.			
	20 cm	30 cm	30 cm	20 cm	30 cm	30 cm	10 cm	20 cm	30 cm
Fstep Correlation coefficients (r)									
Synergy 1	0.64*	0.56*	0.87**	0.84**	0.76**	0.88**	0.61*	0.02	0.69*
Synergy 2	0.95**	0.96**	0.87**	0.88**	0.84**	0.83**	0.59*	0.76**	0.73**
Synergy 3	0.44	0.70*	0.89**	0.74**	0.43	0.85**	0.88**	0.71**	0.85**
Synergy 4	0.96**	0.95**	0.89**	0.91**	0.78**	0.86**	0.89**	0.85**	0.74**
Lstep Correlation coefficients (r)									
Synergy 1	0.94**	0.48*	0.38	0.56*	0.95**	0.54*	0.48*	0.67*	0.03
Synergy 2	0.61*	0.90**	0.40	0.83**	0.91**	0.95**	0.19	0.51*	0.79**
Synergy 3	0.90**	0.43	0.15	0.88**	0.94**	0.71**	0.90**	0.82**	0.29
Synergy 4	0.70*	0.66*	0.95**	0.76**	0.64*	0.80**	0.90**	0.75**	0.76**

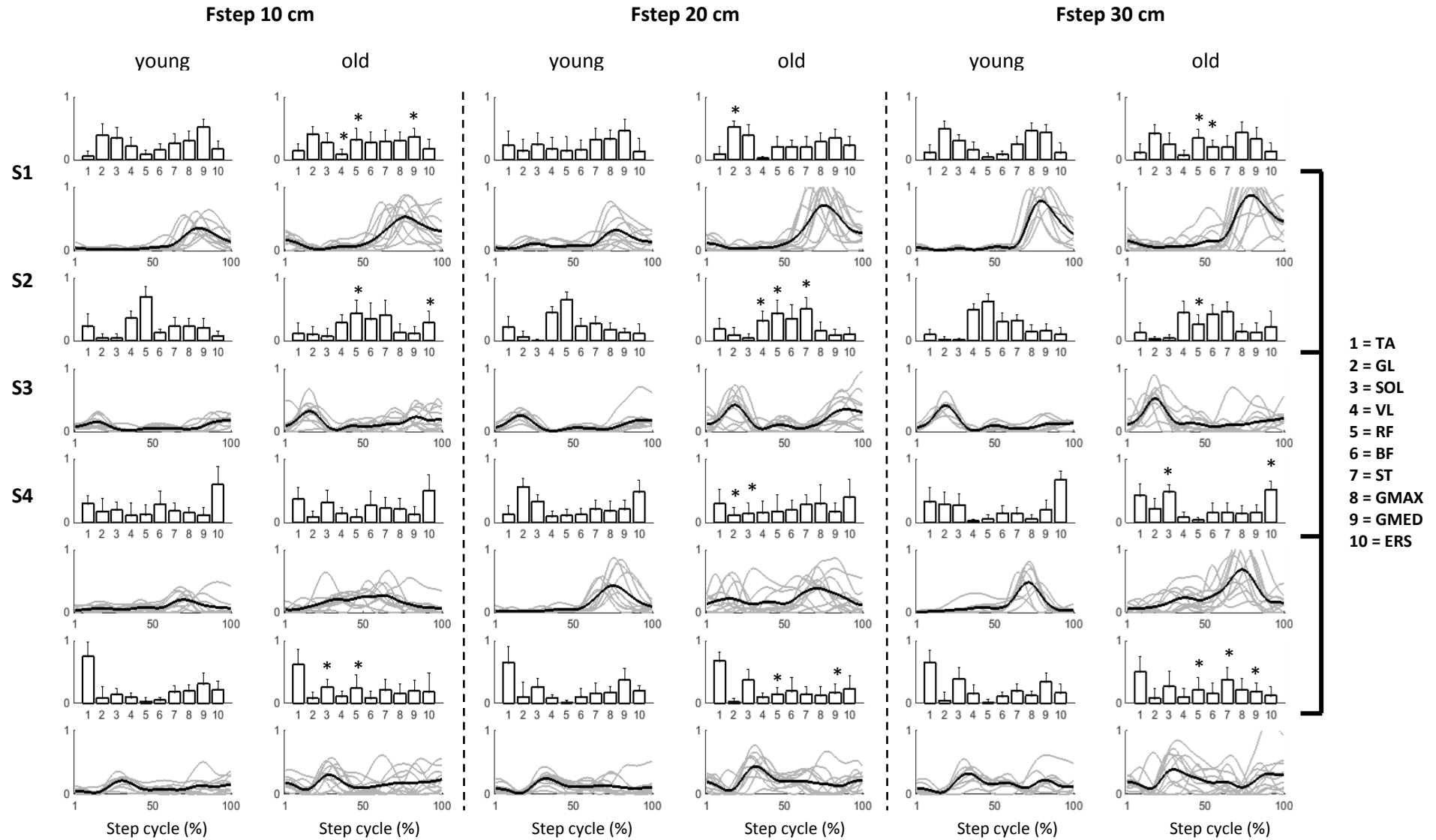


Figure 3: Muscle weightings and temporal activation patterns per synergy (fixed n synergies = 4) extracted during forward stepping (Fstep). Each set of two columns represents muscle synergies extracted from step heights of 10, 20 or 30 cm per age group with young women represented in the left column and older women in the right column. * indicates a significant difference between contributions of individual muscles between age groups.

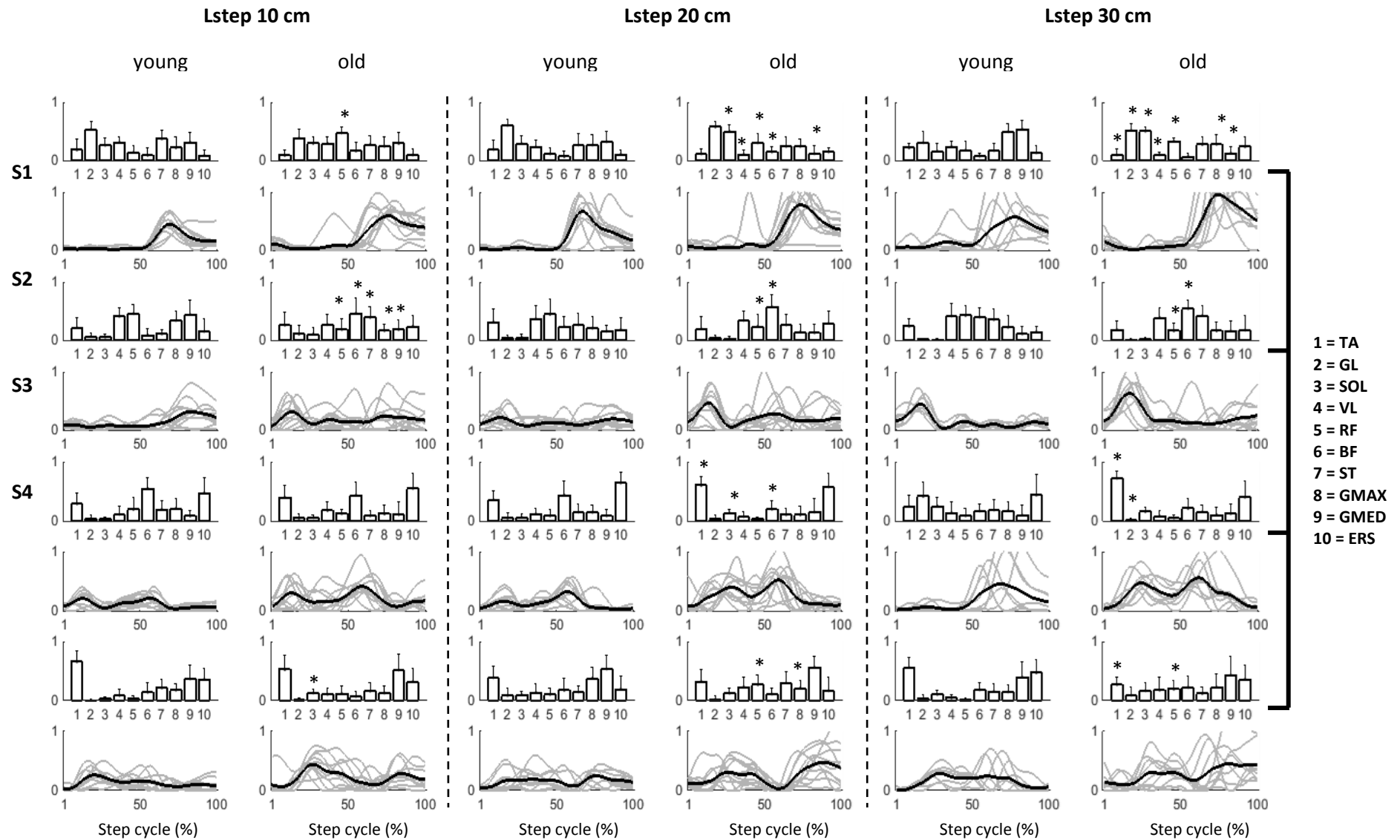


Figure 4: Muscle weightings and temporal activation patterns per synergy (n synergies = 4) extracted during lateral stepping (Lstep). Each set of two columns represents muscle synergies extracted from step heights of 10, 20 or 30 cm per age group with young women represented in the left column and older women in the right column. * indicates a significant difference between contributions of individual muscles between age groups.

Section 2.3. Neuro-motor strategies for step ascent in older women

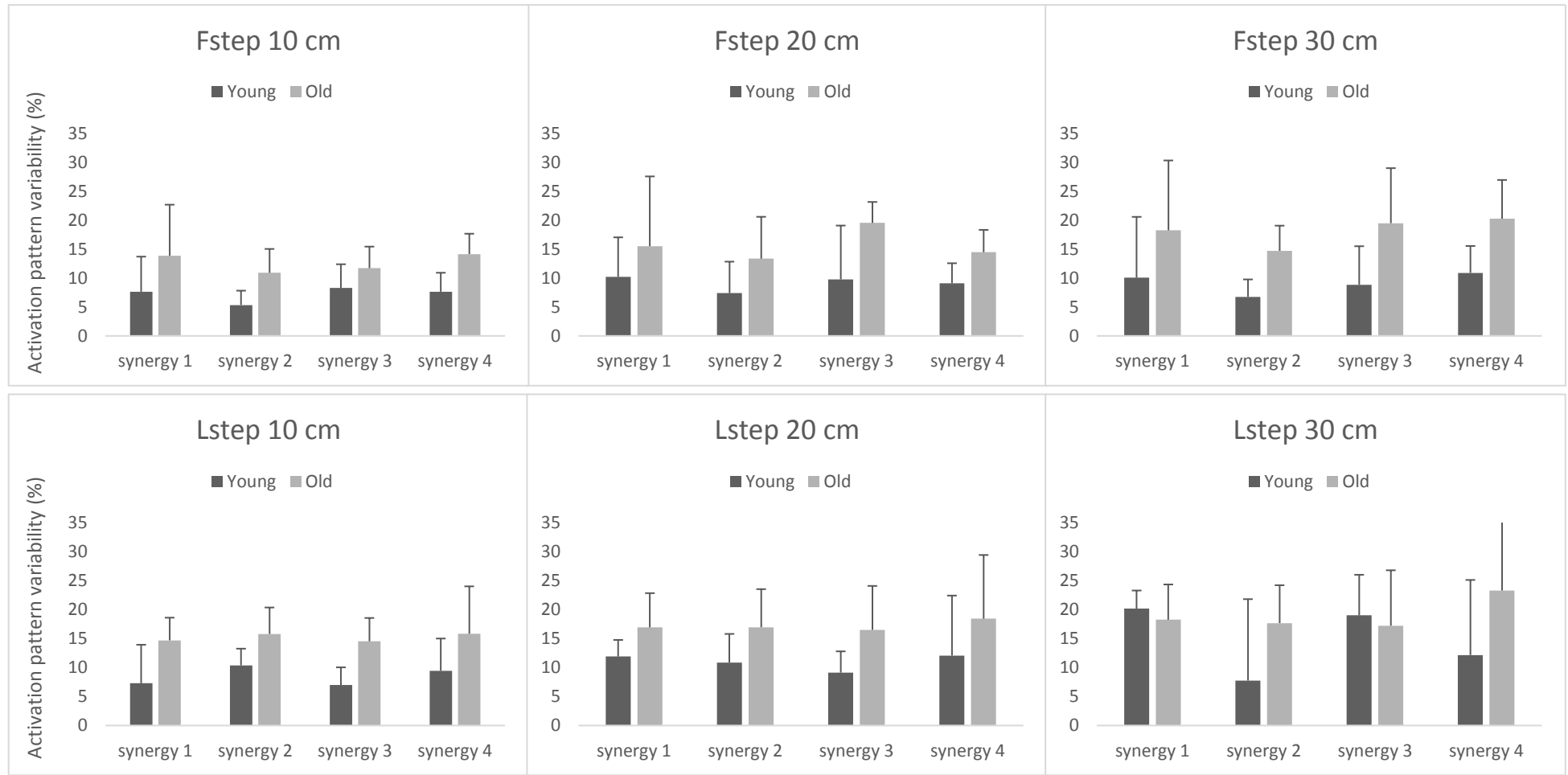


Figure 5: Average standard deviation (SD) of temporal activation patterns between subjects (n synergies = 4). Data is displayed separately for forward (Fstep) and lateral (Lstep) step directions with step heights of 10, 20 and 30 cm.

Discussion

The purpose of this study was to compare motor strategies of young and older women during step ascent by examining muscle synergy organization during stepping tasks with incremental step heights in both forward and lateral directions.

Our results show that synergy recruitment is robust across step heights and age groups for stepping in forward and lateral directions. Contrary to our hypothesis, we found no differences in the number of synergies between age groups and step heights for either age group. However, further analyses of VAF by four synergies revealed step height-dependent differences in dynamic motor control required during forward stepping. Although no overall age x step height interaction effect on VAF was found, additional post-hoc analyses indicated more complex motor strategies exhibited by older women during Fstep, indicated by lower VAF [10], for Fstep. Additionally, Fstep heights of 20 and 30 cm appear to have a significantly lower VAF compared to 10 cm but no difference was observed between 20 and 30 cm heights. Synergy structure (e.g. muscle weightings) for Fstep appeared to be similar between step heights for both age groups, whereas higher variability was found for young women versus older women for Lstep. This might reflect that older women have a more limited pool of muscle synergies (or smaller motor repertoire) to recruit from during less commonly performed movements [12]. Finally, temporal activation patterns were more variable in older compared to young women. This may reflect a relative increase in functional demand imposed by step heights of 20 – 30 cm in older compared to young adults, which requires them to adapt synergy timing [21].

The extraction of four synergies from stair ascent is in agreement with previous studies of locomotion in healthy adults that included a maximum of ten lower limb muscles. Oliveira et al. proposed that the addition of EMG measurements from hip extensors and abductors would likely increase dimensionality [9]. However, our data shows that this is not necessarily true for step ascent. For example, during Fstep gluteus maximus and medius activation coincided with plantar flexor and rectus femoris activation. During Lstep, gluteus medius and erector spinae (which are also not commonly included in synergy analyses) activation appeared to coincide mainly with tibialis anterior activation during lift-off of the trailing foot and trunk stabilization prior to the double support phase after ascent. Although not the primary focus of this study, the differences in synergy organization between Fstep and Lstep are in line with a study by Cook et al. who found that EMG recruitment patterns are task-specific for Lstep and Fstep [38].

There is an ongoing discussion if observed muscle synergies are a result of neural control or a combination of optimization and task constraints [5]. However, a change in the number, structure and recruitment of muscle synergies may allow for discrimination of a variety of pathological changes [8]. In fact, most research examining the effects of neuro-muscular pathologies on synergy organization show reduced synergy number, altered composition and recruitment [39]. However, few studies have investigated the effects of more subtle age-related changes on synergy recruitment [12]. Nevertheless, age-related neurological deterioration might result in pre-clinical deficits in physical performance, which may go undetected during performance of everyday tasks, but may be apparent in more demanding tasks. For example, older adults appear to adopt different stepping strategies compared to young adults, which is likely due to decreased functional capacity [27,40]. This appears to be supported by our data, which show a trend towards increased contribution of the hamstrings and decreased contribution of the quadriceps in synergy 2, indicating an increase in quadriceps/hamstring co-activation for both step directions in older compared to young women. These findings are in line with findings from previous studies that have shown elevated muscle co-activation in older adults during ADL's such as stair climbing and single step descent [41–43], which directly affects muscle synergy organization [19]. Even in healthy subjects the number and structure of muscle synergies have been associated with different motor skill levels [8]. Similarly, our data show that increasing the step height from 20 to 30 cm was associated with an increased contribution of the gluteus medius and maximus to synergy 1 and of the calf muscles to synergy 3 in young women, while the synergy structure of the remaining synergies remained similar. These changes indicate that some synergies reflect basic motor patterns which are activated during a variety of tasks, whereas other synergies can be flexibly recruited to match task-specific demands [3,37], such as those imposed by increased step heights. This is reflected by kinematic analyses of motor strategies for stair negotiation, showing both common and variable patterns, with highest variability often seen at the hip joint [44]. Indeed, our analyses of variability in temporal activation patterns indicate both fixed and variable synergies across step heights, which is evident from the changes in variability of synergies 1 and 3 between step heights of 20 and 30 cm in lateral direction.

Ultimately, muscle synergy analysis was able to detect age- and step height-related differences in healthy adults. However, the fact that the number of extracted synergies over all step heights and between age groups remained equal indicates that the differences found were only subtle. This could be attributable to the relatively healthy cohort of older adults recruited for this study. For example, a previous study by Allen and Franz found that older adults with a history of falls, but without

neurological disorders, did present decreased muscle synergy complexity compared to non-fallers during a perturbation task [12]. Therefore, it might be worthwhile to explore if a more accessible task, such as step ascent with increased height, would be able to distinguish between older fallers and non-fallers in future studies.

Limitations

Some limitations of this study have to be recognized. EMG was only collected from the dominant leg. For this reason differences in motor strategies involving additional push-off force of the trailing leg could not be analyzed [7].

Additionally, the number of trials used for analyses in this study, as well as the fact that trials were averaged, rather than analyzed individually or concatenated, could have affected the number of extracted synergies. For example, Oliveira et al. found that muscle weighting from low numbers of step cycles can result in poor reconstruction quality. Additionally, they found that the way trials are analyzed does not produce major impact on the number of synergies extracted but that averaging or concatenating smaller datasets can also decrease reconstruction quality, with slightly lower accuracy for concatenated signals compared to averaged signals (Oliveira, 2014). Because we aimed to compare synergies on a group level, and in view of the sample size, we chose to average signals rather than concatenating them in order to obtain the best reconstruction quality,

Conclusions

Motor control of young and community-dwelling older women could not be differentiated based on the number of synergies. However, additional analyses of synergy complexity, such as VAF by the given number of synergies, and synergy structure revealed age- and step-height related differences. These results show that synergy analyses of more challenging functional tasks such as step ascent with increased height can detect subtle differences in muscle synergy organization and recruitment patterns between age groups. However, further prospective studies should be conducted to assess if synergy analysis of muscle activation during step ascent with increased step heights can be used as a tool to detect pre-clinical older adults who present increased risk of functional disability and falls.

Conflict of interest statement

The authors declare to have no conflict of interest.

Acknowledgements

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Chapter 3

SUMMARY AND GENERAL DISCUSSION

There were three main aims of this doctoral thesis. First, we explored the potential of bench stepping exercises to achieve sufficient muscle recruitment for improvements in muscle mass and strength, using electromyography (EMG) (**Study 2**), and addressed related methodological choices for signal normalization in older women (**Study 1**). Second, based on these findings, we designed and tested an exercise intervention utilizing bench stepping with incremental step heights to improve muscle volume, strength and functional ability in older women (**Study 3**). Finally, we assessed whether muscle synergy analysis could identify age-related differences in motor strategies of young and older women during step ascent at various step heights and in forward and lateral directions (**Study 4**).

The following sections will summarize the main findings and specific discussion of the four research papers, followed by a general discussion and conclusion.

3.1. Summary of findings

3.1.1. Section 2.1.: Electromyography as a tool to assess training potential for muscle mass and strength during weight bearing exercise

Study 1: In this study, we investigated whether differences in maximum voluntary excitation between isometric and dynamic contractions are age-dependent and how differences in excitation would affect between-subject variability and the amount of normalized signals exceeding 100%. Age-related changes in skin impedance, thickness of subcutaneous fat layers, reduced number of motor units and increased irregularity of motor unit firing rates have been shown to decrease maximum (detectable) muscle excitation [1,2]. Therefore, signal normalization is particularly important for comparisons of EMGs between age groups. In addition, dynamic contractions generally elicit higher excitation compared to isometric contractions [3,4]. Despite the fact that it is more difficult for older adults to perform maximum voluntary contractions [5–7], the possible interaction effect between age and contraction type on maximum voluntary excitation has never been explored. The presence of such an interaction effect could have important implications for comparisons of normalized signals between age groups, affecting between-subject variance and estimation of relative muscle contribution to dynamic task performance. The results from this study showed that there was a significant age x contraction type interaction effect for vastus lateralis and that (sub-)maximum dynamic contractions elicited higher excitation than maximum isometric contractions in young women, whereas no differences were found between contraction types in older women. A possible explanation for these differences is the fact that higher activation obtained from dynamic compared to isometric

contractions can be attributed to higher motor unit firing rates in younger adults [8]. It is likely that older adults have difficulty achieving their maximum motor unit firing rates. Consequently, the age-related decline in motor unit firing rates [9,10] has a larger impact on differences in excitation obtained from dynamic contractions compared to isometric contractions. Both contraction types appeared to underestimate 'true' maximum excitation in older women. However, the generally lower between-subject variance and lower number of signals exceeding 100% indicated normalization to dynamic contractions as the most favorable method overall. Therefore, we chose to use dynamic normalization for all EMG-based analyses included in this thesis.

Study 2: The main aim of this paper was to compare the potential training effects of bench-stepping exercise versus resistance exercise at 60% 1-RM on muscle mass and strength in older women. Previous studies have found that exercise-based improvements appear to be highly task-specific in older adults [11,12]. While traditional resistance exercise is effective in improving muscle mass and strength, exercise with high task-specificity towards activities of daily life is more effective at improving functional ability in older adults [11]. To achieve the best possible effects, exercise programs for older adults should target improvements in both strength and functional ability [13]. Therefore, we examined several task-specific weight bearing exercises with potential to improve muscle mass and strength as well. In a pilot study conducted prior to this study, bench-stepping was found to be the most feasible weight-bearing exercise for older women (discussed in section 3.1.1.). A previous study by Hallage et al. demonstrated that bench-stepping exercise can improve functional performance in community-dwelling older women, however they did not measure improvements of muscle mass and strength directly [14]. We aimed to evaluate the added potential of bench-stepping to improve muscle mass and strength by comparing peak muscle activation between bench-stepping at several step heights and directions versus resistance exercises at 60% 1-RM, which is the threshold for hypertrophy and strength gains set by the American College of Sports Medicine [15]. Our findings show that, for most of the major leg muscles, bench-stepping was able to elicit peak activation comparable to, or higher than, resistance exercise at 60% 1-RM. The step height and direction required to achieve this level of activation varied per muscle but overall, 20-30 cm step heights were required. For the gluteus medius, which is an important muscle for medio-lateral stability [16], only the combination of lateral stepping at a step height of 30 cm was able to elicit sufficient activation. The added training potential associated with increased step heights is in line with findings by Mair et al., who found that an increase in step height from 20 to 25 cm resulted in greater peak force and peak power during the ascent phase of the repeated stepping task in both young and older women [17]. This indicates that bench-stepping exercise can potentially improve muscle mass and strength of most major leg muscles if adequate step heights and directions are incorporated. To ensure adequate

training responses and progression, step heights should exceed those encountered in daily life (~18-22 cm). The need to provide an additional training stimulus during task-specific exercises is in line with a study by Andersen et al., who found that conventional therapeutic exercises do not elicit activation above 40-60% 1-RM and thus have less potential to induce hypertrophy and strength gains [18].

3.1.2. Section 2.2.: Bench-stepping exercise as a way to improve muscle mass, strength and functional ability in older women

Study 3: The purpose of Study 3 was to determine whether a task-specific training program, based on the findings from Study 2, could simultaneously improve muscle volume, strength, power and functional performance in community-dwelling older women. Specifically, the three main aspects from Study 2 that were incorporated were 1) the use of bench-step heights that exceed those encountered in daily life (~18-22 cm) to elicit sufficient muscular activation for hypertrophy and strength gains, 2) the use of incremental step heights in order to provide an additional and progressive training stimulus, and 3) incorporating stepping in both forward and lateral directions to elicit sufficient activation of all major upper leg muscles including the hip abductors, which play an important role in medio-lateral stability. To isolate the training effects obtained from increased step heights and confirm that increased step heights can provide a meaningful training stimulus, training intensity and progression during the 12 week exercise program (dubbed the STEEP program) was determined solely by step height. Training volume and speed remained equal. To account for differences in individual baseline physical ability and to assure similar progression among participants, three entry levels were defined and subjects were assigned to the appropriate entry level based on their performance during the first two weeks of training. The main findings from this study show that the STEEP program significantly improved muscle volume, strength, power and functional ability in older women. By simultaneously targeting functional ability and force/velocity characteristics of the muscles, the STEEP program provides a time-efficient and accessible option for prevention training in older women. These findings support the use of bench-stepping with incremental heights over other task-specific exercises such as stair-climbing, rising from a chair, carrying objects and game-base step training, for which previous studies did not find consistent improvements in muscle mass and strength [11,19,20]. The improvements in muscle volume and isometric strength from the STEEP program were comparable with improvements found in a study by Van Roie et al. after 12 weeks of resistance exercise in older men and women [21]. Relative improvements in strength even exceeded the relative increases in muscle volume. This indicates that muscle strength is not solely determined by muscle volume through increased type II fiber content and/or number of sarcomeres in parallel [22,23]. In addition to possible effects of altered muscle architecture (e.g. pennation angle), neurological changes such as increased

neural drive, which is often associated with short-term training improvements [24], and reduced variability of motor unit firing rates likely play an important role in improving strength [11,22].

In addition, we aimed to assess whether the STEEP program would potentially suffer less from evasion and limited adherence than resistance exercise in older adults [25]. Motivational thresholds and likelihood of long-term adherence were assessed using motivation questionnaires at the start, middle and end of the STEEP program. The outcomes indicated that the STEEP program has a low motivational threshold and that motivation showed a positive trend with time. However, it is important to note that, although motivation can be a strong indicator, it does not guarantee high training adherence. For example, in a follow-up study to their resistance training intervention Van Roie et al. found that long-term adherence to resistance exercise was low in older adults, despite high self-reported motivation [26]. Nevertheless, the high self-reported motivation and adherence to the STEEP program, accessible nature of bench-stepping and high adherence rates to other group-based training programs [27] combined with the functional and physical improvements, suggest that bench-stepping with incremental step heights may be an effective and feasible exercise for prevention training in older women.

3.1.3. Section 2.3.: Neuro-motor strategies for step ascent in older women

Study 4: The main aim of Study 4 was to assess if muscle synergy analysis could identify age-related differences in motor strategies during step ascent at different step heights and in forward and lateral directions. Previous studies have shown that neuro-muscular pathologies can result in a reduced number of synergies and altered synergy organization [28,29]. Age-related neurological changes are more subtle and gradual in nature and often go undetected. Nevertheless, several studies have shown that older adults modulate their motor strategies in order to perform more challenging tasks despite decreases of their functional limits [30,31]. Our results showed no age-related changes with increasing step heights in number of muscle synergies. However, we did find subtle age- and step height-dependent differences in the variance accounted for by the same number of synergies. Furthermore, there was evidence that aging causes a redistribution of synergy organization (e.g. muscle weightings) and temporal activation patterns. These results indicate that synergy analysis during tasks that require older adults to operate closer to their functional limits, such as step ascent with increased heights, might be able to detect early-onset age-related changes. However, additional research is needed to assess if it can distinguish between older adults that have an increased risk of disability and those that do not.

3.2. General discussion

3.2.1. Bench-stepping as a suitable weight-bearing exercise for older women

Several weight bearing exercises were tested prior to the selection of bench stepping for comparison with resistance exercise in **Study 2**. In addition to bench-stepping, these exercises included squats, hopping and fast walking exercises [32]. There were several reasons why bench-stepping was selected as a potential task-specific exercise to improve muscle volume and strength in older women. First, bench-stepping appeared easy to perform with little to no instructions. This is likely attributable to the high degree of functional similarity to activities of daily life, such as stair ascent [33,34]. In a previous study conducted in young and older women, Mair et al. showed that muscle activation patterns during bench-stepping closely resemble stair walking [17]. This is in contrast with squats, which appeared to be harder to execute in a coordinated manner, leading to loss of balance, and were often accompanied by unfavorable kinematic events such as a high degree of valgus alignment, due to weakness of the hip musculature [35]. Hopping exercises were avoided in view of high hip contact forces, which could increase injury risk [32] and put unnecessarily high load on the cartilage [36,37]. Finally, bench-stepping exercise at a moderate pace was preferred over fast walking exercises because of the lower cardio-vascular demand indicated by participants during the pilot phase, likely making bench-stepping more accessible to previously sedentary older adults.

Previous studies investigating the effects of bench-stepping exercise and stair climbing exercise have consistently found improved functional ability in older adults [11,14,19]. However, only a few intervention studies have investigated the effects of bench-stepping exercise and stair climbing on muscle mass, strength or power in older adults. Furthermore, the few available longitudinal studies employed widely varying training programs, either employing weighted vests [11,38,39], different step heights and/or step rates [13,14,19,40]. Therefore, it is not surprising that the results on muscle mass, strength and power across these studies were inconsistent. For example, Kraemer et al. found that bench-stepping resulted in limited improvements of strength and power characteristics, but not in muscle mass, and attributed these improvements to increased stretch-shortening cycle overloading associated with plyometric movements such as increased step heights [13]. Donath et al. also acknowledged the potential benefits of training with increased step heights and compared strength gains between groups training at different step heights (1-step vs. 2-step approach), but did not find significant improvements for either group [19]. These inconsistent findings and differences to results reported in this thesis might be attributable to the fact that stepping exercise is traditionally used as an aerobic training modality and therefore not optimized to improve muscle mass, strength or power, which is illustrated by the use of heart rate monitoring, rather than relative muscle loading to

determine training intensity. Comparisons of muscle activation with resistance exercise at recommended loads for hypertrophy and strength gains in Study 2 provided a way to assess relative muscle loading and indicated the importance of appropriate step height and direction to achieve muscle activation to a level associated with hypertrophy and strength gains. However, the results from Study 2 did not provide any information about the required number of repetitions per session to achieve meaningful training effects, nor about feasibility and safety of bench-stepping exercise involving incremental step heights and forward and lateral stepping directions. These issues were addressed in the design of Study 3. First, the number of repetitions for hypertrophy and strength gains needed to be assessed. In order to achieve the greatest muscular gains, exercise should be performed to momentary muscle fatigue (or momentary concentric muscle failure) [15,21,41]. This could not be assessed during Study 2 as the effects of fatigue on the EMG amplitude and power spectrum (which will be discussed in section 3.2.5. of this general discussion) would have interfered with the comparisons between different exercise types. Fortunately, the previous comparison between bench-stepping and resistance exercise at 60% 1-RM also provided a reference for the number of repetitions required to achieve momentary muscle fatigue in older adults [42,43]. Second, a small pilot study with several potential participants revealed that the exercise program was quite feasible if the initial height of the stepping bench was tailored to the individual physical ability (described as the ability to complete all repetitions at the preset pace for different step heights). This was confirmed by the results of Study 3, with only one drop-out and 100% compliance of the remaining participants to their individual progression programs. The final consideration was safety. In contrast with walking, where there is only a limited single support phase, both bench-stepping and stair ascent involve a pull-up phase where support is shifted from the trailing leg to the leading leg before the bodyweight can be elevated. This poses a significant challenge to balance control, especially in medio-lateral direction [44], and increases the risk of an exercise related fall. Despite this increased challenge to balance control, no falling incidents or injuries occurred during Study 3. In fact, previous research has shown that healthy older women can perform bench-stepping up to 47 cm high without using external support [39]. However, for future studies involving participants with impaired balance control or proprioception, the addition of a hand rail can be considered to improve safety. Additionally, previous research has shown that bench stepping only produces low to moderate skeletal loading [17]. Nevertheless, we need to take into consideration that the increased knee flexion angles associated with incremental step heights could pose a risk due to increased loading at the knee joint. Indeed, some participants in Study 3 reported slight knee pain after they progressed to higher steps. However, this appeared to be a result of altered foot progression angles during step ascent, causing non-uniform knee loading through

increased knee adduction moments [45] and no more pain was reported after they were given instruction on correct (straight) foot placement.

It is important to note that the training intervention in Study 3 involved stepping at a slower pace than some previous studies in order to make it more suitable for participants with minor cardiac and respiratory problems. By omitting exercises that involve continuous fast or explosive contractions (e.g. counter-movement jumps, fast walking and running), we reduced potential training-based improvements in explosive force production (power) and rate of force and velocity development. Power and rate of force development are particularly important for functional performance and fall prevention (e.g. after a perturbation) [46–51] and may be stronger indicators for physical disability than strength [52]. Nevertheless, the results from **Study 3** show that bench-stepping with incremental step heights did improve power and unloaded rate of velocity development by the knee extensors in older women. Another advantage of bench-stepping was that stepping in a lateral direction could be easily incorporated to provide an additional training stimulus targeted at the hip abductors, which play an important role during static and dynamic balance [53–55].

3.2.2. Functional importance of individual lower limb muscles

As discussed in the previous section, different step heights and directions can elicit different activation of individual lower limb muscles. However, before we can understand the implications of these findings we need to understand the functional importance of the lower limb muscles involved. For example, the ankle musculature plays a crucial role in static balance control (ankle strategy) [56] and during push-off [57]. However, this thesis focusses primarily on the role of the upper leg muscles during common dynamic tasks such as step and stair ascent [58]. These include the quadriceps femoris, which are the primary force producers responsible for knee extension during the lifting (or pull-up) phase of step ascent and control the speed of step descent [58], the hamstrings, which play an important role for knee joint stabilization and compensate for greater hip flexion in older adults [31], the gluteus maximus, which is the main hip extender during ascent [58] and the gluteus medius, which is the primary hip abductor and responsible for medio-lateral balance control during static and dynamic tasks [53,59]. As mentioned in the general introduction, older adults operate closer to their maximum physical capacity when performing activities of daily life such as stair negotiation [30,31]. This also means that their functional reserve needed to compensate for unexpected perturbations is limited [50,60]. Consequently, improvements in strength of the muscles that produce moment around the knee and hip joints can lead to increased physical capacity and decreased fall risk. Study 2 shows that a minimal step height of 20 cm in forward direction was required to activate most of these muscles to a level associated with hypertrophy and strength gains. However, this was not the case for the

gluteus medius, which required a minimum step height of 30 cm in lateral direction to elicit sufficient activation. This is in line with previous findings by Stemmons-Mercer et al. who showed greater activation of the quadriceps and gluteus medius during lateral compared to forward stepping [61]. This is likely because, unlike the other upper leg muscles mentioned above, the primary role of the gluteus medius as a hip abductor is medio-lateral balance control and stepping in lateral direction challenges medio-lateral stability [44,53,59]. For this reason, stepping in both forward and lateral direction was incorporated in the training program of Study 3. However, as mentioned in the discussion of Study 3, no improvements in balance performance were detected. This is likely attributable to the relatively easy static balance tasks included in the SPPB causing a ceiling effect that, even with the use of accelerometers, limited our ability to detect subtle changes in balance performance in our relatively healthy cohort.

3.2.3. Individual differences in training-based adaptations of muscle characteristics

Study 3 revealed significant improvements in muscle volume, strength and power of the knee extensor muscles after 12 weeks of bench-stepping with incremental step heights. Muscle volume in the training group improved by an average of 2.72% opposed to an average decrease of -0.97% in the control group, while isometric peak torque at 90° and peak power at a resistance of 20% peak torque improved by 9.6% and 11.2% respectively. However, we cannot ignore the fact that some participants in the intervention group showed little to no hypertrophic response or increase in strength/power. At first glance response was good, with 18 of the 23 participants in the STEEP group showing increases in muscle volume and peak power at a resistance of 20% peak torque, while 19 showed improvements in isometric peak torque at a knee angle of 90°. However, to reliably distinguish responders from non-responders, the ability of the methodology employed to detect changes in muscle volume, strength and power needs to be taken into account. We opted to use CT-scans, rather than MRI-scans to measure muscle volume because the scanning procedure is less intimidating for participants and data processing is less time-consuming. We obtained four 5 mm axial slices from the thigh at the midpoint between the medial edge of the trochanter and the intercondyloid fossa of the femur, and combined these into one 20 mm segment, as a reference for muscle volume pre- and post-intervention. Although this is a commonly used approach to assess muscle volume on older adults [21,62], some caution is advised when interpreting these results, as hypertrophy can be non-uniformly distributed within the muscle and between different agonistic muscles, such as the individual muscles of the quadriceps femoris [63]. One way to reliably distinguish responders from non-responders is by first establishing the minimal detectable change, which is defined as the smallest change that cannot be attributed to the measurement error of the instrument or method used. The minimal detectable change is calculated as the mean difference of test-retest data $\pm 1.96 \times$ the standard deviation. Unfortunately,

due to practical and time constraints, we did not collect test-retest data for the methods included in **Study 3**. However, earlier research using similar methodology found that the minimal detectable change in muscle volume should be higher than 3.86% [62]. For **Study 3**, the measurement error was likely lower as we used the newest CT-scanner available at the university hospital (Somatom Force®, Siemens Medical Solutions, Erlangen, DE), with updated software that allowed for more accurate distinctions between muscle and surrounding tissues, automatic detection of femur length, anatomical midpoint of the femur, and delineation of individual slices, thus eliminating human processing errors. In addition, the new scanner provided the ability to obtain thicker axial slices (4 x 5 mm vs. 10 x 1 mm used by Van Roie et al. [62]). By computerizing delineation and increasing slice thickness overlap between obtained slices could be optimized, which increases test-retest reliability. However, in absence of our own test-retest data we maintained the threshold of 3.86%, which indicated that at least 12 out of 23 participants of the intervention group showed a hypertrophic response. To measure strength and power of the knee extensors we used an isokinetic dynamometer. Minimal detectable change was determined based on a previous study which found a standard error of measurement of 5.7% for isometric peak torque (at 90° knee flexion) and 6% for peak power (at 25% isometric peak torque) [64]). Based on these numbers, we found at least 14 and 13 responders out of 23 participants respectively. No differences in baseline parameters were found between responders and non-responders for any of these outcome parameters ($p > 0.05$). Therefore, we have to assume that the answer to the question why people respond differently to training most likely lies in factors that we did account for in Study 3, such as genetic predisposition and dietary habits [65–67].

3.2.4. Intrinsic and extrinsic factors for training participation in older adults

Knowledge about the training potential of different exercise modalities is an integral part of designing training programs to prevent sarcopenia. However, the potential of individual exercises to elicit physiological improvements is still only part of the puzzle when designing optimized training programs. Exercises with the best possible physiological outcomes can still have limited impact on the prevention of sarcopenia in larger populations, if training initiation and adherence are low. A good example of this is resistance exercise. Resistance exercise has been widely accepted to be a safe and effective way to prevent sarcopenia and improve muscle mass and strength in older adults [66,68]. Nevertheless, initiation rates and adherence of resistance exercise are generally low [25,26]. Motivation and self-efficacy are intrinsic factors that can play an important role in training initiation and adherence in older adults [69]. However, surprisingly little research has been done to compare motivation and self-efficacy between different exercise types. By administering customized motivation questionnaires, we tried to provide some insight into perceived and motivational differences between bench-stepping and resistance exercise in order to assess the likelihood of long-term training

adherence to the STEEP program. Despite the fact that most of the participants in **Study 3** had no prior experience with resistance exercise and could therefore not objectively judge differences in exercise intensity, enjoyability and effectiveness, their subjective responses indicated that bench-stepping, even at higher step increments, was perceived to be more feasible, enjoyable and effective than machine-based resistance exercise. The fact that feelings towards bench-stepping exercise were positive with high scores on item 4, regarding confidence of the participant to be able to complete the next training session, provided a positive indication for self-efficacy and good long-term adherence. However, caution should be taken when associating high motivation with long-term adherence, as a study by Van Roie et al. showed that, despite high self-determined motivation, long-term training adherence was still limited in older adults [26]. Other intrinsic and extrinsic factors, such as lack of time, accessibility, cost of training and social interaction may also play a vital role [26,27,70,71]. Bench-stepping scores well on these factors. It requires limited training time (3 x 40 minutes per week for the STEEP program), is accessible, fairly easy and safe to perform, only requires a stepping bench or any other stable elevated platform, and can be performed in group-based settings [27,71]. The possibility to perform exercise in a group-based setting appears to be a particularly good indicator for long-term adherence. In a systemic review, Farrance, Tsofliou and Clark found that group-based exercise programs have high long-term adherence rates (~70%), which they associated with six themes; social connectedness, perceived benefits, program design, empowering or energizing effects, instructor and individual behavior [27].

Finally, although factors like the possibility for group-based training favor bench-stepping exercise, it is important to point out that, because long-term adherence was not monitored post-intervention and no resistance training group was included for comparison in **Study 3**, no definitive statements can be made with regard to differences in training initiation and long-term adherence based on our results.

3.2.5. EMG as a tool to assess training potential of multi-joint exercises

In **Study 2** the choice to use EMG to determine training potential, rather than inverse dynamics, was based on several considerations. First, inverse dynamics allow for calculation of the net output of all muscles that exert force around the individual joints. However, inverse dynamics does not provide any information about loading of individual muscles involved, due to the mechanical indeterminacy of muscle-joint-systems (i.e. more muscles than kinematic degrees of freedom)[72]. A possible solution to this problem is to estimate individual muscle forces with kinematic modeling using optimization (e.g. minimizing the sum of muscle activations squared [73]). However, objective functions are generic and do not account for individual differences in muscle activation patterns [74].

In addition, inverse dynamics does not account for possible age-related changes in motor recruitment strategies that may increase relative loading (and therefore training potential) of agonists during dynamic contractions. One example is the increased coactivation of antagonist muscles, which decreases net moments, while increasing relative work load of the agonist muscles [17,52,75]. Alternatively, individual muscle loading can be estimated using an EMG-driven musculoskeletal model. The advantage of this approach is that the individual activation patterns are accounted for [74]. When configured appropriately, an EMG-driven model can provide detailed information about individual muscle loading throughout the range of motion and during various tasks. However, for the purpose of this thesis, detailed information about muscle loading at different joint angle was not required. Instead, the maximal activation obtained from the required task, relative to the 'true' maximum obtained during a voluntary maximum contraction was considered sufficient to assess the training potential per individual muscle.

The assumption that the potential of a multi-joint exercise to improve strength can be inferred by knowing the relative activation of the individual muscles involved has been made in previous studies [76,77]. However, it is worth mentioning that the inference of training potential in these studies, as well as ours, was based on EMG signals obtained from a small number of contractions, thus eliminating the potential effects of fatigue. As mentioned in the introduction of this thesis, recent research suggests that high-intensity exercises are not essential to improve neuro-muscular adaptations as long as the training volume is sufficient to achieve maximal effort (momentary muscle failure) and recruit the entire motor unit pool [26,78]. This is reflected by increasing EMG activation with continuous contractions, ultimately leading to recruitment of larger type II muscle fibers, in accordance with Henneman's size principle [79,80]. Based on the concept of gradually increasing recruitment of larger motor units with fatigue, it could be possible to use an EMG-based index to predict the number of repetitions required to achieve momentary muscle failure [81,82]. However, fatigue affects the EMG frequency and amplitude in various ways and is likely mediated by muscle fiber type content and/or area [83,84]. There is a general consensus that fatigue-related decreases in the EMG frequency are primarily related to decreased propagation velocity. However spectral characteristics can change regardless of decreased propagation velocity [84]. Furthermore, although EMG amplitude most likely increases with fatigue due to increased and more synchronized motor unit firing rates, current evidence on this relationship is conflicting [7,82–84]. In light of these issues with EMG-based indexing of fatigue, Study 2 only estimated the effectiveness of bench-stepping exercise in a non-fatigued state.

We also need to take into account that, to derive useful information about task intensity from EMG, reliable assumptions about the EMG-force relationship are required for each individual muscle [85]. Currently, evidence regarding the shape of this relationship is limited and often conflicting, which

is not surprising given the inherent limitations to surface EMG recording such as cross-talk from adjacent muscles, variations in electrode location on the skin relative to the muscle, and the effects of synergistic and antagonistic co-contractions on force output [86]. Some studies show a non-linear relationship, with EMG amplitude increasing either faster at higher forces or more commonly, less fast at higher forces due to phase cancellation [87], while others show a linear relationship [86]. Differences in the shape of this relationship have even been reported in different muscles of the quadriceps femoris (e.g. non-linear for vastus medialis and rectus femoris and linear for the vastus lateralis) [3]. Pincivero et al. found that, during an isometric contraction at low to moderate intensity, the vastus lateralis is recruited to a larger extent than the vastus medialis and rectus femoris, while activation of the vastus medialis only becomes equivalent to activation of the other quadriceps muscles during near-maximum voluntary contractions [88]. Differences in activation between muscles during dynamic tasks could be related to the number of joints over which each muscle exerts its force. For example, the rectus femoris exerts its force over both the hip and knee joint, while the vastii exert their force only over the knee joint. However, the assumption that single- and multi-joint exercises would therefore show non-uniform activation has not been confirmed [3]. These different findings may be attributable to the different contraction modes (e.g. isometric vs. dynamic) involved. A study by Luera et al. found a highly linear relationship for the mono-articulate vastus lateralis and a somewhat less distinct linear relationship for the bi-articulate rectus and biceps femoris during dynamic contractions [89]. These findings were in line with results from a pilot study that we conducted in young adults to explore the EMG/load relationship during unilateral seated knee extensions and hip abductions. The results from this second pilot study showed a fairly linear relationship for both mono-articular muscles (vastus lateralis and gluteus medius) and the bi-articular muscle (rectus femoris) (Figure 4). These findings indicate that the relative intensity of a task can be estimated using peak EMG.

A final consideration when using EMG to assess the training potential of dynamic tasks is the effect of muscle length on EMG amplitude, which is caused by changes in detection volume and relative position of the muscle to the electrodes [90,91]. Although this certainly plays a major role in EMG-based force estimations, an overview of EMG-based studies by Burden found that the majority of research that compared EMG signals from maximum contractions at different joint angles reported little effect on maximal EMG [4]. However, a study by Watanabe et al. did report non-uniform neural activation of the rectus femoris across different knee and hip joint angles. Although increased knee angles only decreased activation in the distal parts of the muscle, different knee joint angles were shown to affect activation during hip flexion [92]. This may indicate that muscle length primarily affects EMG amplitudes in relatively long bi-articular muscles where the number of motor units in the detection volume and relative muscle position can be more variable. This issue could be addressed

using angle-specific normalization. However, this approach is rarely used because it is time consuming and could cause fatigue due to the large number of contractions required [93] and was therefore not applied in our studies.

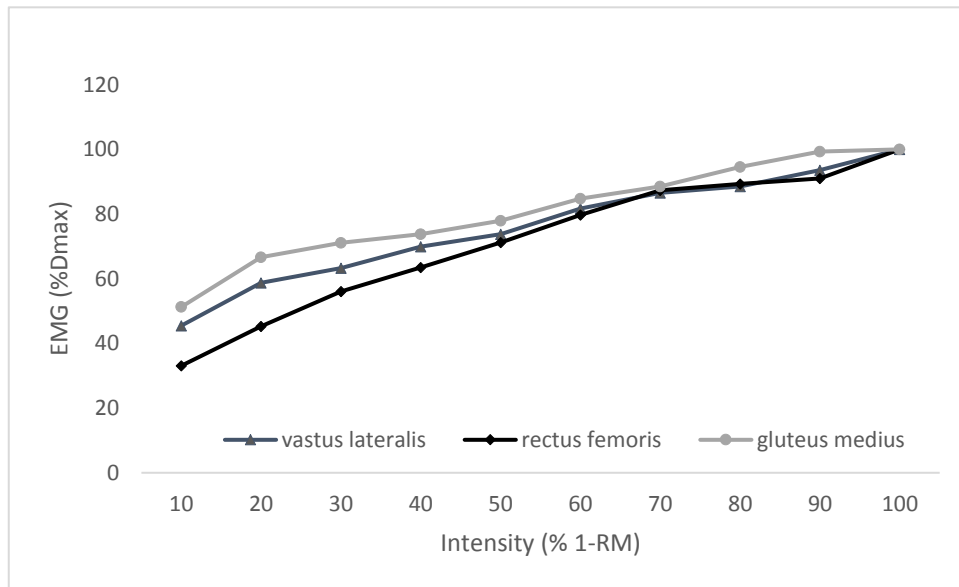


Figure 1: EMG/load relationship of the vastus lateralis and rectus femoris during knee extension and gluteus medius during hip abduction obtained during our pilot study (unpublished data). EMG is normalized to the dynamically obtained

3.2.6. Practical implications for muscle synergy analysis

The main conclusion from **Studies 2 and 3** is that bench-stepping exercises with incremental step heights in both forward and lateral direction are required to elicit sufficient muscular activation in most upper leg muscles to improve muscle mass and strength in older women. By incorporating these findings into the design of a training program aimed at preventing sarcopenia and functional declines, we were able to simultaneously improve muscle volume, force/velocity characteristics and functional performance in community-dwelling older women. However, the age-related neurological changes underlying bench-stepping performance should not be overlooked. Previous research has shown that older adults modulate motor strategy selection, not only to overcome reduced functional capacity, but also to compensate for other factors such as decreased balance performance [9,30,31,94,95]. Assessment of motor strategy selection during more challenging tasks such as step ascent might provide a way to reveal subtle age-related differences that could be precursors of functional deterioration [96–98], and thus be useful for targeting prevention training programs at subjects at risk. In **Study 4**, we discussed the potential of muscle synergy analysis to differentiate age-

related changes in motor strategies. Although the idea of modular organization of muscle activation is certainly not new [99], the last fifteen years have provided evidence of modular organization in a wide range of studies [100]. The potential for muscle synergy analysis has primarily been explored in pathologies that afflict locomotion (e.g. cerebral palsy, stroke survivors and spinal cord injuries) [29,101,102], development of locomotion in children [103], and during a variety of balance and locomotor tasks [104–106]. However, only a few studies have examined the effects of age on muscle synergy number, organization and recruitment [94,96,97]. Although the number, organization and temporal structure of recruited synergies can be subject specific, common synergies can usually be detected across subjects and motor tasks [105,107,108]. By pooling the number and (temporal) organization of extracted synergies by age group and analyzing the differences, we found that synergy organization and recruitment patterns, rather than synergy number, during step ascent could be indicative of age-related changes (e.g. increased antagonist co-contraction or additional agonistic muscle recruitment to enable task performance within (reduced) limits of physical capacity). By assessing muscle synergies during more challenging dynamic tasks, such as bench-stepping with step heights exceeding those encountered in daily life, we could potentially detect early-onset deterioration of functional ability [96] and more effectively target prevention programs by targeting individuals most at risk of developing functional disability. There are currently two major caveats to the application of muscle synergy analysis in clinical practice, being the complexity of synergy analyses, making them hard to interpret, and the wide variety of methodological choices and their implication for detection of synergy numbers, organization and recruitment [100].

3.2.7. Limitations

Some limitations of this PhD project have to be pointed out. First, the studies in this project specifically targeted older women because this group is most at risk for sarcopenia and its consequences [66,109]. Previous research comparing resistance exercise-based improvements between older men and women has shown equal improvements in muscle mass, strength and sit-to-stand time [110], indicating similar levels of muscle plasticity and hypertrophic response. However, additional RCTs should be conducted to assess whether this is the case for bench-stepping with incremental step heights.

Second, improvements in muscle mass and strength of the knee extensors were assessed specifically due to their major contribution to moment generation during the pull-up phase of stair ascent [58]. Knee extensor strength is a good predictors for stair negotiation performance [111]. The lateral stepping component of the STEEP program allowed us to target the hip abductors as well. However, for practical reasons, strength and power of the hip abductors were not assessed in **Study**

3. Although the results from **Study 2** indicated that the gluteus medius could be sufficiently recruited by incorporating lateral stepping at 30 cm, we could not confirm whether the STEEP program improved strength or power of the hip abductors. Additionally, no information is available about the duration of the training-based improvements found in Study 3, because we did not perform a follow-up study to investigate detraining effects due to time constraints.

Third, the primary focus of this PhD project was to improve muscle characteristics, functional ability and to reduce fall risk. However, it is important to note that we only measured improvements of important fall predictors and falling incidents or fall risk were not measured directly. Although we aimed to include mostly sedentary women by excluding those that were already participating in structured exercise programs, their functional ability (indicated by the outcomes of the Short Physical Performance Battery scores in **Study 3**) was fairly high, making it unlikely that they were already at high risk for falling. An effort was made to assess medio-lateral and overall balance control using accelerometry, but no significant improvements were found. This may be attributable to a ceiling effect in balance performance, which could have been addressed by incorporating more challenging balance tasks [112].

Fourth, the studies included in this thesis focus primarily on the effects of functional exercise on muscle characteristics. However, it is important to note that other factors such as nutritional status, medical interventions (e.g. hormone replacement therapy) and genetic predisposition can all have a significant influence on training-based improvements [65–67]. Participants in **Study 3** were instructed not to change their dietary habits and required written consent from their physician with a statement that they did not present any contra-indications for participation in long-term physical exercise and strength testing. Nevertheless, we cannot completely rule out possible interaction effects because we did not track participant dietary habits and medication.

Finally, the absence of a resistance training group in **Study 3** meant that we could only speculate on the potential advantages of bench-stepping exercise over resistance exercise on physical, functional and motivational levels. Despite the fact that there are clear advantages and disadvantages of both exercise types, we cannot presume to make any definitive statements comparing these exercise types, based on our data. Furthermore, the absence of a training group receiving regular bench-stepping exercise meant that we could also not definitively state that bench-stepping exercise with incremental step heights would provide a better training stimulus over bench-stepping exercise at regular heights. Nevertheless, the results of Study 2 and other studies investigating force production during step ascent with increased heights [17] make it reasonable to assume that the STEEP program provides an increased training stimulus for strength gains.

3.2.8. Future directions

The aim of this project was to find an effective training program to prevent sarcopenia and its negative effects on functional performance and in older women. Although the STEEP program resulted in significant improvements in muscle mass, strength and functional performance, no improvements were found for static balance performance. This could be attributable to a lack of sensitivity of the balance tests included in the SPPB. Alternatively, more challenging and dynamic balance tasks such as those included in the Community Balance and Mobility scale may allow for detection of subtle training-based improvements in (young-)older adults [113]. For subjects who already display increased fall risk, future studies could incorporate elements from these balance assessment tools, such as single leg stance and turning motions, into the bench-stepping exercises to simulate the effects of catching a toe and other perturbations during stair ascent.

Although age-related muscle wasting and dynapenia can likely be attenuated by a variety of interventions such as drugs and hormone therapy, the evidence supporting their effectiveness is often conflicting. In contrast, an appropriate diet and exercise appear to be the most effective way to preserve muscle mass, strength and power [114]. When considering different exercise types, the STEEP program appears to be an accessible, well perceived and effective approach for older women. The high accessibility and relatively low perceived physical demand indicate that it would be worthwhile to first explore whether the STEEP program is feasible for community-dwelling older adults with increased fall risk (e.g. clinically diagnosed sarcopenia) and residents of long-term care facilities. Following such a feasibility study, longitudinal RCTs should investigate the effects of bench-stepping with incremental step heights on lower limb muscle characteristics and functional performance compared to commonly employed strength exercise and standard care.

Another future challenge lies in detection of early-onset changes in functional ability. Our results show that muscle synergy analysis is able to detect subtle age-related changes in muscle synergy organization and recruitment patterns. Despite current challenges in methodological standardization, some researchers have even proposed that future applications of muscle synergy analyses could include its use by trainers and physical therapists as a metric to determine whether subjects benefit from a certain type of intervention [29,100], and as a means to effectively adjust functional training interventions (such as the STEEP program) by targeting specific muscle synergy structures or recruitment patterns [100,115].

3.3. General conclusion

The prevention of sarcopenia and its debilitating consequences poses an important and complex challenge in our aging society. Physical exercise has been established as the most effective way to combat the progression of sarcopenia. Despite the facts that muscle plasticity is well maintained with age [109,116,117] and lower limb strength is an important factor for fall prevention in older adults [57], exercise-induced improvements in older adults appear to be highly task-specific [11,12]. However, the majority of studies aimed at improving muscle characteristics in older adults have focused on some form of resistance exercise with limited functional resemblance to activities of daily life such as stair negotiation. In fact, only a few studies have investigated the effects of bench-stepping or stair-based exercises on muscle mass, strength and power in older adults. This is most likely caused by a historical dichotomy between resistance exercise and functional (usually referred to as aerobic) exercise as training modalities. However, several fairly recent studies have signified a shift in this paradigm [41,118]. The results presented in this thesis provide additional evidence that we need to rethink this dichotomous approach towards resistance and functional exercise. With some adaptations to increase muscle recruitment, functional exercises, such as bench-stepping, can become suitable training modalities to improve muscle mass, strength and power and can induce transfer effects on performance of other tasks of daily life such as sit-to-stand transitions. By using EMG to assess muscle recruitment during functionally different exercises, their potential to improve muscle mass and strength could be assessed. Bench-stepping exercise with step heights exceeding those encountered in daily life was found to elicit sufficient muscle recruitment to improve muscle mass and strength for several major leg muscles in older women. Additionally, stepping in a lateral direction was required to recruit the gluteus medius to the same extent. Finally, motivation and training adherence add an extra dimension to the challenge of designing optimal training programs for older adults. Based on these results, we were able to design a task-specific training program, which simultaneously improved muscle mass, force/velocity characteristics and functional performance. We have shown that older women have a positive perception towards bench-stepping exercise which, combined with high accessibility, indicates it to be a promising exercise modality to improve muscle characteristics and functional ability for this population. In addition, by assessing the modular organization of muscular activation during more challenging motor tasks, such as bench-stepping at step heights exceeding those encountered in activities of daily life, we can provide insights into age-related changes in motor strategies.

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APPENDICES

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Personal contribution

The author of this manuscript was responsible for the data collection, data analyses and interpretation, and writing of all chapters included in this PhD thesis.

Conflict of interest statement

The authors confirm that there are no conflicts of interest to declare. The funding agencies were not involved in the design or data analyses of the studies included in this thesis

Appositions

The idea that older adults should not, and will not, participate in high intensity exercise is a form of ageism that is detrimental to devising effective training programs.

Designing effective training programs is not only about optimizing physical outcomes, but also about providing a positive exercise experience. Without this, training initiation and adherence will always be limited.

Global overpopulation is one of the most pressing issues of the modern age. However, in order to find pragmatic and sustainable solutions, politicians and scientists must first overcome the social taboos on birth control policies.

Professional career

Remco Johan Baggen obtained his Bachelor's degree in Health Sciences with a Major in Human Movement Sciences at Maastricht University in 2011. He obtained his Master's degree in Physical Activity and Health, with a specialization in Biology of Human Performance and Health at Maastricht University in 2012. He is a certified therapist with the Dutch Society for Sport & Wellness Massage (NGS). He started his research as a doctoral student in 2014 with the project 'Optimization of Training Programs with Respect to Muscle Adaptations in Elderly', which was part of MOVE-AGE, an Erasmus Mundus joint doctorate program. The majority of his research was performed at the home university KU Leuven. Additionally, he completed two mobility periods at the host university, the Vrije Universiteit Amsterdam. During his time at KU Leuven he served as a council member of the advisory board of the Department of Movement Sciences (2016-2018). He is currently employed as a researcher/coordinator for technology platform ReLab at the Faculty of Rehabilitation Sciences of Hasselt University where he facilitates the use of technological applications for evaluation, prevention, monitoring and physical support in the context of musculoskeletal rehabilitation.

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