

# Neuromechanics of repeated stepping with external loading in young and older women

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## Abstract

**Purpose** An understanding of the neuromechanical responses to bench stepping with external loading is important for exercise prescription, especially in older women who are more at risk than men for disability. This study was designed to describe and compare such responses to repeated bench stepping with external loading between young and older women.

**Methods** Eight young ( $25 \pm 2.7$  years) and nine older ( $70 \pm 3.3$  years) medically stable women performed repeated stepping on a bench of either 20 or 25 cm either unloaded or with 2.5, 5, 7.5 or 10 % of body mass (BM) incorporated into a weighted vest. Ground reaction forces, peak power output and agonist–antagonist neuromuscular activation around the knee joint were evaluated.

**Results** Peak power output was 44 % lower in the older than in the younger women. At a step height of 25 cm, peak

power (PP) in the young women was 7 % greater with an external load of 7.5 % body mass compared with no loading, while in the older women there was a tendency for PP to be higher with an external load of 2.5 % body mass. Neuromuscular activation of the vastus lateralis muscle was 60 % higher in the older than in the young women.

**Conclusions** Older women performed repeated weighted-vest stepping with lower power output but greater knee muscle activation compared to younger counterparts. Peak power output during stepping may be achieved at 7.5 % BM loading in young women and either 2.5 or 10 % BM in older women, depending on desired step height.

**Keywords** Muscle power · Ground reaction forces · Exercise prescription · Elderly

## Abbreviations

ADL	Activity of daily living
APPP	Antero-posterior peak power
BF	Biceps femoris
BM	Body mass
Fopt	Optimal force
FP	Force plate
Fpeak	Peak force
GRF	Ground reaction force
KE	Knee extension
KF	Knee flexion
MVC	Maximum voluntary contraction
PP	Peak power
PRT	Progressive resistance training
RMS	Root mean square
sEMG	Surface electromyography
VL	Vastus lateralis
Vopt	Optimal velocity

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## Introduction

The ageing neuromuscular system has been extensively reviewed, detailing alterations in the neural system and muscle fibres with advancing age (Aagaard et al. 2010). The degenerative loss of skeletal muscle strength and size, known as sarcopenia (Cruz-Jentoft et al. 2010), is one of the main problems encountered by the ageing population. With rapid declines in muscle strength after 50 years of age (Macaluso and De Vito 2004; Skelton et al. 1994), comes the ever increasing difficulty in performing activities of daily living (ADL's), such as climbing stairs, rising from a chair and undertaking household chores (Guralnik et al. 1995; Miszko et al. 2003).

Research consistently shows the benefits of progressive resistance training (PRT) in older adults for improvements in neuromuscular function and functional ability (Latham et al. 2004, Macaluso and De Vito 2004). The strong association between lower limb power and physical function in older adults (Cuoco et al. 2004; Foldvari et al. 2000; Forte and Macaluso 2008; Laudani et al. 2013) makes the ability to generate torque at high angular velocities especially important in this population (Callahan and Kent-Braun 2011). As a result, recent studies have focused on training programmes that target enhancements in muscle power for the prevention of functional capacity deterioration in the elderly. These power training (high velocity) interventions have been shown to be more effective than traditional PRT for improving functional outcomes (Tschopp et al. 2011). However, such interventions rely predominantly on expensive specialised gym-based equipment, thus requiring participants to travel and perform the exercise programmes under the supervision of trained personnel. An alternative to these gym-based training methods, which is low cost, easy to perform, and appropriate for older adults to execute at home without supervision, may be more beneficial. Bench stepping exercise is a multi-joint functional task targeting the lower limbs, which appears to meet these criteria.

Previous studies have described the acute biomechanical responses to bench stepping in young adults (Maybury and Waterfield 1997; Saad et al. 2011; Santos-Rocha et al. 2006; Santos-Rocha et al. 2009; Willett et al. 1998), however, there is very little evidence regarding older populations. Of the few studies available (Salem et al. 2004; Wang et al. 2003), only one examines repeated stepping (Santos-Rocha et al. 2002) focusing on the variations in ground reaction force (GRF) at different step cadences and step heights. Analysis of muscle activation patterns reveals that bench stepping requires both concentric and eccentric quadriceps activity, which closely simulates stair ascent and descent (Willett et al. 1998). While differences in muscle activation between young and older adults have been examined during some ADL's (Bice et al. 2011;

Hortobágyi et al. 2003), bench stepping has yet to be considered. Furthermore, the occurrence of elevated muscle co-activation in older adults compared with their younger counterparts (Larsen et al. 2008; Macaluso et al. 2002) has yet to be evidenced during bench stepping. Nevertheless, the neuromuscular similarities with stair climbing suggest that bench stepping may be an effective training modality for improvements in muscle power and functional fitness in older adults. For example, improvements in muscle power have been noted in older adults following a stair climbing intervention with external loading (Bean et al. 2002) suggesting that a similar outcome may be observed with bench stepping.

An understanding of neuromechanical responses to external loading is important for stepping exercise prescription and injury prevention in healthy adults of all ages. Therefore, identifying the optimal loading conditions associated with desirable fitness outcomes is paramount. The aims of this study were twofold: (1) to investigate the neuromechanical responses to different step heights and external loading patterns during repeated stepping exercise in both young and older women, and (2) to determine the optimal external load associated with peak power output.

## Methods

### Participant selection

Seventeen healthy, female volunteers (eight young and nine older; Table 1) were recruited for this study. All participants were provided with clear written explanation of the study rationale and procedures involved, and signed an informed consent approved by the University ethics committee. Inclusion in the study required participants to meet the criteria of 'medically stable', as determined by a health history questionnaire (Greig et al. 1994), which was reviewed by a medical doctor.

### Maximum voluntary contraction

Maximum isometric voluntary contraction (MVC) was measured during knee extension (KE) and knee flexion (KF) of the dominant limb. Participants were positioned on a dynamometer (Kin Com, Chattanooga, TN, USA) with the trunk upright and the hips and knees flexed at 100° and 90°, respectively. The lateral femoral condyle of the dominant limb was aligned with the axis of rotation of the dynamometer lever arm, and an ankle cuff was placed 2 cm proximal to the lateral malleolus. Straps were secured around the participant's chest and hips, and the arms were crossed at chest height to avoid any movements that may have aided moment generation. A standardised warm-up

**Table 1** Participant characteristics

	Young	Old	<i>t</i>	Cohen's <i>d</i>
Age (years)	24.6 ± 2.67	69.9 ± 3.33		
Stature (m)	1.67 ± 0.02	1.59 ± 0.02	-2.346*	4.00
Body mass (kg)	61.94 ± 3.13	64.4 ± 1.78	0.683	0.97
Leg length (cm)	85.63 ± 0.89	83.94 ± 1.31	-1.065	1.51
MVC EXT (Nm)	118.89 ± 9.26	72.38 ± 6.9	-4.028**	5.70
MVC FLX (Nm)	50.36 ± 2.38	32.88 ± 2.29	-5.296**	7.48

Significant difference between-groups; \*  $p < 0.05$ , \*\*  $p < 0.01$ .  $n = 8$  in both groups,  $df = 14$ . Values are mean ± SD

and familiarisation period consisting of sub-maximal and maximal isometric contractions was performed prior to testing.

The test protocol consisted of one KE followed by one KF. This was repeated three times, with each contraction and each set separated by a 60 and 180 s rest period, respectively. Participants were able to observe their performance on a computer screen and were verbally encouraged to give their best effort and sustain each contraction for at least 3 s. Average values were calculated over a 100 ms window centred around the peak torque and the trial resulting in the highest force value was selected as the MVC.

#### Surface electromyography

Surface electromyography (sEMG) signals were obtained from the vastus lateralis (VL) and biceps femoris (BF) muscles during MVC measurements and continuously throughout the step test protocol. These two muscles were considered to be representative of their constituent muscle groups (Carolan and Cafarelli 1992). The skin was prepared by gently rubbing the appropriate area with fine sandpaper and cleansing with an alcohol solution. Two pre-gelled and self-adhesive foam silver/silver chloride electrodes (PG 10S, FIAB SpA, Florence, Italy) were then positioned over the muscle belly according to SENIAM guidelines (Hermens et al. 1999). A reference electrode was placed over the patella to eliminate ambient noise from the surrounding environment. The sEMG signals were recorded using a lightweight (360 g) portable system (BTS PocketEMG, BTS Bioengineering, Milan, Italy) and were band-pass filtered between 10 and 500 Hz, amplified 1 k and A-D converted at a sampling rate of 2,000 Hz. During the step test protocol, electrode wires were secured to the limb with tape to minimise movement artefact. A switch providing a 5 V pulse was used to synchronise surface electromyography and kinetic data recording systems.

#### Kinetic data capture

Two force plates (Bertec Corp, Columbus, OH, USA) were used to capture kinetic data during the step test protocol. The first (FP1) was positioned at ground level and was the

point of initiation of the step protocol and the second (FP2), was mounted with either a 20-cm step or a 25-cm step. This allowed continuous measurement of GRF's during both ascending and descending phases of the step cycle. Prior to data capture, both FP1 and FP2 were set to zero, only FP2 having one of the two bench steps securely mounted on top. Force plate data were collected at a sampling rate of 1 kHz, low-pass filtered using a fourth-order Butterworth filter at 15 Hz, and were recorded on a PC using Nexus software (Vicon Motion Systems, Oxford, UK). The vertical and antero-posterior components of the GRF were extracted for further analysis.

#### Step test protocol

The step test protocol was performed on two occasions, the first using a bench step of 20 cm and the second using a bench step of 25 cm. The chosen step heights are commonly found in public and residential settings. Every session consisted of five randomised trials, each separated by a rest period of approximately 2 min, which comprised ten consecutive step-ups leading with the dominant limb, performed as quickly as possible. One trial was performed without supplementary weight, while the remaining four trials were carried out with supplementary weights carried in a weighted vest corresponding to 2.5, 5, 7.5 or 10 % of body mass (BM). This protocol was chosen to reflect a power training protocol whereby an individual would perform a number of sets and repetitions. Arms were placed across the chest throughout the trial, to minimise accessory movements, which may have altered stepping performance. For safety purposes, the participant performed a short familiarisation trial comprising 4–5 step-ups with each supplementary load, prior to recording.

#### Data analysis

The sEMG amplitude was expressed as root mean square (RMS) by computer-aided analysis (BTS Myolab, BTS Bioengineering, Milan, Italy) performed over the 1 s epoch corresponding to MVC, as previously described (Macaluso et al. 2003). Percentage co-activation during isometric KE was defined as the RMS of the BF during MVC of the

extensors, divided by the RMS of the BF during MVC of the flexors (Pearson et al. 2002). The RMS of both VL and BF EMG bursts throughout each step movement was normalised to the RMS value obtained during MVC.

Kinetic data were processed using Matlab software (The MathWorks Inc, Natick, MA). The vertical components of the GRF from both force plates were summed and then analysed to obtain the vertical velocity  $v(t)$  of the displacement of the body centre of mass as previously described (De Vito et al. 1998). Power was calculated as the product of the total vertical force and vertical velocity. Values of optimal force and optimal velocity, defined as the vertical force and vertical velocity corresponding to peak power, respectively (Bottinelli et al. 1996) were also considered for further analysis.

### Statistical analysis

Data were analysed using SPSS Statistics version 20 (IBM, Somers, NY, USA), and normal distributions were inspected using the Shapiro–Wilk test prior to analysis. An independent samples *t* test was used to test between group differences for anthropometric variables and MVC values. All kinetic data were analysed using a two-way repeated measures ANOVA with one between-subject factor of age group (old vs. young) and two within-subject factors of step height (20 vs. 25 cm) and load (0, 2.5, 5, 7.5, 10 % BM). *Post hoc* pairwise comparisons with Bonferroni correction were used to identify where any detected

differences lay. Significance was accepted as  $p < 0.05$  and effect size ( $d$ ) values were calculated in accordance with Cohen (1988).

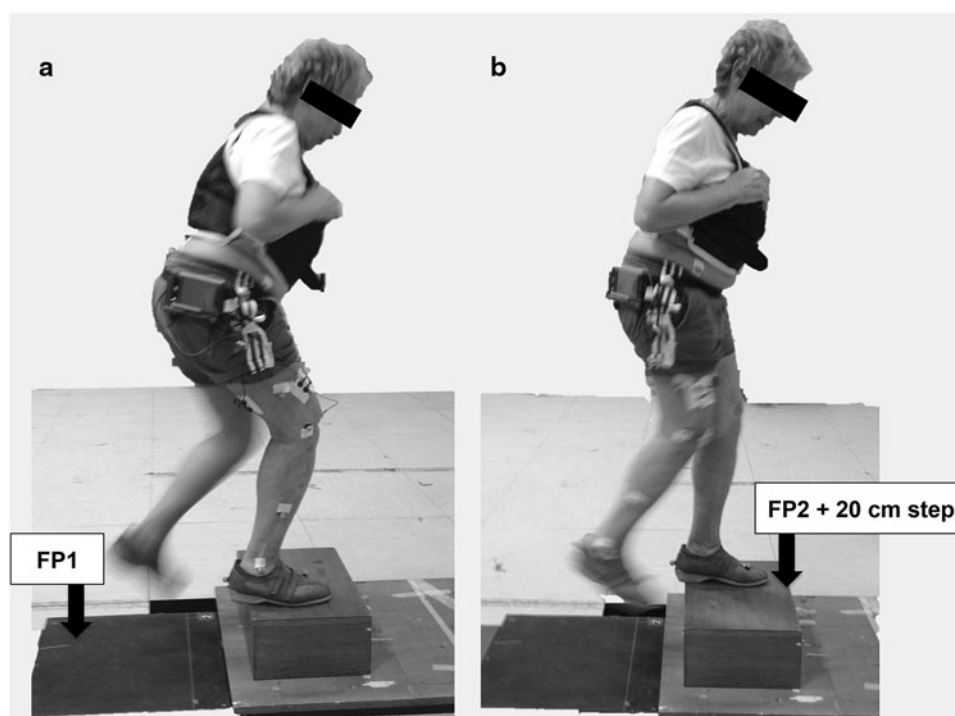
### Results

One older participant was unable to complete all testing conditions, reporting that the 25 cm step was too difficult to perform, therefore, a total of eight older females and eight younger females are included in the analysis. Older women were, on average, 39 and 35 % weaker than the younger women during MVC of the knee extensors and flexors, respectively (Table 1). On average, older women also performed the 10-step trial at a slower pace compared with their younger counterparts (17.6 vs. 9.7 s, respectively).

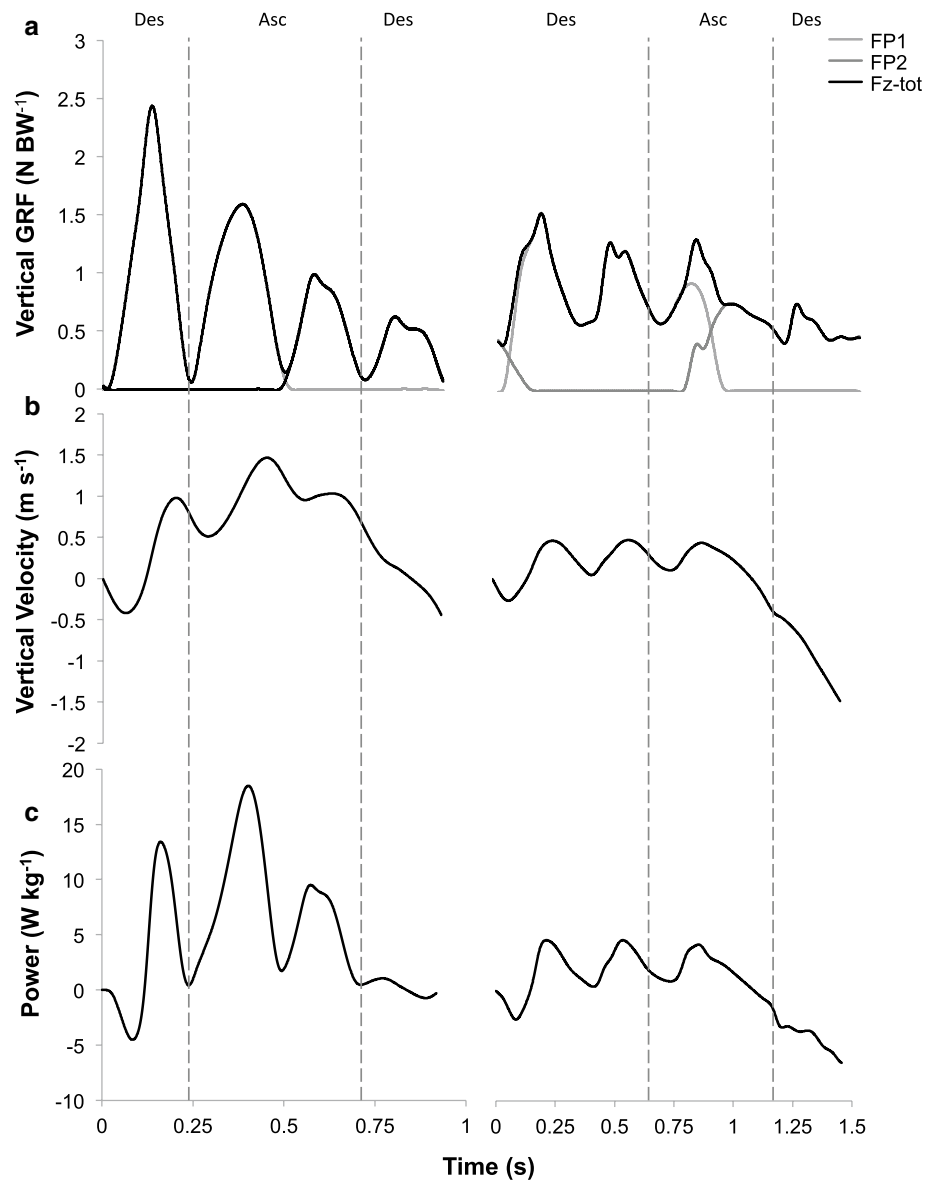
### Stepping strategy

Each step cycle was divided into two phases: an ascent phase, which corresponds to both limbs moving from FP1 to FP2; and a descent phase, which corresponds to both limbs moving back to FP1 (Fig. 1). During the ascent phase, which started at right foot lift-off from FP1 and ended at left foot contact with FP2, GRF patterns differed between age groups (Fig. 2). Young participants ascended the step using predominantly the left limb with vertical GRF of the right limb never exceeding body weight, while older participants used both limbs to

**Fig. 1** An older participant performing, **a** the descent phase and **b** the ascent phase of the stepping task



**Fig. 2** Typical stepping strategy of, **a** one young and, **b** one older female, using a 20-cm step with 0 % body mass loading

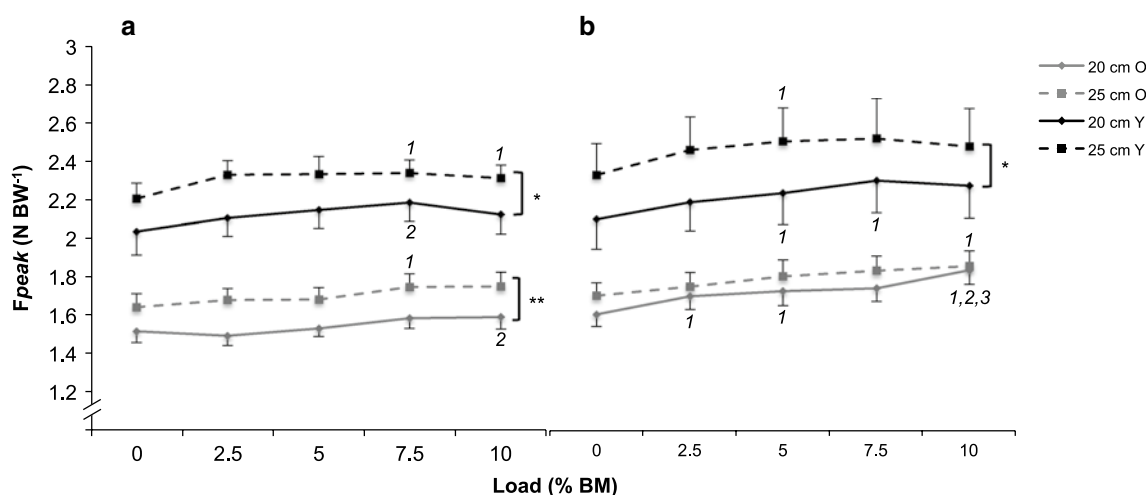


ascend with a small overlap between vertical GRF of the left and the right limbs. During the descent phase, which started at left foot contact with FP2 and ended at right foot lift-off from FP1, both age groups exhibited a similar GRF pattern with a noticeable peak representing right foot contact with FP1 (Fig. 2). The following parameters were calculated for each phase: peak vertical force ( $F_{\text{peak}}$ ), peak vertical power (PP), optimal vertical force ( $F_{\text{opt}}$ ), optimal vertical velocity ( $V_{\text{opt}}$ ) and antero-posterior peak power (APPP). All values of force were normalised with respect to each participant's body weight. The first and last step-ups of each trial were excluded from the analysis, therefore, average values calculated from the remaining step cycles of the task were used for further analysis.

#### Peak vertical force

During ascent, the ANOVA showed significant main effects on  $F_{\text{peak}}$  for age group ( $p < 0.001$ ,  $d = 2.57$ ), step height ( $p < 0.001$ ,  $d = 0.88$ ) and load ( $p < 0.001$ ,  $d = 0.19$ ). In addition, there was a significant interaction between age group and load ( $p < 0.05$ ). During descent, significant main effects for  $F_{\text{peak}}$  were observed for age group ( $p < 0.01$ ,  $d = 1.28$ ), step height ( $p < 0.01$ ,  $d = 0.41$ ) and load ( $p < 0.001$ ,  $d = 0.18$ ) (Fig. 3).

Within-groups analyses revealed a significant main effect during ascent for step height ( $p < 0.05$ ,  $d = 0.92$ ) and load ( $p < 0.001$ ,  $d = 0.21$ ) in the younger group, and step height ( $p < 0.01$ ,  $d = 0.84$ ) and load ( $p < 0.01$ ,  $d = 0.18$ ) in the older group. During descent, significant differences



**Fig. 3** Peak vertical force ( $F_{\text{peak}}$ ) normalised to body weight (N) across all step heights (SH) and loads during, **a** ascent and **b** descent. Values are mean  $\pm$  standard error of the mean (SEM). \* significant

difference  $p < 0.05$ , \*\* significant difference  $p < 0.01$ , 1 significantly greater than 0 %, 2 significantly different from 2.5 %, 3 significantly different from 5 %, Y young, O old

were observed for both step height ( $p = 0.05$ ,  $d = 0.50$ ) and load ( $p < 0.001$ ,  $d = 0.13$ ) in the younger group and load in the older group ( $p < 0.001$ ,  $d = 0.23$ ).

Post hoc comparisons revealed that, during ascent of the 20 cm step, significantly greater  $F_{\text{peak}}$  compared with 2.5 % BM was observed at 7.5 % ( $p < 0.05$ ,  $d = 0.30$ ) and 10 % BM loading ( $p < 0.05$ ,  $d = 0.67$ ) in the young and older groups, respectively. During descent, further significant differences were evident between 0 % and both 5 ( $p < 0.05$ ,  $d = 0.33$ ) and 7.5 % BM ( $p < 0.05$ ,  $d = 0.49$ ) in the younger group, while in the older group differences were observed between 0 % and 2.5 ( $p < 0.01$ ,  $d = 0.53$ ), 5 ( $p < 0.01$ ,  $d = 0.68$ ) and 10 % BM ( $p < 0.01$ ,  $d = 1.30$ ), as well as between 2.5 and 10 % BM ( $p < 0.05$ ,  $d = 0.72$ ), and 5 and 10 % BM ( $p < 0.05$ ,  $d = 0.53$ ). During ascent of the 25 cm step and compared with 0 % BM loading, significantly greater  $F_{\text{peak}}$  was obtained at both 7.5 ( $p < 0.05$ ,  $d = 0.75$ ) and 10 % BM loading ( $p < 0.05$ ,  $d = 0.59$ ) in the younger women, and 7.5 % BM loading ( $p < 0.05$ ,  $d = 0.55$ ) in the older women. During descent, and compared with 0 % BM, differences were observed at 5 % ( $p < 0.05$ ,  $d = 0.41$ ) and 10 % ( $p < 0.05$ ,  $d = 0.79$ ) in the young and older groups, respectively.

#### Peak vertical power

During ascent, the ANOVA showed significant main effects on PP for age group ( $p < 0.001$ ,  $d = 2.20$ ), step height ( $p < 0.001$ ,  $d = 0.94$ ) and load ( $p < 0.01$ ,  $d = 0.19$ ) (Fig. 4a). There were significant interactions between age groups and both step height ( $p < 0.05$ ) and load ( $p < 0.01$ ). During descent, significant main effects on PP were observed

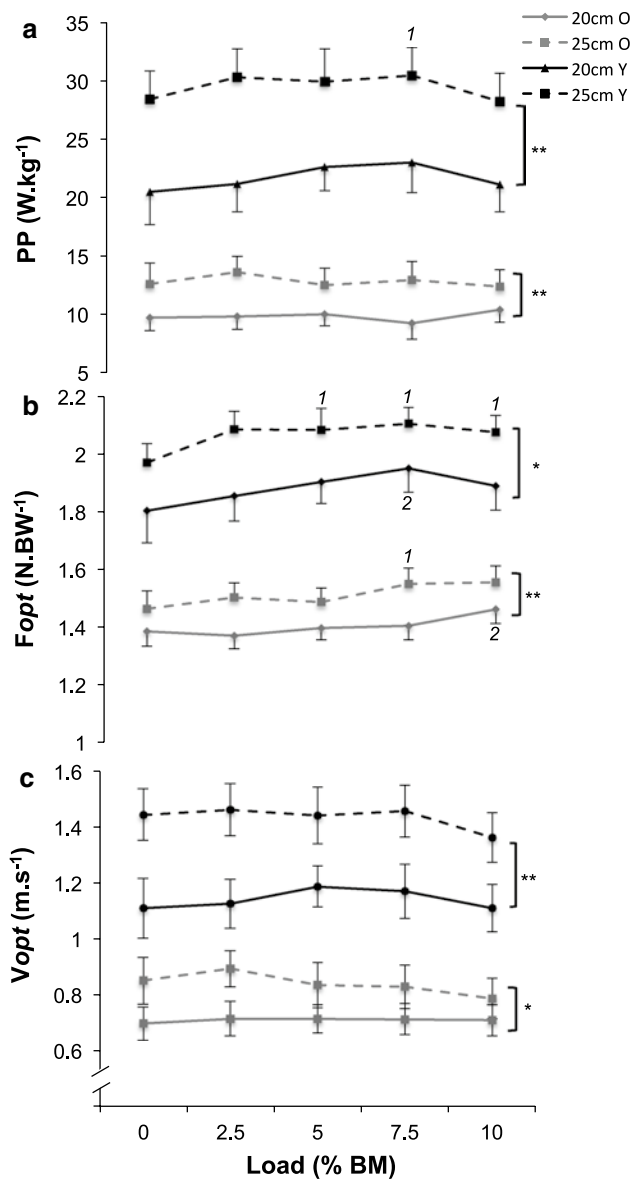
for age group ( $p = 0.01$ ,  $d = 1.07$ ), step height ( $p < 0.001$ ,  $d = 0.68$ ) and load ( $p < 0.01$ ,  $d = 0.17$ ) (Table 2).

Within-groups analyses revealed that during ascent in the younger group there was a significant main effect for step height ( $p < 0.01$ ,  $d = 1.18$ ) and load ( $p < 0.001$ ,  $d = 0.19$ ); at a 25-cm step height pairwise comparisons revealed a significant difference between 0 and 7.5 % BM ( $p < 0.01$ ,  $d = 0.32$ ). During descent in the young group, there was a significant main effect for step height ( $p < 0.01$ ,  $d = 0.70$ ) and load ( $p < 0.05$ ,  $d = 0.15$ ), however, follow-up analysis did not reveal any significant difference in PP between loads at either 20 or 25 cm step heights. In the older group, during both ascent and descent, there was a significant main effect for step height ( $p < 0.01$ ,  $d = 0.70$ ; and  $p < 0.01$ ,  $d = 0.65$ , respectively), but follow-up analysis did not reveal any significant difference in PP between loads at either 20 or 25 cm step heights. Visual inspection of Fig. 4a, however, shows that during ascent of the 25 cm step, there was a tendency for PP to reach its maximum at 2.5 % BM.

#### Optimal vertical force

During ascent, the ANOVA showed significant main effects on  $F_{\text{opt}}$  for age group ( $p < 0.001$ ,  $d = 2.70$ ), step height ( $p < 0.001$ ,  $d = 0.90$ ) and load ( $p < 0.001$ ,  $d = 0.22$ ) (Fig. 4b). There was also a significant interaction between age group and load ( $p < 0.01$ ). During descent, significant main effects on  $F_{\text{opt}}$  were also observed for age group ( $p < 0.05$ ,  $d = 1.07$ ), step height ( $p < 0.05$ ,  $d = 0.39$ ) and load ( $p < 0.001$ ,  $d = 0.18$ ) (Table 2).

Within-groups analyses revealed a significant main effect on  $F_{\text{opt}}$  during ascent for step height ( $p < 0.05$ ,  $d = 1.11$ ) and load ( $p < 0.001$ ,  $d = 0.25$ ) in the younger



**Fig. 4** **a** Peak power (PP), **b** optimal force ( $F_{opt}$ ) and **c** optimal velocity ( $V_{opt}$ ), across all step heights (SH) and loads during ascent in young and older women. Values are mean  $\pm$  SEM. \* significant difference  $p < 0.05$ , \*\* significant difference  $p < 0.01$ , 1 significantly greater than 0 %, 2 significantly different from 2.5 %, Y young, O old

group, and step height ( $p < 0.01$ ,  $d = 0.71$ ) and load ( $p < 0.001$ ,  $d = 0.20$ ) in the older group. During descent, significant effects were evident for step height ( $p < 0.05$ ,  $d = 0.46$ ) and load ( $p < 0.01$ ,  $d = 0.15$ ) in the younger group, and load ( $p < 0.001$ ,  $d = 0.22$ ) in the older group.

Post hoc comparisons revealed that, during ascent of the 20 cm step and compared with 2.5 % BM loading, significant differences were evident at 7.5 % BM ( $p < 0.01$ ,  $d = 0.44$ ) in the young group and 10 % BM ( $p < 0.05$ ,  $d = 0.70$ ) in the older group. With descent, differences were detected between 0 % and both 5 ( $p < 0.01$ ,  $d = 0.48$ )

and 10 % BM ( $p < 0.01$ ,  $d = 0.73$ ) in the older group only. During ascent of the 25 cm step and compared with 0 % BM loading, significantly greater  $F_{opt}$  was obtained at 5 ( $p < 0.05$ ,  $d = 0.58$ ), 7.5 ( $p < 0.01$ ,  $d = 0.62$ ) and 10 % BM loading ( $p < 0.01$ ,  $d = 0.48$ ) in the younger group and 7.5 % ( $p < 0.05$ ,  $d = 0.57$ ) in the older group. During descent, significant differences were observed between 0 % and both 5 ( $p < 0.05$ ,  $d = 0.83$ ) and 7.5 % BM loading ( $p < 0.05$ ,  $d = 0.99$ ) in the older group only.

On average,  $F_{opt}$  at peak power was 89 and 73 % of the corresponding  $F_{peak}$  during ascent and descent, respectively. Similarly, in the older women,  $F_{opt}$  at peak power occurred at 90 and 77 % of the  $F_{peak}$  during ascent and descent, respectively.

#### Optimal vertical velocity

During ascent, the ANOVA showed significant main effects on  $V_{opt}$  for age group ( $p < 0.001$ ,  $d = 2.13$ ), step height ( $p < 0.001$ ,  $d = 0.89$ ) and load ( $p < 0.01$ ,  $d = 0.14$ ; Fig. 4c). During descent, significant main effects on  $V_{opt}$  were observed for age group ( $p < 0.05$ ,  $d = 1.00$ ), step height ( $p < 0.001$ ,  $d = 0.73$ ) and load ( $p < 0.01$ ,  $d = 0.14$ ) (Table 2).

Within-groups analyses revealed that, in the younger group,  $V_{opt}$  was significantly affected by increasing step height ( $p < 0.01$ ,  $d = 1.18$ ) and load ( $p < 0.01$ ,  $d = 0.17$ ) during ascent, and step height ( $p < 0.01$ ,  $d = 0.87$ ) and load ( $p < 0.05$ ,  $d = 0.14$ ) during descent, however, further post hoc analysis did not reveal any significant differences between loads at any stage of the stepping task. There was a significant effect on  $V_{opt}$  for step height in the older group during ascent ( $p < 0.05$ ,  $d = 0.61$ ) and descent ( $p < 0.01$ ,  $d = 0.58$ ).

#### Antero-posterior peak power

A significant main effect on, APPP during ascent was observed for age group ( $p < 0.05$ ,  $d = 1.32$ ), indicating that the younger group exerted a greater magnitude of peak power in the AP plane, compared with the older group. No within-group differences were observed for either step height or load.

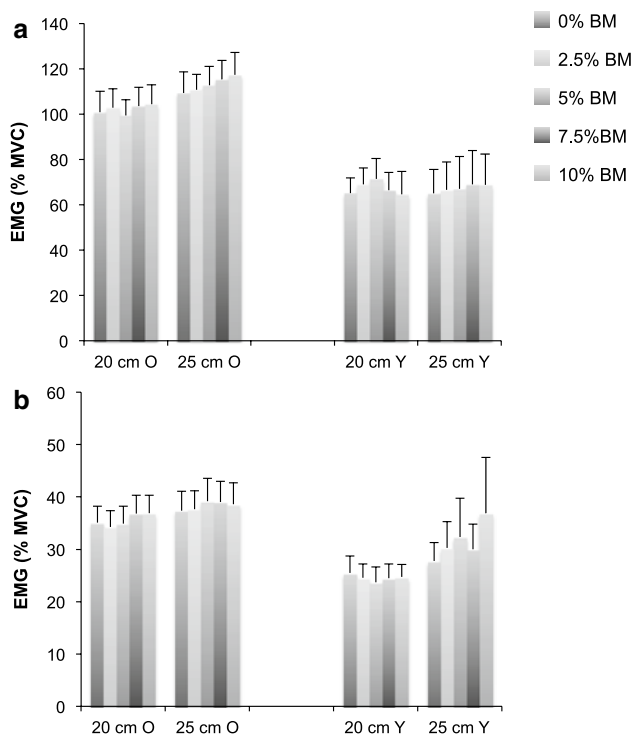
#### Surface electromyography

RMS amplitude during the ascent phase of the stepping task is reported in Fig. 5. Normalised vastus lateralis RMS during ascent was significantly higher in the old compared with the young ( $p = 0.01$ ,  $d = 1.34$ ). Within-group analysis revealed significant main effects for step height ( $p < 0.01$ ,  $d = 0.53$ ), and load ( $p < 0.05$ ,  $d = 0.11$ ) in the older group only. However, further post hoc comparisons did not reveal

**Table 2** Peak power, optimal force and optimal velocity during descent across all step heights (SH) and loads in young and older females

	SH (cm)	Load (% BM)				
		0 %	2.5 %	5 %	7.5 %	10 %
Peak power ( $W\ kg^{-1}$ )						
Older	20	$5.17 \pm 2.06$	$5.53 \pm 2.01$	$5.89 \pm 1.99$	$5.17 \pm 1.70$	$5.76 \pm 2.13$
	25	$6.49 \pm 1.88$	$7.00 \pm 1.89$	$6.96 \pm 2.12$	$6.81 \pm 1.83$	$6.66 \pm 2.29$
Younger	20	$8.71 \pm 3.53$	$8.95 \pm 3.70$	$9.47 \pm 3.86$	$9.58 \pm 3.91$	$8.76 \pm 3.72$
	25	$11.78 \pm 4.47$	$13.29 \pm 4.62$	$12.72 \pm 4.55$	$12.79 \pm 5.72$	$11.46 \pm 4.64$
Optimal force ( $N\ BW^{-1}$ )						
Older	20	$1.31 \pm 0.17$	$1.38 \pm 0.16$	$1.39 \pm 0.17$	$1.38 \pm 0.14$	$1.43 \pm 0.17$
	25	$1.35 \pm 0.13$	$1.43 \pm 0.18$	$1.45 \pm 0.17$	$1.47 \pm 0.17$	$1.45 \pm 0.17$
Younger	20	$1.64 \pm 0.30$	$1.67 \pm 0.30$	$1.74 \pm 0.34$	$1.76 \pm 0.37$	$1.71 \pm 0.35$
	25	$1.77 \pm 0.37$	$1.91 \pm 0.41$	$1.92 \pm 0.38$	$1.96 \pm 0.46$	$1.88 \pm 0.40$
Optimal velocity ( $m\ s^{-1}$ )						
Older	20	$1.39 \pm 0.14$	$1.40 \pm 0.13$	$1.42 \pm 0.13$	$1.38 \pm 0.12$	$1.40 \pm 0.14$
	25	$1.49 \pm 0.14$	$1.49 \pm 0.13$	$1.48 \pm 0.14$	$1.47 \pm 0.13$	$1.46 \pm 0.15$
Younger	20	$1.52 \pm 0.14$	$1.52 \pm 0.15$	$1.53 \pm 0.14$	$1.53 \pm 0.14$	$1.50 \pm 0.14$
	25	$1.65 \pm 0.14$	$1.68 \pm 0.12$	$1.65 \pm 0.13$	$1.63 \pm 0.19$	$1.60 \pm 0.16$

Values are mean  $\pm$  SD



**Fig. 5** Muscle activation (RMS) of **a** the vastus lateralis (VL) and **b** the biceps femoris (BF) muscle relative to maximum isometric voluntary contraction (MVC) RMS, during the ascent phase of a 20- and 25-cm step, in young and older females. Values are mean  $\pm$  SEM

any significant difference in RMS between loads at either 20 or 25 cm step heights. Percentage co-contraction of the biceps femoris muscle during MVC of the knee extensors was significantly greater in the older group (23 %) compared with the younger group (12 %;  $p < 0.05$ ).

## Discussion

This study describes the effects of different step heights and external loading on the acute kinetic and neuromuscular responses to a stepping task, and compares these effects between young and older women. The main findings are fourfold; (1) older women displayed lower kinetic responses but a greater magnitude of neuromuscular activity compared with younger women, (2) increasing step height resulted in significantly greater values for all kinetic parameters during ascent in both young and older women, (3) peak vertical force increased with increasing external load in both age groups demonstrating an effective overload stimulus and (4) at a step height of 25 cm, young women reached peak power during ascent with an external load of 7.5 % BM, while older women tended to reach peak power with an external load of 2.5 % BM. Overall, the results demonstrate that older participants performed repeated weighted-vest stepping with lower power output but greater knee muscle activation compared to young participants.

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. In particular, the higher peak power was associated with an increase in both of its determinants, optimal force and optimal velocity. During the descent phase, parameters of force were unaffected by a change in step height in the older group, however, peak power was significantly greater at 25 cm compared with 20 cm, apparently related to an increase in the optimal velocity at peak power. In the younger group, peak force, peak power, optimal force and optimal velocity were all increased during descent with increasing step height. It has previously been shown that



vertical GRF's (during descent) increase with increasing bench height in young adults (Horvatin-Fučkar et al. 2008; Maybury and Waterfield 1997), however, a paucity of stepping research in older adults, makes it difficult to interpret the results of the older group. Perhaps a more controlled descent in the older group provided a greater ability for the absorption of force, regardless of step height. Thus, it may be argued that, while the descent strategy was sufficiently different to affect a change in peak power at different step heights, this did not alter the ability for force absorption on landing in the older group.

At both step heights, increasing external load resulted in a corresponding increase in peak vertical force, demonstrating that external loading in the form of a weighted vest is an effective overload stimulus during a repeated stepping task. For example at 25 cm, external loads of 7.5 and 10 % BM in the young group and 7.5 % in the older group resulted in a significantly greater peak force during ascent compared with no loading. During the descent phase, 5 and 10 % BM loading were required in the young and old, respectively. Thus external loading between 5 and 10 % BM will significantly increase the vertical force associated with the task, however, these forces, on average, do not exceed 2.58 BW in the young and 1.86 BW in the old across all step heights and loading categories. These force values are in line with previous research examining unloaded stepping in young adults (Horvatin-Fučkar et al. 2008; Maybury and Waterfield 1997; Santos-Rocha et al. 2002; Santos-Rocha et al. 2006; Scharff-Olson et al. 1997) and suggest that weighted stepping is associated with moderate and low skeletal loading intensity, respectively (Shaw et al. 2001), and may be safe to perform as part of a training regimen.

Similarly, in the younger women, increasing external load up to 7.5 % BM resulted in a corresponding increase in peak power at both step heights. When stepping up onto a 25-cm step, young women exhibited a significantly greater peak power output—equivalent to 7 %—with 7.5 % BM compared with no loading. The same result was also suggested when using the 20 cm step, although this did not reach significance. Conversely, older participants did not show any significant change in peak power between different loading conditions. It is of note, however, that older women showed a trend for peak power at 10 and 2.5 % BM loading at 20 and 25 cm, respectively. This indicates that the optimal external load for peak power output differs between young and older women. Reductions in the force generating capacity of the ageing musculature (Skelton et al. 1994) are known to result in a shift in the force velocity spectrum determining peak power (Allison et al. 2013). Such physiological changes may therefore alter the threshold for optimal performance, in that older individuals achieve peak power with lesser force (or load) compared to their younger counterparts.

Overall, these results partially agree with those published by Salem et al. (2004) who showed, in older adults, that increasing external load from 0 to 5 % BM increased peak moments, powers, and impulses at the hip, knee and ankle joints when stepping onto a 21 cm step. While increasing from 5 to 10 % BM did not further influence peak kinetic output, the authors reported an additional increase in average extensor moments. Our results suggest that 10 % BM loading may be optimal at 20 cm, while 2.5 % BM loading may be optimal at 25 cm for peak power output in older females, however, it should be noted that the expression of peak power is different. For example, the current study describes a 'global' assessment of peak power calculated by the vertical component of GRF, while Salem et al. (2004) assessed power locally at specific joints. The discrepancy may also be explained by differences in the speed of movement as well as the motor task performed (one step-up vs. repeated stepping).

One of the main findings from this study was that the older group adopted a different stepping strategy compared with the younger group, likely due to decreased functional capacity as a result of ageing. Inspection of the GRF's over a step cycle reveals that the vertical force trace never reaches zero, indicating that the older group had one foot in contact with the force plates at all times. This may have been a safety strategy employed by the older participants to provide a base of support at all instances of the stepping cycle. This observation may also be attributed to the speed of the movement, for example the young group appear to have performed a 'running step' where each foot contact is associated with a distinguishable peak in force, while the older group, moving at a slower pace, performed a 'basic step' where instances of weight transfer are more obvious. Age-related remodelling in muscle composition, due to decrements in the number and size of fast-twitch muscle fibres (Harridge 2003) and an increased number of hybrid fibres (Macaluso and De Vito 2004), results in slower contractile properties of the muscle and probably contributes to the observed decline in velocity of movement.

The greater normalised sEMG amplitude detected in the older group during the stepping task denotes a greater neuromuscular activation of the quadriceps muscles compared with their younger counterparts (Macaluso et al. 2002; Macaluso and De Vito 2003; Duffy et al. 2012). This supports earlier research reporting greater EMG activity in older adults when compared to younger adults performing ADL's such as stair ascent, stair descent, chair rise and obstacle clearance during level walking (Bice et al. 2011; Hortobágyi et al. 2003). Since kinetic parameters were lower in the older group compared to the younger group, this indicates that they were operating closer to a threshold of maximum force to complete the stepping task. Indeed, Alexander et al. (1997) reported that older adults require up

to 87 % of their knee strength to rise from a chair, whereas younger adults required only up to 49 % to perform the same task. In addition, elderly individuals tend to show elevated muscle co-activation during ADL's such as stair climbing and single step descent (Hortobágyi and DeVita 2000; Larsen et al. 2008) as well as during dynamic explosive movements (Häkkinen et al. 1998). This antagonist activation indicates the presence of a compensatory mechanism for age-related neuromotor impairments, resulting in greater leg stiffness and thus permitting successful task execution (Hortobágyi and DeVita 2000). Our results show a trend for increased antagonist muscle activation in the older group during the stepping task, and hence may have contributed to a decreased net force output and greater leg stiffness compared with the young.

Additional factors that may influence the stepping strategy in the older females may be related to the difficulty in performing eccentric muscle contractions during a dynamic movement. In a study of adults with anterior knee pain, it was found that the descent phase of a stepping task was performed with lower GRF and lesser intensity thus modifying the gait pattern in comparison with healthy controls (Saad et al. 2011). The authors suggested that this was a protective mechanism adopted by the anterior knee pain group due to the challenging nature of the task, and it is possible that this eccentric muscle action was perceived in the same way by our older cohort. Furthermore, it has been shown that elders descend steps with a different limb orientation, which results in a straighter limb on ground contact (Hortobágyi and DeVita 1999). These concepts, together with the above mentioned increased antagonist muscle activation observed in the older participants, lend support to the previous conclusion that older adults may alter stepping strategy to absorb vertical forces more effectively. Taken together, these results assist in explaining why older females displayed a reduced peak power capacity compared with their younger counterparts during both the descent and ascent phases of the stepping task.

It should be noted that the study was not without limitations. The results obtained are confined to a female population within two age categories and therefore are not generalizable to other population segments. Loading categories were restricted to the supplementary weight increments available with the vest (250 g). This introduced slight error to the % BM calculation. Significant differences in body stature were found between young and older participants. From a methodological point of view, it might be argued that such differences have the potential to affect the kinetic response to bench stepping in both age groups. However, it must be noted that movement velocity may be affected by leg length rather than body stature (Hof 1996), and in the present study there were no differences in leg length between young and older participants.

Research suggests that muscle power is more important for the successful performance of ADL's than muscle strength (Evans 2000; Foldvari et al. 2000; Miszko et al. 2003) and indeed, many researchers have highlighted the benefits of high-velocity resistance training interventions over traditional PRT programmes for enhancement in muscle power (reviewed by Tschopp et al. 2011). Bottaro et al. (2007) demonstrated that high-velocity resistance training is a safe and effective way to improve muscle power and functional performance in older adults. However, if the goal of an exercise programme is to prolong independence in an older age group through the enhancement of functional fitness, then this programme should conform to the principle of training specificity (McCafferty and Horvath 1977). Bean et al. (2009) investigated adaptations to a multi-task exercise programme incorporating ADL's and using weighted vests (InVEST). They reported significant improvements in muscle strength, power and parameters of functional fitness after 16 weeks of training, with superior improvements in muscle power compared with traditional PRT. In conclusion, based on the results from this study, and in consideration of previous research, older adults may encounter favourable adaptations in muscle power by performing small amounts of step exercise with a weighted vest equivalent to either 2.5 or 10 % BM, depending on desired step height.

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**Conflict of interest** The authors declare that they have no conflict of interest.

**Ethical standards** The above outlined experiment complied with the ethical standards and laws of the country in which it was carried out.

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