Experimental Gerontology 61 (2015) 38–46

Contents lists available at ScienceDirect

Experimental Gerontology

journal homepage: www.elsevier.com/locate/expgero

# Effects of short-term training combining strength and balance exercises on maximal strength and upright standing steadiness in elderly adults

Félix Penzer, Jacques Duchateau, Stéphane Baudry *

*Laboratory of Applied Biology, ULB-Neurosciences Institute (UNI), Université Libre de Bruxelles (ULB), 808 route de Lennik, 1070 Brussels, Belgium*

ARTICLE INFO

*Article history:*
Received 4 June 2014
Received in revised form 17 November 2014
Accepted 18 November 2014
Available online 20 November 2014

Section Editor: Christiaan Leeuwenburgh

*Keywords:*
Strength training
Balance training
Ageing
H reflex
MEP

ABSTRACT

This study investigated the effects of two training programmes of 6 weeks combining strength and balance exercises in different proportions. One training programme [n = 10; 71.4 (6.3) years] consisted mainly of strength exercises (ST) and the other programme [n = 8; 71.4 (6.4) years] included a majority of balance exercises (BT). Maximal strength of lower leg muscles and centre of pressure (CoP) steadiness during upright stance in various sensory conditions were measured before and after training. The input–output relation of motor evoked potential (MEP) induced by transcranial magnetic stimulation and H reflex was also assessed in soleus during upright standing. The maximal strength of the ankle plantar flexor muscles increased after training programmes ($p < 0.001$) with a trend for greater gain in ST (+35.7%) compared with BT (+20.8%, $p = 0.055$). The gain in strength was positively correlated with the increase in voluntary activation ($p < 0.001$). Both training programmes decreased maximal amplitude and mean fluctuations of CoP displacements recorded in the backward–forward direction when standing on a foam mat ($p < 0.05$) but not on a rigid surface. The electromyographic activity of the ankle plantar flexor muscles during upright standing decreased ($p < 0.05$) after training but not for the tibialis anterior. Results obtained for H reflex and MEP input–output relations suggest an increased efficacy of Ia afferents to activate low-threshold motor neurones and a decrease in corticospinal excitability after training. This study indicates that short-term training combining strength and balance exercises increases maximal strength and induces change in the neural control of lower leg muscles during upright standing.



## 1. Introduction

Ageing is associated with reduced maximal strength (Baudry et al., 2005; Vandervoort and McComas, 1986) and impaired balance (Baudry and Duchateau, 2012; Billot et al., 2010), measured as an increased magnitude of the fluctuations of the centre of pressure (CoP steadiness). CoP steadiness reflects the ability of an individual to maintain the vertical projection of the centre of mass within the base of support with minimal postural sway (Shumway-Cook et al., 1988). The decrease in CoP steadiness likely reflects alterations in the control of upright standing that should place elderly adults at a higher risk of falls (Horak et al., 1989). Even though a decrease in maximal strength predisposes elderly adults to functional limitations (Clark and Manini, 2012) and contributes to alter CoP steadiness (Billot et al., 2010; Orr, 2010), there is little evidence for a positive effect of strength training on CoP steadiness (Howe et al., 2011; Orr et al., 2008). In contrast, training programmes consisting of exercises challenging postural balance improve balance control but not muscle strength (Howe et al., 2011; Wolfson et al., 1996). Because of these specific adaptations, it was suggested that a combined strength and balance exercise programme (Brouwer et al., 2003; Granacher et al., 2011) would improve motor function and postural stability, a requisite for limiting the age-related increase in the risk of falls (Horak et al., 1989). In that context, a relevant parameter to address is the influence of the respective amount of balance and strength exercises to include in the training programme. Indeed, the extent of strength gain in response to strength training depends on the number of sets composing the training programme (Borst et al., 2001; Hansen et al., 2012; Kraemer et al., 2000) and, similarly, the amount of balance exercise determines in part the extent of the improvement in CoP steadiness (Howe et al., 2011).

During upright standing, recent work suggests a decreased efficacy of Ia afferents to activate spinal motor neurones accompanied by an increased corticospinal excitability during upright standing in elderly compared with young adults (Baudry et al., 2014a; Papegaaij et al., 2014b). These changes may reflect adaptations in response to the age-related alterations within the nervous and muscular systems (Papegaaij et al., 2014a), such as the decrease in muscle mass, number of motor units (Vandervoort, 2002), loss of distal large myelinated sensory axons, and altered anatomical and physiological characteristics of

*Abbreviations:* CoP, centre of pressure; MEP, motor evoked potential; TMS, transcranial magnetic stimulation; REO, rigid, eyes open condition; REC, rigid, eyes closed; FEO, foam, eyes open condition; aEMG, average value of the rectified electromyogramme; MVC, maximal voluntary contraction; CAR, central activation ratio.

* Corresponding author at: Laboratory of Applied Biology, Faculty for Motor Sciences, Université Libre de Bruxelles, 808, route de Lennik, CP 640, 1070 Brussels, Belgium.
*E-mail address:* sbaudry@ulb.ac.be (S. Baudry).

http://dx.doi.org/10.1016/j.exger.2014.11.013
0531-5565/

muscle spindles (Shaffer and Harrison, 2007). In young adults, balance training decreased corticospinal excitability in tibialis anterior during various balance tasks (Beck et al., 2007; Schubert et al., 2008) whereas no significant change in H-reflex amplitude, that assesses the synaptic efficacy of Ia afferents to discharge motor neurones, was reported after similar training (Taube et al., 2007). Such data, however, are not available in elderly adults, especially regarding combined training. Accordingly, it is of particular interest to investigate whether this type of training programme may influence neural adjustments during upright standing in elderly adults.

The current study, therefore, had a double objective: 1) to investigate the changes in maximal strength and CoP steadiness following two training programmes including both strength and balance exercises but in different proportions: one training programme (ST) mainly consisted of strength exercises and the other programme (BT) included mainly balance exercises; and 2) to study whether corticospinal excitability and synaptic efficacy of Ia afferents to discharge motor neurones change after the training programmes when assessed during upright standing. We expected the gain in strength to be greater in elderly adults enrolled in the ST programme, but greater improvement in CoP steadiness for those participating in the BT programme. Furthermore, based on the increased MEP and decreased H reflex during upright standing in elderly compared with young adults (Baudry et al., 2014a), likely related to age-related changes in maximal strength (Baudry et al., 2014b) and proprioceptive system (Goble et al., 2011), we hypothesize that both training programmes can reverse these changes in different proportions.

## 2. Methods

### 2.1. Subjects

Twenty two subjects aged over 60 years volunteered to participate in this study. All subjects signed an informed consent and underwent a medical examination prior to their participation in the study. Approval for the project was obtained from the local Ethics Committee, and all procedures used in this study conformed to the Declaration of Helsinki.

Individuals with Parkinson's disease, multiple sclerosis, diabetes, stroke or cardiac incidents were excluded from this study. Volunteers who had orthopaedic problems within 12 months prior to the study were not enrolled. Participants were not institutionalized, neurologically damaged, depressed (Geriatric Depression Scale < 10), at risk for dementia (Montreal Cognitive Assessment > 26) or taking medications that could influence balance (sedatives, hypnotics, antidepressants and benzodiazepines; Woolcott et al., 2009).

The twenty subjects were randomly assigned either to ST (10 subjects) or BT (10 subjects). Due to injury unrelated to training, two subjects in BT had to stop their participation. A total of 18 subjects completed the 6-week training (93% compliance to training sessions), with the ST group composed of 10 subjects [2 men, age: 71.4 (6.3) years, height: 163.5 (6.4) cm, weight: 60.3 (10.2); mean (SD)] and the BT group composed of 8 subjects [2 men, age: 71.4 (6.4) years, height: 166.0 (5.5) cm, weight: 67.6 (13.7) kg]. Each subject participated in at least one familiarization session and two experimental sessions lasting 2–3 h (one before and one after the 6-week training programme). During the familiarization session, subjects practiced the different tasks used during the experimental sessions. Among the 18 subjects that have completed the training, six had participated in an additional experimental session performed six weeks before the start of the training programme, to serve as a control group. During this period, no training was carried out and the subjects maintained their normal daily activities. Two additional subjects, who did not perform the training thereafter, were incorporated in the control group that was therefore composed of 8 subjects [2 men, age: 70.1 (5.9) years, height: 165.2 (5.9) cm, weight: 65.9 (12.6) kg].

### 2.2. Experimental protocol

#### 2.2.1. Force platform

Subjects were requested to stand on a force platform (OR6-6-2000, Advanced Mechanical Technology, Watertown, MA, USA) to record the ground reaction forces allowing to track the CoP position. The signals from the force platform were sampled at 100 Hz, A/D converted (Power 1401, 16-bit resolution, Cambridge Electronic Design, UK) and stored on a computer. Subjects stood in a bipodal position with a 10-cm distance between feet (heel to heel) and the forefoot oriented laterally with a 30-degree angle between feet (each foot was rotated 15° from the forward direction). Subjects stood with the arms at their sides and were instructed to refrain from performing any head or limb movements; this was aided by asking them to fix a target positioned at eye level 1.5 m in front of them. Three balance conditions were assessed consisting of standing upright on a rigid surface (wooden support) placed over the force platform with their eyes either open (rigid, eyes open condition: REO) or closed (rigid, eyes closed condition: REC), and on a foam mat [Balance-pad Airex (50 × 41 × 6 cm); Sins, Switzerland] with their eyes open (foam, eyes open condition: FEO) (Baudry and Duchateau, 2012; Baudry et al., 2014b).

#### 2.2.2. Surface electromyogramme

The surface electromyogramme (EMG) signals were recorded from soleus, gastrocnemius medialis and tibialis anterior of the right leg with surface electrodes (silver–silver chloride electrodes of 8-mm diameter) placed in a bipolar configuration with an inter-electrode (centre to centre) distance of 2 cm. Before attaching the electrodes, the skin was shaved when necessary and cleaned with a solution of alcohol, ether, and acetone to reduce the impedance at the skin–electrode interface. The electrodes were filled with gel and attached longitudinally over each muscle belly with adhesive tape. The electrodes for soleus were placed 3 cm below the muscle–tendon junction of the gastrocnemius medialis in line with the Achilles tendon. The electrodes for gastrocnemius medialis were placed midway between the femoral condyle and the muscle–tendon junction. The electrodes for tibialis anterior were placed at one third of the distance between the fibular head and the lateral malleolus, and 1 cm lateral to the tibia. Particular attention was drawn to place the electrodes at the same locations across experimental sessions by taking anatomical landmarks. The reference electrodes were placed over the tibia. The EMG signals were amplified (1000×) and band-pass filtered (10–1000 Hz) prior to A/D sampling at 2 kHz (Power 1401, 16-bit resolution, Cambridge Electronic Design, UK) and storage on a computer.

#### 2.2.3. Electrical nerve stimulation and transcranial magnetic stimulation

Electrical stimuli (1-ms duration) applied to the tibial nerve were delivered via a constant current stimulator (DS7A, Digitimer, Hertfordshire, UK), that was connected to two surface electrodes (silver–silver chloride electrodes of 8-mm diameter) attached to the skin with adhesive tape at the knee level of the right leg. The cathode was placed in the popliteal fossa and the anode located just above the patella (Schieppati, 1987). The optimal site of stimulation was determined during upright standing by moving a pen electrode (cathode) until the site to elicit an H reflex in soleus with the largest amplitude at a given intensity was identified. The input–output relations for H reflex and M wave were determined in REO by progressively increasing the stimulus intensity in steps of 1 mA (5 stimulations by step) until the M-wave amplitude reached a plateau ($M_{max}$; Schieppati, 1987).

Transcranial magnetic stimulation (TMS) was applied over the left motor cortex by a double-cone coil (Magstim 200 stimulator, Magstim, Dyfed, UK). The optimal site of stimulation was determined by moving the coil until the site eliciting a motor evoked potential (MEP) in soleus with the largest amplitude at a given intensity was identified. A custom-made helmet was used to maintain the position of the coil without constraining upright standing. A previous experiment performed in our laboratory indicated that the postural stability was not influenced by keeping the coil on the head during unperturbed upright standing (Baudry et al., 2014b). The input–output relation was determined during bipedal upright standing by increasing the stimulation intensity in steps of 4–10% of the maximal output of the stimulator (5 stimulations by step) up to 100% of the stimulator output or until the MEP amplitude reached a plateau ($MEP_{max}$). The active motor threshold was defined during upright standing as the intensity at which four responses (>50 μV) out of five stimulations were discerned above background EMG level (Baudry et al., 2014a,b).

### 2.2.4. Maximal voluntary contraction

The torque developed during a maximal voluntary isometric contraction (MVC) with the ankle plantar flexor muscles of the right leg was recorded with the subjects seated in a custom-made ergometric device. The ankle and knee angles were positioned at 90° and 0° (full knee extension), respectively, and the foot tightly attached to a footplate that was connected to a force transducer (model 1085247-6005, Kistler, Winterthur, Switzerland). The force transducer signal was amplified and low-pass filtered at 200 Hz. Subjects performed at least three MVCs of the plantar flexor muscles. When peak torque of the two greatest MVCs was within 5% of each other, the greatest value was taken as the maximum. Otherwise, additional trials were performed until the 5% criterion was achieved (all subjects reached the 5% criterion within 5 MVCs). Moreover, trains of three pulses triggered 10 ms apart (3-pulse train; stimulus intensity of 120% of the lowest stimulus intensity eliciting $M_{max}$) were delivered to the tibial nerve during at least two of the plantar flexor MVCs (second and third MVCs), and to the remaining MVCs in the case the 5% criterion was not reached. The superimposed train was used to assess the degree of voluntary activation (Kent-Braun and Le Blanc, 1996). In addition, three 3-pulse trains applied over the tibial nerve were delivered at rest before each MVC. Three MVCs were also performed with the ankle dorsiflexor muscles.

### 2.2.5. Six-minute walk test

A 6-minute walk test was performed according to the guidelines of the American Thoracic Society (ATS, 2002). On a 30-m long corridor with marks every metre, the subjects performed as many round-trips as possible (one foot had always to be in contact with the ground) without the encouragements from the experimenter. The total distance walked was determined. To allow subjects to become accustomed to this test, a trial was performed during the familiarization session.

### 2.2.6. Experimental session

Each session started with the 6-min walk test followed by 30 min of rest. After the rest period and the placement of EMG recording and stimulation electrodes, each experimental session began with the recording of three sequences of 1 min in each balance condition (REO, REC, FEO). Subjects were allowed to rest as long as needed between trials to avoid fatigue, and the order of balance conditions was counterbalanced across subjects. Thereafter, the input–output relations for H reflex, M wave and MEP performed in REO were recorded. The input–output relations were only recorded in REO to prevent large balance perturbations that may have increased the risk of a fall event in REC or FEO. Then, in the ergometric device for strength measurement, 3-pulse trains were delivered at rest followed by plantar flexion and dorsiflexion MVCs.

## 2.3. Training protocol

The two training programmes consisted of two 1-h sessions per week (at least 48 h apart) over a period of six weeks. Each session started by a warm up (~10 min) that was identical for both training programmes, consisting of 5 min of cycling and 5 min of bodyweight exercises: standing calf raises, squat, and leg raises (forward and backward). The training sessions ended with stretching exercises of the lower limbs (5 min). In addition, two body-weight exercises involving spine flexors and erectors were also performed during each session. The authors documented and supervised all the training sessions.

### 2.3.1. Training exercises

Three strength exercises, performed on specific machines (Technogym®) that mainly involved muscles of the lower limbs and pelvis (leg press machine, calf raises on the leg press machine with knee extended, and hip extension machine), were performed with sets of 10 repetitions. The velocity of movement was not directly controlled but subjects were asked to perform the exercises at a moderate velocity to ensure a correct execution of the movement. Additionally, ankle dorsiflexions were performed against elastic bands. The order of the exercises changed across sessions. The balance exercises (30-s duration each) consisted of maintaining balance on different surfaces: rigid surface, foam mat (Airex, Sins, Switzerland) and BOSU® balance trainer (BOSU®, Ashland, OH, USA), vision conditions (eyes open, eyes closed) and feet conditions (bipodal natural feet position, joined, and tandem, and unipodal standing on each foot). The subjects were asked to retain balance in each exercise.

### 2.3.2. Training programmes

The strength and balance exercises that composed the main part of the session were similar in both groups (ST and BT) but the number of sets performed for each exercise differed across training programmes. In ST, one session was composed entirely of strength exercises (3 sets per exercise; 90-s rest) and one session composed of balance (1 set per exercise; ~6 exercises) and strength (1 set per exercise) exercises. In contrast, BT consisted of one weekly session devoted solely to balance exercises (~10 exercises, 3 sets per exercise; 30-s rest) and one session consisting of balance and strength exercises (similar to the second session of ST). Overall, 3/4 of the total amount of exercises in ST consisted of high-resistance exercises, whereas balance exercises composed 3/4 of the exercises in BT. The initial load used during the strength exercises corresponded to the maximal load a subject was able to move for 10 repetitions. This load was determined during the second session (the first session being used to familiarize the subjects with the machines) by increasing gradually the load until the subject could not perform more than 10 repetitions. On average, 4 sets were required to determine this load. Subsequently, when subjects were able to perform more than 10 repetitions within a set, the load was increased in a personalized manner (increment of 2.5 to 5%) during the course of the training programme. Similarly, the elastic bands used for the ankle dorsiflexion exercise were adjusted (increasing the degree of stretching and using an additional elastic band) to produce resistance that did not permit subjects to perform more than 10 repetitions (movements) per set. The difficulty of the balance exercises throughout the training program was increased by first changing the feet position from bipodal natural position to unipodal standing on the rigid surface and then by performing these exercises with eyes closed. Thereafter, the same progression for feet and vision conditions was applied when performing the exercises on the foam mat and on the BOSU®. The increase in exercise difficulty was triggered on a personalized basis by the ability of subjects to perform the 3 sets (30 s per trial) of a same exercise without losing balance.

## 2.4. Data reduction

After the force platform signals were low-pass filtered (cut-off frequency: 10 Hz), CoP parameters were computed for a 40-s epoch starting 10 s after the beginning of each trial without stimulation. The maximal forward–backward and side to side amplitude ($CoP_{max}$) and standard deviation ($CoP_{sd}$) of the CoP were determined with a 10-s moving window (throughout the 40-s epoch) to remove the influence of slow shifts in CoP position (Duarte and Freitas, 2010). The CoP mean velocity was also calculated. The average value of the rectified

EMG (aEMG) was calculated for each muscle during the same 40-s epoch used to measure CoP parameters. The statistical analysis of CoP parameters and associated EMG was performed on the average value of the three trials. The antagonist coactivation ratio was calculated by dividing the aEMG value averaged across the three plantar flexor muscles by those of the tibialis anterior, and then multiplied by 100 to provide a percentage of coactivation (average value of the plantar flexor aEMG / tibialis anterior aEMG x 100).

Peak torque during each MVC was measured, and the greatest value was taken as the maximum strength capacity of the subject. The aEMG associated with peak torque during plantar flexion and dorsiflexion MVC was determined over a 1-s epoch, and used as the reference to normalize the EMG activity of corresponding muscles during upright standing. In addition, the raw EMG signal from soleus was normalized with the $M_{max}$ amplitude to check for peripheral changes (muscle mass, subcutaneous tissue) and recording conditions between experimental sessions. The central activation ratio (CAR) for the plantar flexor muscles was calculated according to the following equation: MVC torque / (MVC torque + superimposed torque) (Kent-Braun and Le Blanc, 1996). The ratio was then multiplied by 100 to provide a percentage of full activation. The greatest CAR value was used in the analysis. Peak torque, time to peak and 1/2 relaxation time were measured from the mechanical response to the 3-pulse trains delivered at rest to assess training-related changes in contractile properties of the plantar flexor muscles.

The peak-to-peak amplitude and area of the H reflex, MEP and M wave were computed off-line from the unrectified EMG signal. The H-reflex and MEP amplitudes were normalized to $M_{max}$. As the peak-to-peak amplitude and area of the evoked responses exhibited similar features, only the peak-to-peak amplitudes are reported in the manuscript. In addition, the ascending part of the input–output relations for H reflex, M wave and MEP was fitted by a general least squares model (Klimstra and Zehr, 2008; Vila-Chã et al., 2012) (Fig. 1). Only the relations with $r^2 > 0.90$ were used for analysis, a threshold that was reached in each case. From the curve fitting analysis, the following parameters were determined: stimulus intensity at 50% of the maximal amplitude of the evoked potential ($H_{50}$, $M_{50}$, $MEP_{50}$), stimulus intensity at the maximal amplitude of the evoked potential ($H_{max}$, $M_{max}$, $MEP_{max}$), and the slope ($H_{sl}$, $MEP_{sl}$) of the ascending limb of the input–output relations calculated for the part of the curve corresponding to the stimulus intensity associated with $H_{50}$ and $MEP_{50}$. Moreover, the stimulus intensities (expressed relative to the stimulus intensity associated with $M_{50}$ and $MEP_{50}$) coinciding with the H-reflex and MEP variables computed from the pre-training input–output relations were used as inputs to the equations obtained for the post-training relations (Dragert and Zehr, 2011). To differentiate the parameters obtained from the fitted curves and from the standard recruitment curve, the predicted parameters were identified with "@" (Klimstra and Zehr, 2008; Vila-Chã et al., 2012) (Fig. 1). The predicted variables have been documented to be more sensitive parameters to training-induced changes (Dragert and Zehr, 2011; Klimstra and Zehr, 2008).

### 2.5. Statistics

Prior to the comparison of each dependent variable, the gaussian distribution of the data was verified by using Kolmogorov–Smirnov test. The effects of training were analysed by 2-way ANOVAs (programme × training) with Tukey post-hoc test when ANOVAs were significant. Pearson product–moment correlations were calculated for the association between changes in various variables. Paired Student t-tests were used to compare the dependent variables for the control group. The level of statistical significance was set at $p < 0.05$ for all comparisons. Values are expressed as mean (SD) in the text and tables and mean (SEM) in the figures.

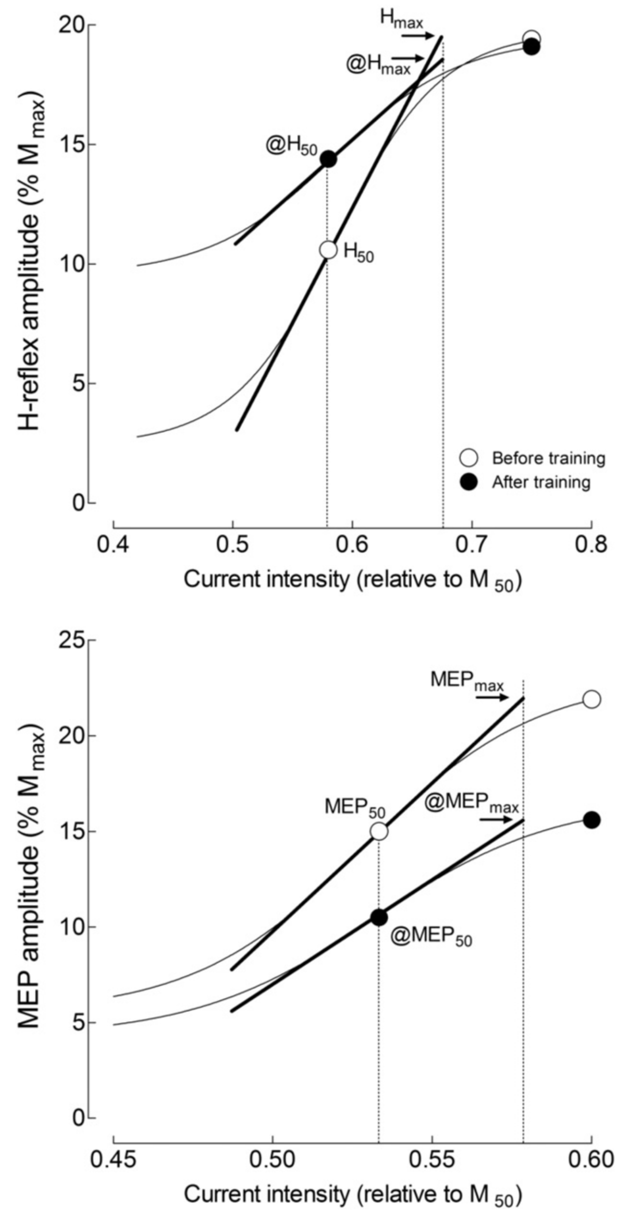


**Fig. 1.** Representative data for one subject (BT group) of the H-reflex (top panel) and motor evoked potential (MEP; bottom panel) parameters measured before training (○), and the same parameters predicted after training (●) by the current intensity associated with $H_{50}$ and $MEP_{50}$ (@$H_{50}$; $MEP_{50}$) and $H_{max}$ and $MEP_{max}$ (@$H_{max}$; @$MEP_{max}$); $H_{max}$, the maximum amplitude of the H reflex; $H_{50}$, H reflex with an amplitude of 50% of $H_{max}$; $MEP_{max}$, the maximum amplitude of MEP; $MEP_{50}$, MEP with an amplitude of 50% of MEP; the thick lines represent the slope of the input/output relation at $H_{50}$ (top panel) and $MEP_{50}$ (bottom panel).

## 3. Results

### 3.1. MVC and 3-pulse train

Before training, the maximal MVC torque of plantar flexor muscles was 91.7 (43.8) N·m and 90.2 (38.3) N·m for ST and BT groups, respectively, and did not differ significantly between groups. After training, MVC torque increased significantly (training main effect, $F_{1,16} = 49.8$, $p < 0.001$) with a trend for greater improvement for ST (+35.7%) compared with BT (+20.8%) (programme × training, $F_{1,16} = 4.3$, $p = 0.055$; effect size = 0.54) (Fig. 2, top panel). The gain in torque was negatively correlated with the pre-training MVC torque when data from ST and BT were pooled together [$MVC_{gain}$ (%) = $-0.74 \times MVC_{before}$ (N·m) + 72.2, r = 0.68, p =

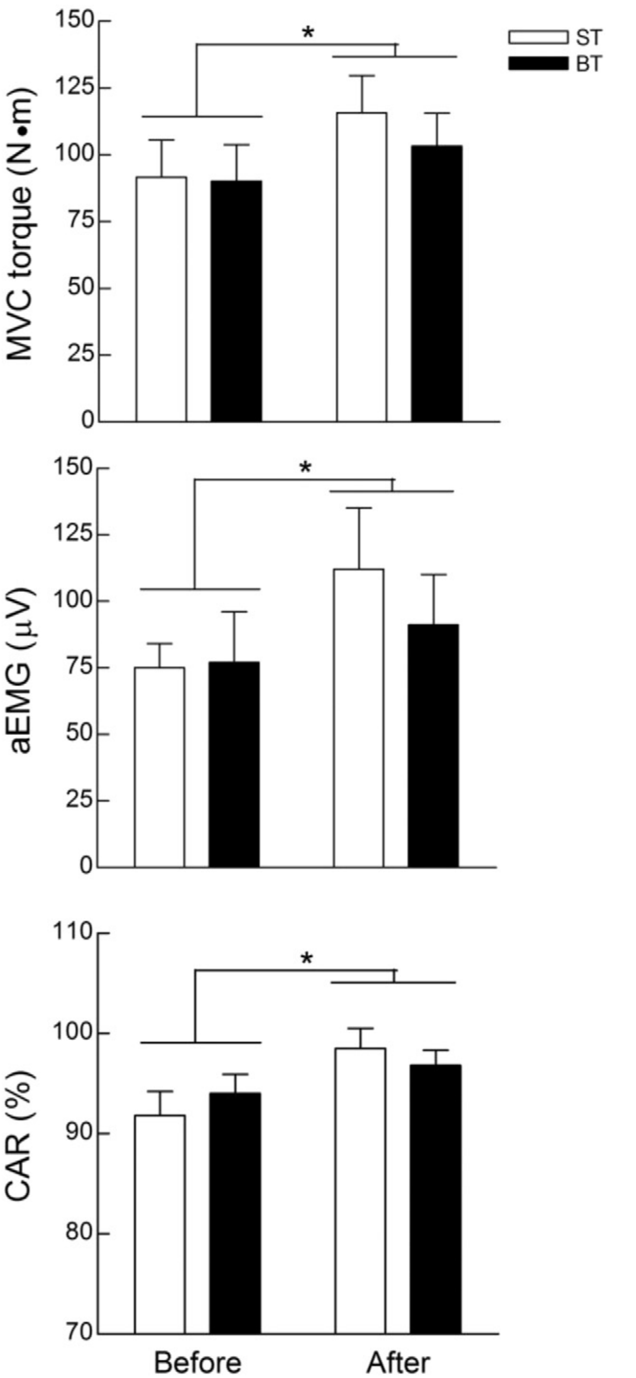


**Fig. 2.** MVC torque (top panel), associated EMG of plantar flexor muscles (mid panel) and central activation ratio (CAR; bottom panel) recorded during maximal voluntary plantar flexion contraction before and after training for strength (ST; open bars) and balance (BT; filled bars) training. Values are presented as mean (SE). * denotes a significant effect (training main effect) of training.

0.002]. Those changes were accompanied by an increase in aEMG for the plantar flexor muscles (training main effect, $F_{1,16} = 14.8$, $p = 0.002$) (Fig. 2, mid panel). After normalization with the corresponding $M_{max}$, the aEMG of soleus remained significantly greater than the pre-training value (training main effect, $F_{1,16} = 5.2$, $p = 0.037$). In agreement, the CAR increased after both training programmes (training main effect, $F_{1,16} = 22.7$, $p < 0.001$) without differences between groups (programme main effect, $F_{1,16} = 0.09$, $p = 0.77$) (Fig. 2, bottom panel). The gain in maximal torque was positively correlated with the gain in CAR when data from ST and BT were pooled together [$MVC_{gain}$ (%) = 3.2 × $CAR_{gain}$ (%) + 8.4, $r = 0.87$, $p < 0.001$].

The peak torque produced in response to the 3-pulse train applied to the tibial nerve did not change after training [before: 19.1 (2.7) N·m; after: 20.1 (2.1) N·m; training effect, $F_{1,16} = 0.8$, $p = 0.41$], regardless of the training programme [programme × training, $F_{1,16} = 2.3$, $p = 0.16$]. Similarly the time to peak [before: 167.2 (28.9) ms; after: 163.9 (0.52) ms, training effect, $F_{1,16} = 0.4$, $p = 0.57$] and 1/2 relaxation time [before: 122.1 (24.9) ms; after: 121.5 (2.1) ms; training effect, $F_{1,16} = 0.05$, $p = 0.83$] did not change with training, regardless of the training programme (programme × training, p values = 0.49 and 0.36 for time to peak and relaxation time, respectively).

Before training, the MVC torque produced by the dorsiflexor muscles was 21.0 (5.0) N·m and 23.6 (7.1) N·m for ST and BT, respectively, and did not differ significantly between groups. After training, it increased to 29.1 (6.9) N·m for ST and 25.9 (7.1) N·m for BT (training main effect, $F_{1,16} = 14.8$, $p = 0.002$) with a trend for greater improvement for ST (+41.7%) compared with BT (+11.8%) (programme × training, $F_{1,16} = 4.4$, $p = 0.056$, effect size = 1.1). The aEMG of tibialis anterior increased during MVC from 177.3 (82.2) μV before training to 254.5 (96.6) μV after training (training main effect, $F_{1,16} = 10.5$, $p = 0.005$).

### 3.2. Balance and 6-min walk test

Table 1 summarizes CoP parameters and associated leg muscles aEMG during the balance tests. The training programmes decreased $CoP_{max}$ (training main effect, $F_{1,16} = 19.6$, $p < 0.001$) and $CoP_{sd}$ (training main effect, $F_{1,16} = 13.7$, $p = 0.002$) recorded in the backward–forward direction during FEO, whereas no significant change was observed when subjects stood on a rigid surface (REO, REC). The gain in $CoP_{max}$ ($r = 0.14$; $p = 0.13$) and $CoP_{SD}$ ($r = 0.13$; $p = 0.14$) was not correlated with the change in MVC torque. The aEMG of plantar flexor muscles (expressed relative to the MVC value) decreased significantly after training for both ST and BT during REO (training main effect, $F_{1,16} = 11.7$, $p = 0.003$), REC ($F_{1,16} = 13.2$, $p < 0.001$) and FEO ($F_{1,16} = 4.7$, $p = 0.045$) whereas aEMG of tibialis anterior did not vary, regardless of balance conditions and training programme. However, when expressed relative to $M_{max}$, aEMG for soleus did not change significantly after training for REO (training effect, $F_{1,16} = 2.0$, $p = 0.19$), REC ($F_{1,16} = 0.4$, $p = 0.55$) and FEO ($F_{1,16} = 0.9$, $p = 0.36$), regardless of the training programme. The antagonist coactivation ratio did not change significantly after training for REO (training effect, $F_{1,16} = 0.5$, $p = 0.62$), REC ($F_{1,16} = 1.0$, $p = 0.27$) and FEO ($F_{1,16} = 1.2$, $p = 0.19$).

The distance walked during the 6-min test increased from 560.1 (96.5) m before training to 581.8 (103.0) m after training (training main effect, $F_{1,16} = 13.2$, $p = 0.003$) with no difference between training programmes (programme × training, $F_{1,16} = 0.8$, $p = 0.52$).

### 3.3. Evoked potentials

The $M_{max}$ amplitude was not significantly changed after training (training effect, $F_{1,16} = 0.69$, $p = 0.42$), regardless of the training programme (programme × training, $F_{1,16} = 0.10$, $p < 0.76$). Furthermore, neither the $H_{max}$ (training effect, $F_{1,16} = 1.5$, $p = 0.24$) nor the $MEP_{max}$ (training effect, $F_{1,16} = 1.6$, $p = 0.23$) was changed after training (Table 2). In contrast, the $H_{sl}$ (training main effect, $F_{1,16} = 4.8$, $p = 0.044$) and $MEP_{sl}$ ($F_{1,16} = 5.9$, $p = 0.031$) were significantly reduced after training. The normalized (% stimulus intensity at $M_{50}$) stimulus intensity at $H_{50}$ (training main effect, $F_{1,16} = 5.3$, $p = 0.036$) was significantly reduced after training whereas the stimulus intensity (% stimulus intensity at $MEP_{50}$) required to evoke $MEP_{max}$ was significantly increased (training main effect, $F_{1,16} = 10.6$, $p = 0.006$) in both training programmes (Table 2). The stimulus intensities relative to $H_{max}$ and $MEP_{50}$ did not change significantly after training ($p > 0.05$).

Fig. 1 illustrates for one subject the H-reflex (top panel) and MEP (bottom panel) amplitudes before training, and the predicted (@) H-

**Table 1**
CoP parameters and EMG activity of plantar flexor (PF) muscles and tibialis anterior before and after the two training programmes [strength training (ST) and balance training (BT)] during bipedal upright standing on a rigid surface with eyes open (REO) and eyes closed (REC), and with eyes open on foam surface (FEO).

| | ST | | | | | | BT | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | REO | | REC | | FEO | | REO | | REC | | FEO | |
| | Before | After | Before | After | Before | After | Before | After | Before | After | Before | After |
| $CoP_{velocity}$ (mm/s) | 9.7 (1.9) | 8.8 (2.0) | 11.8 (3.0) | 10.5 (2.8) | 23.6 (5.7) | 20.3 (8.3) | 10.7 (4.1) | 10.2 (2.5) | 14.7 (6.9) | 15.7 (6.9) | 24.4 (7.5) | 25.0 (4.4) |
| BF-$CoP_{max}$ (mm) | 18.5 (5.7) | 17.5 (6.1) | 22.4 (8.7) | 19.2 (4.5) | 45.6 (13.4) | 30.4* (8.2) | 21.6 (4.0) | 19.3 (7.3) | 28.1 (6.7) | 22.3 (6.3) | 42.7 (10.6) | 33.8* (8.3) |
| BF-$CoP_{SD}$ (mm) | 3.1 (0.7) | 2.7 (1.0) | 3.5 (0.9) | 3.2 (0.9) | 7.1 (1.9) | 5.1* (1.6) | 3.5 (0.5) | 3.1 (1.2) | 4.4 (0.9) | 4.1 (1.6) | 6.9 (2.0) | 5.8* (1.4) |
| StS-$CoP_{max}$ (mm) | 10.9 (4.3) | 12.0 (6.2) | 12.3 (2.8) | 13.0 (7.3) | 37.7 (18.1) | 30.2 (10.4) | 13.6 (5.2) | 11.3 (4.1) | 13.4 (6.9) | 14.6 (5.5) | 33.9 (10.9) | 34.7 (9.2) |
| StS-$CoP_{SD}$ (mm) | 1.6 (0.8) | 1.9 (1.3) | 1.8 (0.7) | 2.2 (1.5) | 5.3 (2.0) | 5.3 (1.8) | 2.0 (0.7) | 1.8 (0.8) | 2.4 (2.0) | 2.2 (1.1) | 5.7 (2.0) | 5.4 (1.1) |
| aEMG - PF muscles (% MVC) | 22.2 (11.1) | 15.4* (6.3) | 21.2 (10.8) | 15.6* (6.6) | 22.1 (8.5) | 18.4* (7.2) | 28.3 (6.8) | 20.0* (10.0) | 28.7 (9.0) | 18.3* (8.1) | 26.5 (6.5) | 21.0* (6.3) |
| aEMG - tibial anterior (% MVC) | 7.9 (11.1) | 15.5 (13.4) | 7.5 (3.5) | 13.9 (10.3) | 12.2 (15.0) | 12.0 (9.2) | 13.7 (12.3) | 14.4 (10.4) | 14.2 (12.9) | 8.7 (10.5) | 9.2 (6.0) | 7.1 (7.7) |

$CoP_{velocity}$: mean velocity of the CoP; BF-$CoP_{max}$ and StS-$CoP_{max}$: maximal displacement of the centre of pressure in the backward-forward and side-to side directions, respectively. BF-$CoP_{SD}$ and StS-$CoP_{SD}$: standard deviation of the centre of pressure in the backward-forward and side-to side directions, respectively; aEMG: averaged value of the rectified EMG. * denotes a significant effect (training main effect) of training. Data are presented as mean (SD).

reflex and MEP amplitudes obtained after training by the stimulus intensities associated with 50% of maximal amplitude (@$H_{50}$, @$MEP_{50}$) and maximal amplitude (@$H_{max}$, @$MEP_{max}$) calculated before training. The figure shows an increase in @$H_{50}$ and a decrease in @$MEP_{max}$ accompanied by a decrease in $H_{sl}$ and $MEP_{sl}$ after training. Similar results were obtained for the two groups of subjects (Fig. 3), with a significant increase in @$H_{50}$ (training main effect, $F_{1,16} = 5.5$, $p = 0.033$) after training whereas the @$MEP_{max}$ was reduced (training main effect, $F_{1,16} = 6.9$, $p = 0.021$), regardless of the training programmes.

### 3.4. Control group

For the eight subjects involved in the control group, none of the measured CoP parameters changed at 6 weeks (Table 3). Furthermore, maximal plantar flexor torque [before: 61.8 (28.4) N·m; after: 68.0 (26.2) N·m; $p = 0.57$] and CAR [before: 89.4 (11.9) %; after: 91.0 (6.3) %; $p = 0.69$] did not vary. Finally, the amplitude of the evoked potentials and characteristics of their respective recruitment curve did not change after the 6-week period (Table 4).

## 4. Discussion

The main findings of this study are: 1) the lack of significant difference in the effects of the two training programmes on the measured parameters, even though the gain in maximal strength tended to be greater for ST; 2) a slight improvement in CoP steadiness (maximal amplitude and mean fluctuations of the CoP in the backward–forward direction) during unstable balance condition accompanied by a decrease in plantar flexor muscles activity during upright standing regardless of the balance conditions; and 3) a slight reduction in @$MEP_{max}$ and the increase in @$H_{50}$ during unperturbed upright standing. This study demonstrates that short-term training which combines strength and balance exercises increases maximal strength and induces changes in the neural control of lower leg muscles during upright standing.

### 4.1. Maximal strength

The two training programmes that consisted of only two weekly sessions for 6 weeks led to similar (BT) or slightly larger gain (ST) in MVC strength compared with previous studies targeting ankle plantar flexor muscles (Scaglioni et al., 2002) or quadriceps muscles (Häkkinen et al., 2001) although these latter studies investigated longer training periods. When expressed as gain per session, strength increased to a greater extent in the present study [ST = 4.0 (3.4)% per session; BT = 6.8 (8.0)% per session] compared with that of Scaglioni et al. (2002) (0.4% per session) or Häkkinen et al. (2001)(0.6% per session). The differences in gain per session between studies reflect in part the faster strength gain occurring during the first weeks of training (Duchateau and Hainaut,

**Table 2**
Electrophysiological parameters recorded during bipedal upright standing on rigid surface with eyes open for the two training programmes [strength training (ST) and balance training (BT)].

| | ST | | BT | |
|---|---|---|---|---|
| | Before | After | Before | After |
| $M_{max}$ (mV) | 5.5 (2.0) | 4.8 (1.6) | 5.7 (2.4) | 5.4 (3.0) |
| $H_{max}$ (% $M_{max}$) | 26.7 (27.9) | 26.5 (22.0) | 22.8 (14.9) | 19.5 (9.9) |
| $H_{sl}$ | 126.1 (199.0) | 105.1 (142.7) * | 166.2 (237.9) | 101.9 (160.9) * |
| Stimulus intensity at $H_{50}$ (% 50% $M_{max}$) | 0.60 (0.06) | 0.57 (0.08) * | 0.59 (0.08) | 0.52 (0.08) * |
| Stimulus intensity at $H_{max}$ (% 50% $M_{max}$) | 0.78 (0.09) | 0.75 (0.12) | 0.90 (0.25) | 0.86 (0.19) |
| $MEP_{max}$ (% $M_{max}$) | 18.1 (8.4) | 16.1 (7.4) | 22.7 (12.7) | 17.4 (13.7) |
| $MEP_{sl}$ | 64.0 (37.0) | 50.0 (20.9) * | 66.6 (48.2) | 37.4 (26.1) * |
| Stimulus intensity at $MEP_{50}$ (% $MEP_{50}$) | 0.99 (0.06) | 0.99 (0.08) | 0.99 (0.07) | 1.04 (0.05) |
| Stimulus intensity at $MEP_{max}$ (% $MEP_{50}$) | 1.20 (0.04) | 1.34 (0.20) * | 1.26 (0.09) | 1.46 (0.20) * |

$M_{max}$: maximal amplitude of the M wave; $H_{max}$: maximal amplitude of the H reflex; $MEP_{max}$: maximal amplitude of the MEP; $H_{sl}$ and $MEP_{sl}$: slope of the input–output relation for the H reflex and MEP, respectively; Stimulus intensity at $H_{50}$, $MEP_{50}$: Stimulus intensity associated with an H reflex and MEP of 50% of their respective maximal amplitude; Stimulus intensity at $H_{max}$ and $MEP_{max}$: Stimulus intensity associated with $H_{max}$, $MEP_{max}$. The stimulus intensity for the H reflex was normalized to the stimulus intensity associated with a M-wave amplitude of 50% of $M_{max}$. Data are presented as mean (SD). * denotes a significant effect (training main effect) of training.

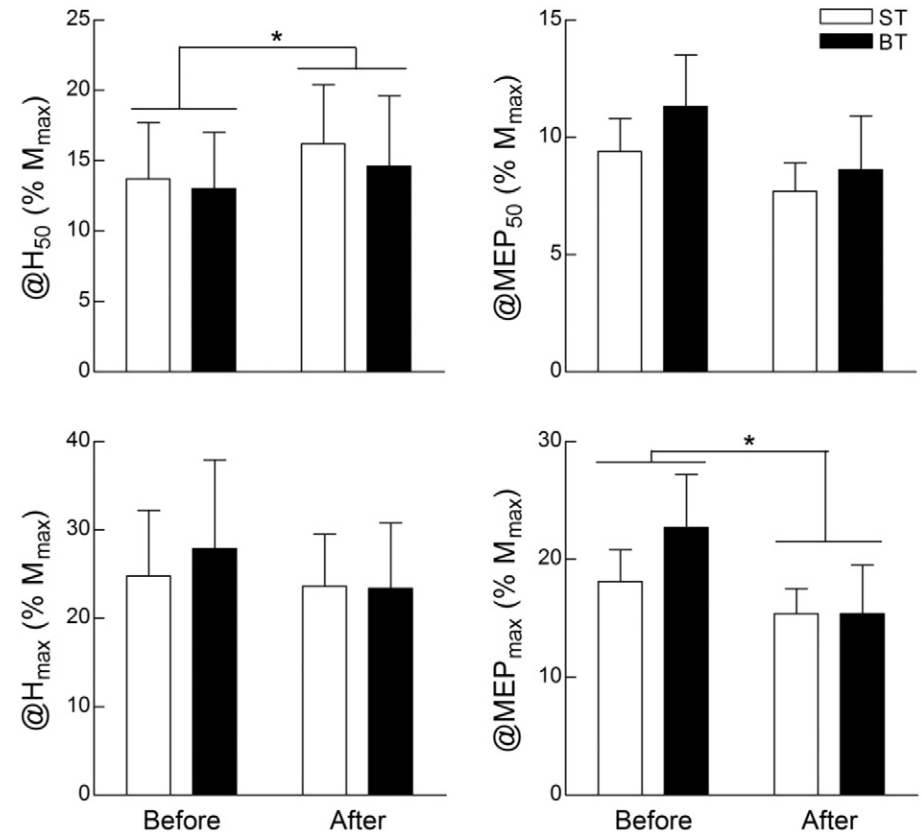


**Fig. 3.** Predicted H-reflex and MEP amplitudes evoked by the current intensity associated with $H_{50}$ (@$H_{50}$) and $MEP_{50}$ (@$MEP_{50}$), and at $H_{max}$ (@$H_{max}$) and $MEP_{max}$ (@$MEP_{max}$) observed before strength (ST) and balance training (BT). Values are presented as mean (SE). * denotes a significant effect (training main effect) of training.

1988) due to neural adaptations, as supported by the association of the strength gain with the increase in CAR and the lack of changes in peak torque produced in response to a 3-pulse train. Furthermore, compared with the study of Scaglioni et al. (2002), during which only one set of calf-rise exercise was performed three times per week for 16 weeks, our training programme (BT) consisted of a minimum of one set of calf-rise exercise and one set of leg press exercise. Although the latter exercise involves mainly the knee extensors, the contribution of the plantar flexor muscles is not negligible. In addition, as the soleus EMG activity during bipedal upright standing represented ~25% of the maximal activity measured during an MVC at the beginning of the training, the balance exercises performed with only one leg likely induced an activation greater than 50% of the maximum for this muscle, which could have induced strength gain, at least for the weakest subjects. In agreement, the gain in MVC torque was negatively correlated with the initial MVC torque, even when analysing separately the gain for the balance group ($r^2 = 0.57$, $p = 0.031$). Consistent with this assumption, dorsiflexor muscles were less activated during upright standing (~10% MVC) and consequently, balance exercises should have influenced to a lesser extent the maximal dorsiflexion strength in the BT group (+10%) than in the ST group (+41%). Together, these results suggest that combining strength exercises with balance exercises in a 2-day

**Table 3**
CoP parameters and EMG activity of plantar flexor (PF) muscles and tibialis anterior before and after the control period during bipedal upright standing on a rigid surface with eyes open (REO) and eyes closed (REC), and with eyes open on foam surface (FEO).

| | REO | | REC | | FEO | |
|---|---|---|---|---|---|---|
| | Before | After | Before | After | Before | After |
| $CoP_{velocity}$ | 11.0 | 10.8 | 10.8 | 10.3 | 26.3 | 24.2 |
| (mm/s) | (1.9) | (2.9) | (2.9) | (2.4) | (5.4) | (8.3) |
| BF-$CoP_{max}$ | 18.5 | 19.9 | 19.9 | 17.4 | 44.6 | 39.9 |
| (mm) | (3.4) | (5.0) | (5.0) | (5.0) | (8.8) | (10.7) |
| BF-$CoP_{SD}$ | 2.8 | 3.8 | 4.1 | 4.1 | 10.2 | 10.0 |
| (mm) | (0.7) | (1.9) | (0.9) | (1.8) | (2.6) | (2.9) |
| StS-$CoP_{max}$ | 10.2 | 13.3 | 13.3 | 17.1 | 34.1 | 40.1 |
| (mm) | (1.8) | (7.4) | (5.0) | (8.0) | (13.3) | (13.4) |
| StS-$CoP_{SD}$ | 4.6 | 4.8 | 4.1 | 5.4 | 12.0 | 13.0 |
| (mm) | (1.4) | (1.5) | (1.8) | (1.2) | (2.2) | (1.9) |
| aEMG-PF muscles | 22.1 | 25.4 | 24.1 | 22.6 | 27.1 | 24.1 |
| (% MVC) | (11.8) | (19.5) | (9.7) | (15.3) | (15.0) | (12.2) |
| aEMG-tibial anterior | 9.1 | 7.7 | 8.8 | 6.3 | 8.6 | 8.8 |
| (% MVC) | (3.2) | (3.0) | (3.4) | (2.9) | (4.1) | (2.8) |

$CoP_{velocity}$: mean velocity of the CoP; BF-$CoP_{max}$ and StS-$CoP_{max}$: maximal displacement of the centre of pressure in the backward–forward and side-to-side directions, respectively. BF-$CoP_{SD}$ and StS-$CoP_{SD}$: standard deviation of the centre of pressure in the backward–forward and side-to-side directions, respectively; aEMG: averaged value of the rectified EMG. Data are presented as mean (SD).

**Table 4**
Electrophysiological parameters recorded during bipedal upright standing on rigid surface with eyes open for the control group.

| | Before | After |
|---|---|---|
| $M_{max}$ (mV) | 5.3 (1.6) | 5.4 (1.7) |
| $H_{max}$ (% $M_{max}$) | 21.2 (14.0) | 18.0 (9.7) |
| $H_{sl}$ | 110.6 (60.1) | 102.7 (45.7) |
| Stimulus intensity at $H_{50}$ (% 50% $M_{max}$) | 0.58 (0.03) | 0.58 (0.04) |
| Stimulus intensity at $H_{max}$ (% 50% $M_{max}$) | 0.75 (0.03) | 0.79 (0.05) |
| $MEP_{max}$ (% $M_{max}$) | 16.1 (12.2) | 17.5 (8.4) |
| $MEP_{sl}$ | 82.6 (41.3) | 85.2 (56.8) |
| Stimulus intensity at $MEP_{50}$ (% $MEP_{50}$) | 1.14 (0.08) | 1.19 (0.03) |
| Stimulus intensity at $MEP_{max}$ (% $MEP_{50}$) | 1.0 (0.06) | 0.97 (0.04) |

$M_{max}$: maximal amplitude of the M wave; $H_{max}$: maximal amplitude of the H reflex; $MEP_{max}$: maximal amplitude of the MEP; $H_{sl}$ and $MEP_{sl}$: slope of the input–output relation for the H reflex and MEP, respectively; stimulus intensity at $H_{50}$, $MEP_{50}$: Stimulus intensity associated with an H reflex and MEP of 50% of their respective maximal amplitude; stimulus intensity at $H_{max}$ and $MEP_{max}$: Stimulus intensity associated with $H_{max}$, $MEP_{max}$. The stimulus intensity for the H reflex was normalized to the stimulus intensity associated with a M-wave amplitude of 50% of $M_{max}$. Data are presented as mean (SD).

per week design is sufficient to improve strength in leg muscles of untrained elderly adults, with a greater effect on the weakest individuals. Regarding the trend and effect size, it is very likely that a longer training period would have increased the MVC torque to a greater extent for ST compared with BT.

In contrast to previous work reporting greater strength gain after multiple-set compared with single set protocols in both young (Borst et al., 2001; Hansen et al., 2012; Kraemer et al., 2000) and elderly adults (Galvão and Taaffe, 2005), an interesting finding from the present study is the lack of significant difference in strength gain between the two training programmes. There is, however, a trend for greater improvement after ST (+35.7%) than BT (+20.8%; effect size = 0.54) that is reversed when expressed as %gain per set of strength exercises involving the plantar flexor muscles (calf raises and leg press machines; ST: 0.7%/set; BT: 1.6%/set). In addition to the difference in the number of sets per strength exercise, the two programmes differed by the number of sessions during which strength exercises were performed. In the BT group, subjects performed only one set per week of each strength exercise whereas in the ST group, subjects performed a total of four sets of each exercise. However, as already mentioned, balance exercises performed with one leg likely represent moderate to high loads for the weaker subjects, and those exercises should have contributed to an increase in muscle strength in the BT group.

### 4.2. CoP steadiness

Previous studies reported either an absence of change (Buchner et al., 1997; Manini et al., 2007; Wolfson et al., 1996) or an improved CoP steadiness (Liu-Ambrose et al., 2004; Messier et al., 2000) after ST in elderly adults. These contrasting findings likely originate from the variety of training regimen used (intensity, duration, frequency) and the assessment of postural stability (feet position, duration of the trials). In the present study, strength exercises were accompanied by balance exercises in order to combine the effects of both exercise types. Regardless of the relative amount of strength and balance exercises in the two groups, training slightly improved CoP steadiness in the most unstable balance condition (foam surface), but only in backward–forward direction. This might represent the effects of increased strength of the muscles controlling ankle plantarflexion and dorsiflexion, even though the lack of correlation of strength gain with CoP steadiness minimizes such possibility. Furthermore, the lack of significant difference in EMG activity after normalization to the $M_{max}$ indicates that the reduced EMG activity (expressed relative to EMG recorded during MVC) of the plantar flexor muscles during upright standing after training should mainly reflect the increase in maximal EMG recorded during the MVC. In the absence of change in the coactivation ratio, the results further suggest that the improved CoP steadiness after training should have involved subtle neural changes. Nonetheless, the increased difference in EMG between upright stance and MVC after training indicates an enhanced reserve in muscle activation for upright standing and locomotion.

### 4.3. Corticospinal and spinal pathways

Despite the lack of change in $H_{max}$ and $MEP_{max}$ after training, the slope of the input–output relations for H reflex and MEP decreased. In the absence of change in $H_{max}$, the decrease in $H_{sl}$ and the increase in @$H_{50}$ suggest that training influenced the lower part of the H-reflex recruitment curve, likely through a reduction in Ia presynaptic inhibition (Tucker et al., 2005). In contrast, the decrease in @$MEP_{max}$ that accompanies the decrease in $MEP_{sl}$ suggests a reduction in the number of motor units recruited by the corticospinal pathway after training when assessed at the highest intensity used before training. Such decrease in corticospinal excitability is in agreement with the decrease in MEP amplitude from tibialis anterior observed during balance tasks after BT training in young adults (Beck et al., 2007; Schubert et al., 2008). Interestingly, elderly adults exhibit greater corticospinal excitability and reduced efficacy of Ia afferents to activate soleus motor neurones during upright standing compared with young adults (Baudry et al., 2014a). The present results suggest that training may reverse the age-related changes in the neural control of lower leg muscles during upright standing towards those encountered in young adults. The absence of correlation of strength gain and improvement in CoP steadiness with neural adjustments recorded during upright standing, however, questions the factors triggering the latter adjustments.

### 4.4. Functional implications

In addition to the slight increase in CoP steadiness during upright standing on a foam mat, the two training programmes led to a significant increase in the distance walked in 6 min. This improvement in performance, that may be due in part to increased physical activity associated with commuting to the training centre, can have contribute to reduce the risk of falls in this population (Stenhagen et al., 2013). It is also worth noting that only healthy elderly adults living at home participated in this study, raising the possibility that greater effects could even be observed in elderly who undergo limitations in locomotor or balance capacity. In the context of physical activity programmes for elderly adults, our results suggest that a slower increase in the mechanical constraints on joints, tendon and muscles can be obtained by starting with training session containing mainly balance exercises before incorporating sessions mainly composed of strength exercises.

## 5. Conclusion

In conclusion, this study indicates that short-term training combining strength and balance exercises can improve maximal strength and induce neural changes related to the control of leg muscles during upright standing, regardless of the respective amount of strength and balance exercises that composed the training programmes. Nonetheless, those changes were accompanied by only minor improvement in CoP steadiness, suggesting that gains in strength and postural steadiness may not be closely related in healthy elderly adults. It remains unknown, however, whether longer training durations could induce differences in neuromuscular adaptations and CoP steadiness between the two training programmes.

## Acknowledgements

The authors acknowledge Gregory Carlier, ergotherapist at the Geriatric department of the Erasmus Hospital (Brussels), for his assistance in designing the training programmes.

Stéphane Baudry is currently supported by a grant of the "Fonds National de la Recherche Scientifique (FRS-FNRS)" (1B24013F) of Belgium.
The authors declare no competing financial interests.

## References

American Thoracic Society, 2002. ATS statement: guidelines for the six-minute walk test. Am. J. Respir. Crit. Care Med. 166, 111–117.
Baudry, S., Duchateau, J., 2012. Age-related influence of vision and proprioception on Ia presynaptic inhibition in soleus muscle during upright stance. J. Physiol. 590, 5541–5554.
Baudry, S., Klass, M., Duchateau, J., 2005. Postactivation potentiation influences differently the nonlinear summation of contractions in young and elderly adults. J. Appl. Physiol. 98 (4), 1243–1250.
Baudry, S., Penzer, F., Duchateau, J., 2014a. Input–output characteristics of soleus homonymous Ia afferents and corticospinal pathways during upright standing differ between young and elderly adults. Acta Physiol. 210, 667–677.
Baudry, S., Penzer, F., Duchateau, J., 2014b. Vision and proprioception do not influence the excitability of the corticomotoneuronal pathway during upright standing in young and elderly adults. Neuroscience 268, 247–254.
Beck, S., Taube, W., Gruber, M., Amtage, F., Gollhofer, A., Schubert, M., 2007. Task-specific changes in motor evoked potentials of lower limb muscles after different training interventions. Brain Res. 1179, 51–60.
Billot, M., Simoneau, E.M., Van Hoecke, J., Martin, A., 2010. Age-related relative increases in electromyography activity and torque according to the maximal capacity during upright standing. Eur. J. Appl. Physiol. 109, 669–680.
Borst, S.E., De Hoyos, D.V., Garzarella, L., Vincent, K., Pollock, B.H., Lowenthal, D.T., Pollock, M.L., 2001. Effects of resistance training on insulin-like growth factor-I and IGF binding proteins. Med. Sci. Sports Exerc. 33 (4), 648–653.
Brouwer, B.J., Walker, C., Rydahl, S.J., Culham, E.G., 2003. Reducing fear of falling in seniors through education and activity programs: a randomized trial. J. Am. Geriatr. Soc. 51 (6), 829–834.
Buchner, D.M., Nicola, R.M., Martin, M.L., Patrick, D.L., 1997. Physical activity and health promotion for older adults in public housing. Am. J. Prev. Med. 13 (6), 57–62.
Clark, B.C., Manini, T.M., 2012. What is dynapenia? Nutrition 28 (5), 495–503.
Dragert, K., Zehr, E.P., 2011. Bilateral neuromuscular plasticity from unilateral training of the ankle dorsiflexors. Exp. Brain Res. 208 (2), 217–227.
Duarte, M., Freitas, S.M., 2010. Revision of posturography based on force plate for balance evaluation. Rev. Bras. Fisioter. 14 (3), 183–192.
Duchateau, J., Hainaut, K., 1988. Training effects of sub-maximal electrostimulation in a human muscle. Med. Sci. Sports Exerc. 20 (1), 99–104.
Galvão, D.A., Taaffe, D.R., 2005. Resistance exercise dosage in older adults: single-versus multiset effects on physical performance and body composition. J. Am. Geriatr. Soc. 53 (12), 2090–2097.
Goble, D.J., Coxon, J.P., Van Impe, A., Geurts, M., Doumas, M., Wenderoth, N., Swinnen, S.P., 2011. Brain activity during ankle proprioceptive stimulation predicts balance performance in young and older adults. J. Neurosci. 31 (45), 16344–16352.
Granacher, U., Muehlbauer, T., Zahner, L., Gollhofer, A., Kressig, R.W., 2011. Comparison of traditional and recent approaches in the promotion of balance and strength in older adults. Sports Med. 41 (5), 377–400.
Häkkinen, K., Kraemer, W.J., Newton, R.U., Alen, M., 2001. Changes in electromyographic activity, muscle fibre and force production characteristics during heavy resistance/power strength training in middle-aged and older men and women. Acta Physiol. Scand. 171, 51–62.
Hansen, E.A., Rønnestad, B.R., Vegge, G., Raastad, T., 2012. Cyclists' improvement of pedaling efficacy and performance after heavy strength training. Int. J. Sports Physiol. Perform. 7 (4), 313–321.
Horak, F.B., Shupert, C.L., Mirka, A., 1989. Components of postural dyscontrol in the elderly: a review. Neurobiol. Aging 10 (6), 727–738.
Howe et al. 2011. Keen DA, Yue GH, Enoka RM. Training-related enhancement in the control of motor output in elderly humans. J. Appl. Physiol. 77(6): 2648–58, 1994.
Kent-Braun, J.A., Le Blanc, R., 1996. Quantitation of central activation failure during maximal voluntary contractions in humans. Muscle Nerve 19, 861–869.
Klimstra, M., Zehr, E.P., 2008. A sigmoid function is the best fit for the ascending limb of the Hoffmann reflex recruitment curve. Exp. Brain Res. 186 (1), 93–105.
Kraemer, W.J., Ratamess, N., Fry, A.C., Triplett-McBride, T., Koziris, L.P., Bauer, J.A., Lynch, J.M., Fleck, S.J., 2000. Influence of resistance training volume and periodization on physiological and performance adaptations in collegiate women tennis players. Am. J. Sports Med. 28 (5), 626–633.
Liu-Ambrose, T., Khan, K.M., Eng, J.J., Janssen, P.A., Lord, S.R., McKay, H.A., 2004. Resistance and agility training reduce fall risk in women aged 75 to 85 with low bone mass: a 6-month randomized, controlled trial. J. Am. Geriatr. Soc. 52 (5), 657–665.
Manini, T., Marko, M., VanArnam, T., Cook, S., Fernhall, B., Burke, J., Ploutz-Snyder, L., 2007. Efficacy of resistance and task-specific exercise in older adults who modify tasks of everyday life. J. Gerontol. A Biol. Sci. Med. Sci. 62 (6), 616–623.
Messier, S.P., Royer, T.D., Craven, T.E., O'Toole, M.L., Burns, R., Ettinger Jr., W.H., 2000. Long-term exercise and its effect on balance in older, osteoarthritic adults: results from the Fitness, Arthritis, and Seniors Trial (FAST). J. Am. Geriatr. Soc. 48 (2), 131–138.
Orr, R., 2010. Contribution of muscle weakness to postural instability in the elderly. A systematic review. Eur. J. Phys. Rehabil. Med. 46 (2), 183–220.
Orr, R., Raymond, J., Fiatarone Singh, M., 2008. Efficacy of progressive resistance training on balance performance in older adults. A systematic review of randomized controlled trials. Sports Med. 38 (4), 317–343.
Papegaaij, S., Taube, W., Baudry, S., Otten, E., Hortobágyi, T., 2014a. Aging causes a reorganization of cortical and spinal control of posture. Front. Aging Neurosci. 6, 28.
Papegaaij, S., Taube, W., Hogenhout, M., Baudry, S., Hortobágyi, T., 2014b. Age-related decrease in motor cortical inhibition during standing under different sensory conditions. Front. Aging Neürosci. http://dx.doi.org/10.3389/fnagi.2014.00126.
Scaglioni, G., Ferri, A., Minetti, A.E., Martin, A., Van Hoecke, J., Capodaglio, P., Sartorio, A., Narici, M.V., 2002. Plantar flexor activation capacity and H reflex in older adults: adaptations to strength training. J. Appl. Physiol. 92, 2292–2302.
Schieppati, M., 1987. The Hoffmann reflex: a means of assessing spinal reflex excitability and its descending control in man. Prog. Neurobiol. 28, 345–376.
Schubert, M., Beck, S., Taube, W., Amtage, F., Faist, M., Gruber, M., 2008. Balance training and ballistic strength training are associated with task-specific corticospinal adaptations. Eur. J. Neurosci. 27 (8), 2007–2018.
Shaffer, S.W., Harrison, A.L., 2007. Aging of the somatosensory system: a translational perspective. Phys. Ther. 87 (2), 193–207.
Shumway-Cook, A., Anson, D., Haller, S., 1988. Postural sway biofeedback: its effect on reestablishing stance stability in hemiplegic patients. Arch. Phys. Med. Rehabil. 69 (6), 395–400.
Stenhagen, M., Ekström, H., Nordell, E., Elmståhl, S., 2013. Falls in the general elderly population: a 3- and 6-year prospective study of risk factors using data from the longitudinal population study 'Good ageing in Skane'. BMC Geriatr. 13, 81.
Taube, W., Gruber, M., Beck, S., Faist, M., Gollhofer, A., Schubert, M., 2007. Cortical and spinal adaptations induced by balance training: correlation between stance stability and corticospinal activation. Acta Physiol. 189, 347–358.
Tucker, K.J., Tuncer, M., Türker, K.S., 2005. A review of the H-reflex and M-wave in the human triceps surae. Hum. Mov. Sci. 24 (5–6), 667–688.
Vandervoort, A.A., 2002. Aging of the human neuromuscular system. Muscle Nerve 25 (1), 17–25.
Vandervoort, A.A., McComas, A.J., 1986. Contractile changes in opposing muscles of the human ankle joint with aging. J. Appl. Physiol. 61 (1), 361–367.
Vila-Chã, C., Falla, D., Correia, M.V., Farina, D., 2012. Changes in H reflex and V wave following short-term endurance and strength training. J. Appl. Physiol. 112 (1), 54–63.
Wolfson, L., Whipple, R., Derby, C., Judge, J., King, M., Amerman, P., Schmidt, J., Smyers, D., 1996. Balance and strength training in older adults: intervention gains and Tai Chi maintenance. J. Am. Geriatr. Soc. 44 (5), 498–506.
Woolcott, J.C., Richardson, K.J., Wiens, M.O., Patel, B., Marin, J., Khan, K.M., Marra, C.A., 2009. Meta-analysis of the impact of 9 medication classes on falls in elderly persons. Arch. Intern. Med. 169, 1952–1960.