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Neural and muscular factors both contribute to plantar-flexor muscle weakness in older fallers

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ABSTRACT

Plantar-flexor muscles are key muscles in the control of postural sway. Older fallers present lower maximal plantar-flexor performance than older non-fallers; however, the mechanisms underlying this motor impairment remain to be elucidated. This study aimed to determine whether muscular and neural factors are both involved in the lower maximal plantar-flexor performance of older fallers. The maximal voluntary contraction (MVC) torque, resting twitch torque, voluntary activation level (VAL), and electromyographic (EMG) activities for the soleus, gastrocnemius medialis, gastrocnemius lateralis and tibialis anterior during plantar-flexor MVCs were recorded in 23 older non-fallers (age: 83.3 ± 3.9 years) and 25 older fallers (age: 84.0 ± 4.1 years). The maximal plantar-flexor Hoffmann reflex normalized to the maximal motor potential (H_{\max}/M_{\max}) was measured to assess the efficacy of spinal transmission from the Ia-afferent fibers to the α -motoneurons. Older fallers presented lower plantar-flexor MVC torque, resting twitch torque, VAL and EMG activity ($P < 0.05$). No significant differences between older fallers and non-fallers were found for the H_{\max}/M_{\max} ratio and dorsi-flexor coactivation. The current findings showed for the first time that both neural and muscular factors associated with the plantar-flexors contributed to the specific alteration of maximal motor performance in older fallers. The lack of a difference in the H_{\max}/M_{\max} ratio indicated that the efficacy of spinal transmission from the Ia-afferent fibers to the α -motoneurons was not involved in the lower voluntary muscle activation of older fallers. This suggests that supraspinal centers are likely to be involved in the lower voluntary muscle activation observed in older fallers.

1. Introduction

Falls are a common adverse event during aging. More than 30% of people older than 75 years experience one or more falls annually (Tinetti et al., 1988), causing injury, loss of function, and death (Fried et al., 2017). Given that the aging population is growing intensely, knowledge of the major risk factors contributing to falling is crucial.

One of the main risk factors for falls in older people is the weakness of lower extremity muscles (Tinetti et al., 1988; Landi et al., 2012), especially the plantar-flexor muscles (Perry et al., 2007; LaRoche et al., 2010; Cattagni et al., 2014a; Cattagni et al., 2016). Plantar-flexor muscles are strongly required in the generation and the transmission of

force to the ground in various functional activities such as during perturbed/unperturbed standing balance (Loram et al., 2001; Morasso and Schieppati, 1999; Runge et al., 1999) or gait (McGowan et al., 2008; Akizuki et al., 2001), supporting weight of body and providing stability at the ankle and feet during these tasks. In this context, maintain a high level of plantar-flexor muscle strength and power is important to prevent falls. The maximal voluntary contraction (MVC) strength of these muscles is however drastically affected during aging (Vandervoort and McComas, 1986; Hunter et al., 2000). Although the ankle muscle strength produced to maintain body balance is relatively submaximal ($\sim 5\%$ of the MVC torque in young adults, $\sim 11\%$ in elderly non-fallers and $\sim 19\%$ in elderly fallers (Cattagni et al., 2016)), the age-

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related muscle weakness has been associated with increased postural sways, reduced anteroposterior limit of stability, gait disorders, and increased risk of falling after an experimental gait perturbation (Cattagni et al., 2014a; Cattagni et al., 2016; Melzer et al., 2009; Rubenstein and Josephson, 2002; Pijnappels et al., 2008). For example, it has been demonstrated a strong relationship between plantar-flexor MVC strength and the center of pressure displacement during bipedal and unipedal stance (Cattagni et al., 2014a; Cattagni et al., 2016; Billot et al., 2010a). It has also been reported lower plantar-flexor MVC strength as well as lower explosive strength (power or rate of force development) in older fallers than in older non-fallers (Perry et al., 2007; LaRoche et al., 2010; Cattagni et al., 2014a; Cattagni et al., 2016; Skelton et al., 2002). While the neuromuscular mechanisms underlying the age-related decline in plantar-flexor MVC strength are well documented (Vandervoort, 2002), the contributions of both muscular and neural factors to the lower plantar-flexor MVC strength in older fallers remain to be determined.

At the muscle level, contractile properties can be indirectly examined by evoking a resting twitch using a single supramaximal stimulus of the motor nerve and analyzing the resulting torque signal. Twitch torque amplitude is well correlated with muscle size, especially for the plantar-flexor muscles, even if other factors such as muscle quality (i.e. muscle specific tension and muscle typology/property), efficacy of the excitation–contraction coupling process and tendon stiffness may also influence it (Ryan et al., 2011; Behrens et al., 2016). Twitch torque amplitude may be used, therefore, to estimate intrinsic muscle strength-generating capacity (i.e. regardless of neural activation). It is known that the twitch torque amplitude of the plantar-flexor muscles is altered with aging (Scaglioni et al., 2003), highlighting an age-related decline in muscle quantity (atrophy) and quality (Scaglioni et al., 2016). In summary, we can expect a specific alteration of intrinsic muscle strength-generating capacity in older fallers leading to a lower twitch torque compared to non-fallers. At the neural level, the voluntary activation level (VAL) of the α -motoneuron pool, i.e., the (in) ability of the central nervous system to fully activate skeletal muscle (Hunter et al., 2016), can be assessed using the twitch interpolation technique. While changes in the VAL with age are controversial (Scaglioni et al., 2003; Dalton et al., 2014; Morse et al., 2004; McPhee et al., 2018), a deficit in VAL could be involved in the lower muscle strength of older fallers. Given that the regulation of α -motoneuron activity depends on supraspinal and spinal inputs, it is also of interest to investigate possible differences in the excitability of the spinal reflex pathway (peripheral level). The spinal reflex pathway of the plantar-flexor muscles is generally assessed using surface electromyography (EMG) by measuring the amplitude of the maximal Hoffmann (H) reflex (H_{\max}), normalized to the maximal M-wave (direct motor response, M_{\max}). This H_{\max}/M_{\max} ratio is known to represent the efficiency of spinal transmission from the Ia-afferent fibers to the α -motoneuron pool (Schieppati, 1987; Kido et al., 2004; Koceja et al., 1995). Interestingly, an age-related decrease in the H_{\max}/M_{\max} ratio (Kido et al., 2004) was associated with postural instability in older people (Koceja et al., 1995). Due to higher postural instability in older fallers (Tinetti et al., 1988; Cattagni et al., 2014a), a reduced H_{\max}/M_{\max} ratio in older fallers may be expected. Finally, the MVC torque reflects the algebraic sum of torques produced by the agonist and antagonist muscles and thus is affected by their level of activation (Cattagni et al., 2016; Billot et al., 2010b)(Cattagni et al., 2016; Koceja et al., 1995)(Billot et al., 2010b; Kubo et al., 2004). Consequently, differences in plantar-flexor MVC torque between older fallers and non-fallers could be explained, at least in part, by changes in dorsal-flexor coactivation. Although it is unlikely that a difference in coactivation between older fallers and non-fallers was observed, we proposed to assess the tibialis anterior (i.e. the main dorsi-flexor) activation during plantar-flexor MVCs.

This study aimed therefore to investigate the neuromuscular mechanisms underlying plantar-flexor weakness in older fallers. We hypothesized that muscle weakness would result from alterations at both

Table 1
Participants' characteristics.

	Non-fallers	Fallers
Age, year	83.3 \pm 3.9	84.0 \pm 4.1
Body mass, kg	61.8 \pm 9.9	63.4 \pm 9.5
Body height, cm	159.9 \pm 7.6	161.2 \pm 9.8
Body mass index, kg/m ²	24.1 \pm 2.8	24.4 \pm 2.5
MMSE score	28.2 \pm 1.5	27.7 \pm 1.4
Physical activity level (score)	6.6 \pm 1.7	6.3 \pm 1.3

Data are presented as mean \pm SD. MMSE: mini-mental state examination. Note that no statistical difference was observed between groups.

neural (reduction in VAL) and muscular (reduction in twitch torque amplitude) levels.

2. Methods

2.1. Participants

Forty-eight volunteers aged 75–90 years participated in this experiment: 23 older non-fallers (mean age \pm standard deviation [SD]: 83.3 \pm 3.9 years; 6 men and 17 women) and 25 older fallers (84.0 \pm 4.1 years; 7 men and 18 women). All baseline characteristics [body height, body mass, body mass index, mini-mental state examination (MMSE) score and level of physical activity score] are summarized in Table 1. The history of falls in the previous year and the level of physical activity using the updating Baecke physical activity questionnaire in French (Vol et al., 2011) (where 3 is the lowest score and 15 is the highest score) were recorded by interview during the inclusion visit. A fall was defined as “an unexpected event in which the participants come to rest on the ground, floor, or lower level” (Lamb et al., 2005). Participants who had fallen unexpectedly at least once in the previous year were included in the older fallers group. The MMSE was used to assess the cognitive status of the participants (Folstein et al., 2018). Exclusion criteria included musculotendinous injury, osteoarticular trauma and lower limb surgery in the year prior to inclusion, serious visual impairment, body mass index $>$ 30 kg/m², impaired cognitive status (MMSE \leq 25), the use of medication interacting with neural and muscular functions and comorbidities altering neuromuscular function and balance control such as myopathy, neurological disease, psychiatric disease, vestibular disease, chronic obstructive pulmonary disease, neuro-orthopedic pathology, peripheral arterial disease, diabetes mellitus, and metastatic disease. The study experimental design was approved by the ethics committee of Nantes Ouest IV (reference number: 726/2015), and it was conducted according to the Helsinki Statement. Participants provided written informed consent.

2.2. Experimental procedure

Because a greater asymmetry in muscle strength production and/or power between the legs may be observed in older fallers, in comparison with non-fallers (Perry et al., 2007; Skelton et al., 2002), both legs were evaluated separately in a randomized order. Participants were tested in a seated position with the trunk inclined backward at 20° to the vertical, the leg extended and the ankle joint fixed at 90° (Fig. 1A). The H-reflex and M-wave recruitment curves of the soleus (SOL), gastrocnemius medialis (GM) and gastrocnemius lateralis (GL) were performed to obtain the H_{\max} (Fig. 2A) and the M_{\max} (Fig. 2B) responses for the plantar-flexor muscles and the resting twitch recorded at M_{\max} (Fig. 2B). Two minutes after a standardized warm-up (see below), the participants performed three 4–5 s dorsi-flexor MVCs separated by a three-minute rest period. After the dorsi-flexor MVCs, the participants performed a standardized warm-up for the plantar-flexor muscles. After two-minute rest period, they performed three 5-s plantar-flexor MVCs separated by a three-minute rest period. Paired stimuli were delivered

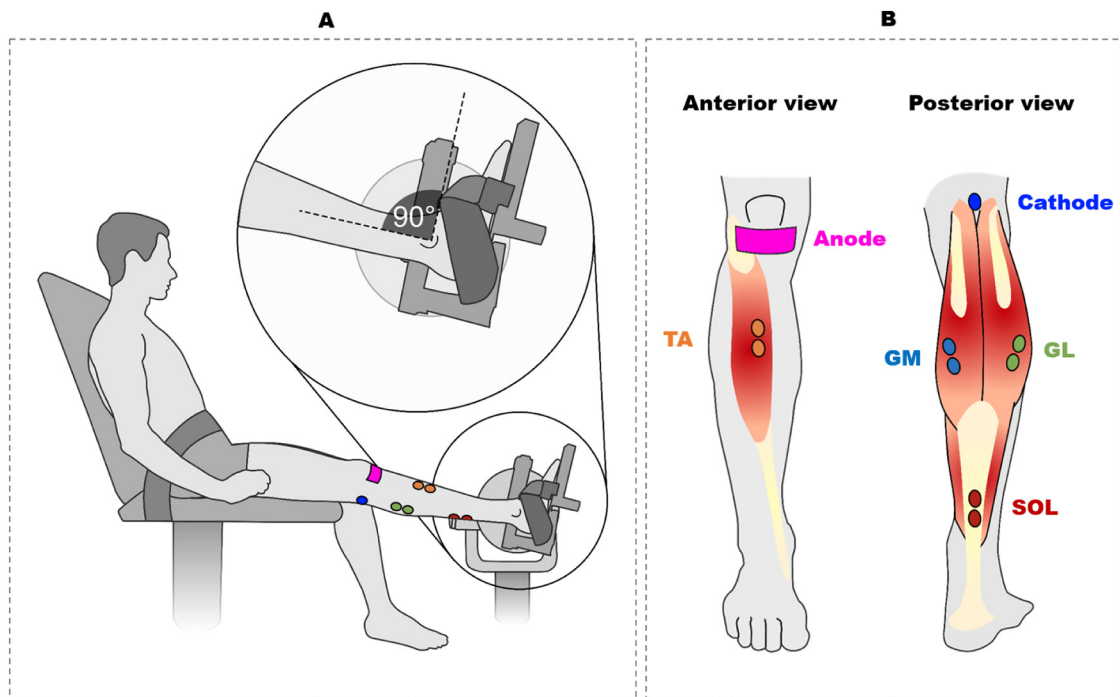


Fig. 1. Participant position (A) and placement of the electromyographic (EMG) and stimulation electrodes (B). SOL: soleus; GM: gastrocnemius medialis; GL: gastrocnemius lateralis.

during (superimposed doublet), and 3–4 s after (potentiated doublet), the MVC to investigate plantar-flexor VAL using the twitch interpolation technique (Strojnik & Komi, 2015; Allen et al., 1995) (Fig. 2C). Throughout the participants' attempts to produce maximal effort, standardized verbal encouragement was provided during all MVC efforts. The standardized warm-up for dorsi-flexor and plantar-flexor muscles consistently included nine 4–5 s submaximal isometric contractions (3 contractions at 25%, 50% and 90% of the estimated MVC torque) separated by 10 s. The standardized warm-up was also used to familiarize participants with plantarflexion and dorsiflexion contractions.

2.3. Data collection

2.3.1. Torque recordings

Torque was measured with the foot secured by straps to the footplate of a custom-made ergometer (I.U.T. Génie Mécanique, Dijon, France) used in previous studies (Cattagni et al., 2014a; Cattagni et al., 2016). The footplate was connected to a strain-gauge transducer (Société Doerler-Vandoeuvre, France), placed on the axis of the device, and an amplifier (PM Instrumentation, model 1300B).

2.3.2. Electrophysiological recordings

At the beginning of the experimental session, the participants' skin was carefully prepared by shaving and cleaning with alcohol. Pairs of silver chloride (Ag-AgCl) surface electrodes (Kendall Medi-Trace™, Canada) of 1 cm diameter with an inter-electrode distance (center-to-center) of 2 cm were used to record the EMG activity of the ankle muscles (Fig. 1B). The SOL recording electrodes were placed along the mid-dorsal line of the right leg, ~5 cm below the insertion of the two heads of the gastrocnemii on the Achilles tendon. The GM and GL recording electrodes were fixed longitudinally over the middle of the muscle belly. The EMG activity of the tibialis anterior was also recorded to assess any potential coactivation. For this muscle, the electrodes were positioned on a line, one third of the distance between the fibula and the tip of the medial malleolus. The reference electrodes were placed on the patella of the left leg.

The torque and EMG signals were both sampled at 2 kHz using two synchronized Biopac acquisition systems (MP35, Biopac, Goleta, USA), and stored with commercially available software (BIOPAC student Lab Pro, Biopac, Goleta, USA), for off-line analysis. The EMG signal was amplified using a bandwidth frequency ranging from 5 Hz to 500 Hz (gain = 500).

2.3.3. Electrical stimulation

The electrophysiological responses (the H-reflex and the M-wave) of the SOL, GM, and GL were evoked by percutaneous stimulation of the posterior tibial nerve with a single rectangular pulse (1 ms), and a high voltage (400 V), delivered by a Digitimer stimulator (Model DS7-AH, Hertfordshire, UK). A self-adhesive cathode (1 cm-diameter, Ag-AgCl) was placed in the popliteal fossa and the anode (5 × 10 cm, Medicompex SA, Ecublens, Switzerland) was placed on the anterior surface of the knee (Fig. 1B). The optimum cathode position (the site where the greatest H-reflex potential in the SOL was evoked), was located with a hand-held cathode ball (0.5 cm-diameter). Once the position was determined, the cathode electrode was fixed to this site using tape, as recently recommended to optimize the participant's comfort (Cattagni et al., 2017). The H-reflex and M-wave recruitment curves were performed by using 4 mA increments until the intensity evoking maximal M-wave responses (M_{\max}) and maximal twitch torque amplitude (i.e. optimal intensity) was achieved. Four stimuli were delivered at each intensity interspaced by a 10-s interval. A supramaximal intensity (120% of the optimal intensity) was then used for the paired stimuli evoked during and after the MVC efforts.

2.4. Data analysis

2.4.1. Evoked responses and contractile properties

For the SOL, GM, and GL, the peak-to-peak amplitudes of the H_{\max} , the $M_{\text{at-Hmax}}$ (the M-wave recorded with the H_{\max}) and the M_{\max} were calculated as the mean of four recordings (Cattagni et al., 2014b). The H_{\max}/M_{\max} ratio was calculated to assess the proportion of motor units that were activated by the Ia afferents and potential differences in the balance between excitation and inhibition at the spinal level

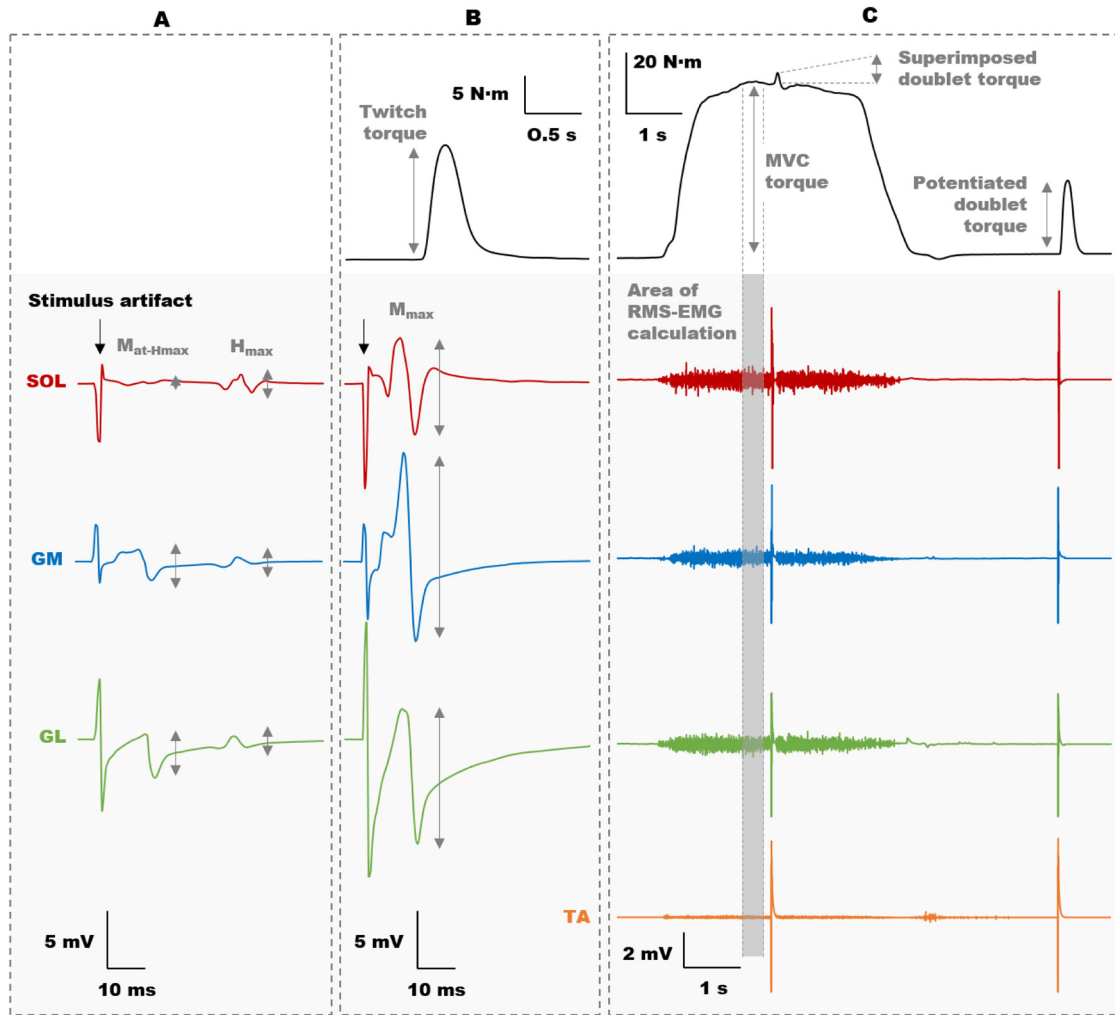


Fig. 2. Typical raw mechanical (white area) and electrophysiological (light gray area) traces during the H-reflex and M-wave recruitment curve (A & B) and the plantar-flexor maximal voluntary contraction (MVC) effort (C). A represents the EMG recordings for soleus (SOL), gastrocnemius medialis (GM) and gastrocnemius lateralis (GL) obtained at their respective maximal H-reflex (H_{max}) stimulation intensity. B represents torque and EMG recordings for SOL, GM, and GL obtained during maximal direct motor response (M_{max}) stimulation. C represents torque and EMG recordings for SOL, GM, GL and tibialis anterior (TA) obtained during the maximal voluntary contraction using the twitch interpolation technique. $M_{at-Hmax}$ represents the M-wave associated with H_{max} .

(Schieppati, 1987). To determine whether the same proportion of α -motoneurons was activated by the electrical stimulation between the groups, the $M_{at-Hmax}/M_{max}$ ratio was compared (Cattagni et al., 2014b). The plantar-flexor contractile properties were measured from the twitch associated with the M_{max} stimulation. They included peak twitch torque, contraction time (the delay from twitch onset to peak torque), half-relaxation time (duration from peak torque to half peak torque value), mean twitch torque development (ratio of peak twitch torque to twitch contraction time), neuromuscular efficiency (twitch-torque/ M_{max}) (Simoneau et al., 2007) and electromechanical delay (duration from the first onset of the M-wave in the plantar-flexor muscles to the onset of the twitch response). Manual identification of signal onsets being the 'gold standard' method (Tillin et al., 2010; Dotan et al., 2016), twitch onset and M-wave onset were visually determined. For each parameter, the mean of the four twitch/EMG responses was considered for further analysis.

2.4.2. MVC torque and muscle activation

The MVC torque was considered as the highest peak torque value measured over the three trials. The VAL was quantified by measuring the superimposed torque response to nerve stimulation during the MVC effort (Allen et al., 1995). The VAL was estimated according to the following formula, including the Strojnik and Komi (Strojnik & Komi,

2015) correction:

$$VAL = \left(1 - \frac{\text{superimposed doublet} \times \frac{\text{Torque}_{at \text{ stimulation}}}{MVC \text{ torque}}}{\text{Potentiated doublet}} \right) \times 100$$

The EMG activity of the SOL, GM, GL and tibialis anterior during the plantar-flexor MVC efforts was quantified as the root mean square (RMS) value over a 0.5 s interval around the peak MVC torque (Fig. 1B). The RMS value was consistently taken prior to the time of the superimposed stimulus. The maximal RMS-EMG (EMG_{max}) values of the plantar-flexor muscles were then normalized to the M_{max} amplitude for the respective muscles to obtain the EMG_{max}/M_{max} ratio [arbitrary units (a.u.)]. To provide an index of antagonist muscle coactivation during the plantar-flexor MVC effort, the tibialis anterior RMS-EMG recorded during the plantar-flexor MVC efforts was normalized to the RMS-EMG recorded during the highest dorsi-flexor MVC (EMG_{antag}).

2.5. Statistical analysis

Statistical tests were performed in Statistica v10.0 (Statsoft, Tulsa, OK, USA). Distributions consistently passed the Kolmogorov-Smirnov

normality test, and thus, all data are reported as the mean \pm SD. The level of significance was set at $P < 0.05$. For clarity, data from both legs were averaged, since all initial statistical analyses revealed no significant main effect or interaction for “leg”.

Independent *t*-tests (fallers vs. non-fallers) were used to examine all baseline characteristics (Table 1), and the MVC torque, contractile properties, VAL, and tibialis anterior EMG_{antag}. Finally, separate analysis of variance tests (ANOVAs) were performed on the amplitudes for the M_{\max} , the H_{\max} , and the H_{\max}/M_{\max} , $M_{\text{at-Hmax}}/M_{\max}$ and $\text{EMG}_{\max}/M_{\max}$ ratios; with group ($\times 2$: fallers vs. non-fallers) as the between-participants factor, and muscle ($\times 3$: SOL, GM vs. GL) as the within-participants factor. Post hoc analyses were performed using Tukey HSD comparisons. Partial eta squared ($\rho\eta^2$) values have been reported as measures of the effect size, with $\rho\eta^2 > 0.14$ considered to be a very large effect and $0.07 < \rho\eta^2 < 0.14$ considered to be a moderate effect (Cohen, 1988).

3. Results

No significant differences in any of the participant characteristics (i.e., anthropometric data and MMSE score) were found between fallers and non-fallers (Table 1).

3.1. MVC torque and twitch contractile properties

The plantar-flexor MVC torque was significantly lower (-26.6% , $P < 0.001$, $\rho\eta^2 = 0.37$) in fallers than in non-fallers (Fig. 3A). Likewise, the plantar-flexor resting twitch torque was statistically lower (-12.5% , $P < 0.05$, $\rho\eta^2 = 0.10$) in fallers than in non-fallers (Fig. 3B). No difference between non-fallers and fallers was found for twitch contraction time (non-fallers: 142 ± 18 ms vs. fallers: 149 ± 42 ms), half-relaxation time (non-fallers: 156 ± 17 ms vs. fallers: 162 ± 32 ms), neuromuscular efficiency (non-fallers: 3.1 ± 1.4 N·m·mV⁻¹ vs. fallers: 3.1 ± 1.3 N·m·mV⁻¹), and electro-mechanical delay (non-fallers: 36 ± 2 ms vs. fallers: 36 ± 2 ms) (all P values > 0.4 and all $\rho\eta^2$ values < 0.02). Importantly, a significant difference ($P < 0.05$, $\rho\eta^2 = 0.09$) was found for mean rate of twitch torque development (non-fallers: 92.8 ± 23.2 N·m·s⁻¹ vs. fallers: 78.9 ± 22.2 N·m·s⁻¹, -15%).

3.2. VAL and EMG activities

The VAL was significantly lower (-11.3% , $P < 0.05$, $\rho\eta^2 = 0.12$) in fallers than in non-fallers (Fig. 3C). For the $\text{EMG}_{\max}/M_{\max}$ ratio, the ANOVA revealed only a main group effect ($F_{(1, 46)} = 8.2$, $P < 0.01$, $\rho\eta^2 = 0.15$), indicating a lower $\text{EMG}_{\max}/M_{\max}$ ratio for the plantar-flexor muscles of fallers (-24.2%) (Fig. 4A,B,C). For the $\text{EMG}_{\text{antag}}$, the ANOVA failed to reveal any difference between groups ($F_{(1, 46)} = 2.1$, $P = 0.16$, $\rho\eta^2 = 0.04$) (Fig. 4D).

3.3. Evoked potentials

The evoked potentials values are reported in Table 2. The ANOVA revealed no main effect for group (M_{\max} : $F_{(1, 46)} = 1.0$, $P = 0.32$, $\rho\eta^2 = 0.02$) and muscle (M_{\max} : $F_{(2, 92)} = 1.5$, $P = 0.22$, $\rho\eta^2 = 0.03$) for the M_{\max} , indicating that their amplitudes were not different between fallers and non-fallers for all the plantar-flexor muscles. For the H_{\max} and the H_{\max}/M_{\max} ratio, no significant difference between groups was found (H_{\max} : $F_{(1, 46)} = 0.3$, $P = 0.56$, $\rho\eta^2 = 0.01$; H_{\max}/M_{\max} : $F_{(1, 46)} = 0.0$, $P = 0.99$, $\rho\eta^2 = 0.00$), irrespective of the plantar-flexor muscle. A significant muscle effect (H_{\max} : $F_{(2, 92)} = 41.1$, $P < 0.001$, $\rho\eta^2 = 0.02$; H_{\max}/M_{\max} : $F_{(2, 92)} = 33.4$, $P < 0.001$, $\rho\eta^2 = 0.42$) showed a higher H_{\max}/M_{\max} ratio for SOL compared to GM and GL ($P < 0.001$). No difference between the gastrocnemii was shown. When considering the $M_{\text{at-Hmax}}/M_{\max}$ ratio, there was no main effect for group ($F_{(1, 46)} = 0.0$, $P = 0.87$, $\rho\eta^2 = 0.00$), irrespective of the plantar-

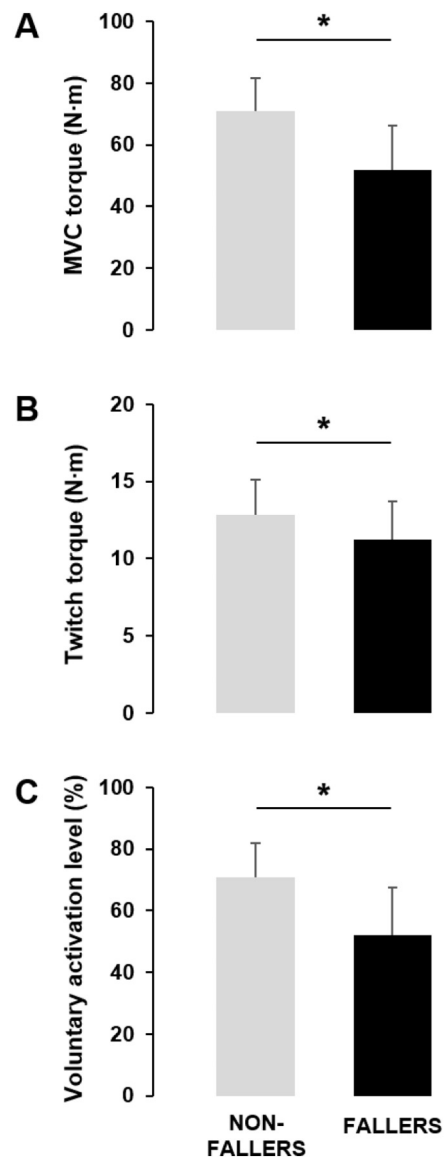


Fig. 3. Maximal voluntary contraction (MVC) torque (A), twitch torque (B) and voluntary activation level (C) for the plantar-flexor muscles in older non-fallers and fallers. Data represent means \pm SD. *Significant difference between groups, $P < 0.05$. MVC: maximal voluntary contraction.

flexor muscle.

4. Discussion

The main finding of the present study is that both voluntary activation failure and alteration of contractile properties contribute to the specific muscle weakness observed in older fallers. Indeed, a lower plantar-flexor activation and twitch torque were observed in fallers than in non-fallers. In addition, the lack of any difference between groups in the H_{\max}/M_{\max} ratio suggests that voluntary activation failure in fallers is not explained by change in the efficacy of the spinal reflex pathway.

4.1. Maximal neuromuscular performance

Low muscular strength and power in the lower extremities is known to be one of the crucial risk factors for balance disorders and falls in older adults (Tinetti et al., 1988; Landi et al., 2012; Todd and Skelton, 2004). The current results provide additional evidence for the specific

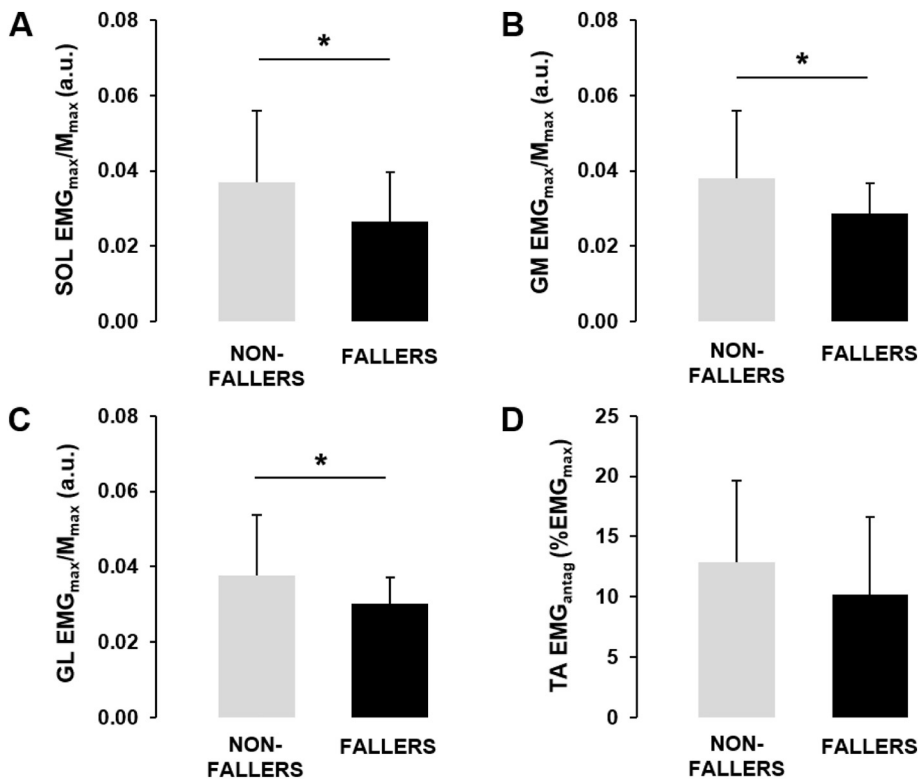


Fig. 4. Agonist (A, B & C) and antagonist (D) electromyographic (EMG) activities during the maximal voluntary contraction of the plantar-flexor muscles in older non-fallers and fallers. Data represent means \pm SD. *Significant difference between groups, $P < 0.05$. For the plantar-flexor muscles (A, B & C), the maximal RMS-EMG activity (EMG_{max}) was normalized to the maximal direct motor response (M_{max}). For the tibialis anterior (TA, D), the submaximal RMS-EMG activity (EMG_{antag}) recorded during maximal voluntary plantarflexion was expressed as a percentage of its maximal RMS-EMG activity recorded during maximal voluntary dorsiflexion. SOL: soleus; GM: gastrocnemius medialis; GL: gastrocnemius lateralis.

Table 2
Evoked potentials in older non-fallers and fallers.

		Non-fallers	Fallers
SOL	M_{max} , mV	4.5 ± 2.4	4.3 ± 2.4
	H_{max} , mV	1.1 ± 0.9	0.9 ± 0.8
	H_{max}/M_{max} , %	26.5 ± 20.4	23.2 ± 18.6
	$M_{at-Hmax}/M_{max}$, %	36.6 ± 25.4	33.5 ± 24.1
GM	M_{max} , mV	5.2 ± 2.8	4.6 ± 2.3
	H_{max} , mV	0.5 ± 0.4	0.5 ± 0.4
	H_{max}/M_{max} , %	10.0 ± 8.7	12.4 ± 13.9
	$M_{at-Hmax}/M_{max}$, %	42.8 ± 30.8	49.5 ± 26.2
GL	M_{max} , mV	4.5 ± 1.8	4.0 ± 1.6
	H_{max} , mV	0.6 ± 0.4	0.5 ± 0.5
	H_{max}/M_{max} , %	13.7 ± 12.5	14.9 ± 15.4
	$M_{at-Hmax}/M_{max}$, %	42.3 ± 28.6	43.2 ± 29.8

Data are presented as mean \pm SD. SOL: soleus; GM: gastrocnemius medialis; GL: gastrocnemius lateralis. M_{max} : maximal direct motor response (M-wave); H_{max} : maximal Hoffmann reflex. $M_{at-Hmax}$: M-wave associated with H_{max} . Note that no statistical difference was observed between groups.

decline of plantar-flexor MVC torque in older fallers. Indeed, we found a 27% reduction in plantar-flexor MVC torque in older fallers, in accordance with previous studies reporting a decline of $\approx 25\%$ – 34% (Perry et al., 2007; LaRoche et al., 2010; Cattagni et al., 2014a; Cattagni et al., 2016). Overall, these findings support the belief that falls occur in some postural perturbation situations when the neuromuscular reserve required to counteract imbalance is likely insufficient. Given the clinical relevance of preventing muscle weakness and falls in older people, the current study aimed to clarify the specific mechanisms (i.e. muscle and neural factors) underpinning the low plantar-flexor MVC torque in older fallers.

4.2. Muscle factors

By using peripheral nerve stimulation, it is possible to non-invasively assess intrinsic muscle contractile properties without the influence of voluntary neural drive. Resting twitch torque measurements

provide a good representation of intrinsic muscle torque-generating capacity, since they are well correlated with muscle cross-sectional area (Ryan et al., 2011; Behrens et al., 2016). In the current study, the twitch torque amplitude was 12% lower in fallers. This indicates that intrinsic muscle function alterations are likely to contribute to the lower plantar-flexor MVC torque of fallers. We therefore assumed that the age-related alterations in muscle function are more pronounced in older fallers. These age-related alterations include i) a decline in muscle size, volume and mass (Morse et al., 2004; Csapo et al., 2014) (i.e. muscle quantity), mainly due to the loss of muscle fiber innervation by α -motoneurons (Campbell et al., 1973); and/or ii) a decline in muscle quality, as revealed by the age-related drop in muscle specific strength (i.e. strength per unit cross-sectional area), mainly resulting from the accumulation of non-contractile tissues in muscle (e.g. intramuscular adipose and connective tissues infiltration) and changes in muscle typology/property (Morse et al., 2004; McPhee et al., 2018; Csapo et al., 2014; D'Antona et al., 2003). It is important to note that the assessment of intrinsic plantar-flexor torque-generating capacity was not direct in the present study, which precludes a more accurate identification of potential differences i) within plantar-flexor muscles and ii) in muscle quantity and/or quality. Therefore, we recommend that future work should perform magnetic resonance imaging analyses in older fallers and non-fallers to compare plantar-flexor architecture by examining volume, anatomical and/or physiological cross-sectional area and non-contractile tissue infiltration. However, even if no direct measurement of muscle quantity has been performed, our results provide significant new insights into muscle function using analyses of twitch contractile kinetics. The between-group differences in twitch torque and mean rate of twitch torque development may suggest i) a lower proportion of fast-twitch fibers, as lately reported in elderly females presenting a recent fall-related fracture in comparison with age-matched healthy elderly controls (Kramer et al., 2017), and/or ii) a lower tendon stiffness in older fallers. Indeed, as a result of physiological differences between type I and II fibers that induce faster cross-bridge cycling rates for type II fibers, the rate of strength development is higher in type II than in type I fibers (see (Maffiuletti et al., 2016) for review). However, it

should be acknowledged that this result is actually not confirmed by the twitch contraction time, which may be also influenced by muscle typology (Doherty and Brown, 1997; Lewis et al., 2018), since no differences in twitch contraction and half-relaxation time were observed between groups, suggesting that contractile kinetics were similar in both groups. In addition, it has been shown that changes in tendon compliance may alter the rate of twitch torque development (Mayfield et al., 2016).

The lack of any difference in the M_{\max} between groups suggests no specific peripheral alteration localized at the level of the axon or sarcolemma in fallers. However, although the twitch torque was reduced in older fallers, the twitch-torque/ M_{\max} ratio was similar between groups, indicating no particular neuromuscular efficiency adaptations in older fallers. The electromechanical delay is another feature of muscle quality. It is influenced by physiological factors, including i) propagation of action potentials along the sarcolemma and excitation-contraction coupling, and ii) biomechanical factors including muscle force transmission along the series elastic component, i.e. muscle-tendon stiffness (Nordez et al., 2009). The lack of any difference in electromechanical delay between groups suggests no specific alteration of this muscle feature in older fallers.

4.3. Neural factors

Changes in MVC torque can also be the consequence of a reduced ability of the central nervous system to fully activate muscles. The VAL and the EMG/ M_{\max} ratio are two markers of muscle activation. The results showed a lower VAL (−11%) in fallers, associated with a concomitant reduction in the EMG/ M_{\max} ratio. This indicates that older fallers present a specific efferent neural drive alteration resulting from changes in the recruitment of plantar-flexor motor units. In addition, the H_{\max}/M_{\max} ratio was measured for the first time in older fallers to assess whether changes in muscle activation could be related to a nervous system dysfunction at the spinal level. Interestingly, no difference in the H_{\max}/M_{\max} ratio between non-fallers and fallers was found. This strongly suggests that the efficacy of the monosynaptic reflex is not involved in the lower muscle activation observed in older fallers. Moreover, while a lower level of the H_{\max}/M_{\max} ratio was associated with postural instability in older people (Koceja et al., 1995), our results confirm that the efficacy of the transmission from Ia afferents to the α -motoneurons would not be a relevant fall risk indicator. This relative preservation of peripheral nerve function, including the spinal pathway, in older fallers suggests that the corticospinal tract is likely to be the main contributor to their muscle activation deficit. According to the size principle of motor unit recruitment, the fast-twitch motor neurons would have the highest recruitment thresholds (Henneman et al., 1974). Therefore, it can be assumed that neural drive sent by supra-spinal structures is not strong enough to recruit fast-twitch motor neurons with high excitability thresholds. Further studies are needed using transcranial magnetic stimulation and/or electroencephalography, to better determine the mechanisms of the central deficit (e.g. corticospinal excitability) in older fallers.

In addition to activation failure, excessive antagonist activity may also cause muscle weakness. Indeed the MVC torque reflects the algebraic sum of torques produced by the agonist and antagonist muscles, and thus it is affected by their level of activation (Kubo et al., 2004). No difference in tibialis anterior coactivation was observed between the groups, suggesting that antagonist muscle activity during plantar-flexor MVCs is not a mechanism underlying the decline in plantar-flexor MVC torque in older fallers.

4.4. Conclusion

This study shows that the specific alteration of maximal motor performance in older fallers is the consequence of both neural and muscular impairments. The relative preservation of spinal reflex

excitability in older fallers suggests that the corticospinal pathway is likely to be the main factor underlying the neural impairments. With regard to the relative preservation of neuromuscular plasticity with age (Toien et al., 2017; Aagaard et al., 2010), the present findings highlight the importance of falls prevention programs for frail older people to strengthen both the muscular and neural functions of the postural muscles. This may include well-known methods for improving muscle neural activation (e.g. muscle-tendon vibration, motor imagery, electrical or magnetic brain stimulation), and the intrinsic strength-generating capacity of muscle (e.g. eccentric exercises or neuromuscular electrical stimulation).

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Update

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Corrigendum

Corrigendum to “Neural and muscular factors both contribute to plantar-flexor muscle weakness in older fallers” [Exp. Gerontol. 112 (2018) 127–134]



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The authors regret to inform the readers that an error happened in Fig. 3C, which does not illustrate the correct values of voluntary activation level.

The correct values of voluntary activation level are $85.3 \pm 10.9\%$ for non-fallers and $75.7 \pm 15.3\%$ for fallers. Now this figure has been

corrected as appropriate.

The authors confirm that this change does not alter the conclusions of the paper.

The authors would like to apologize for any inconvenience caused.

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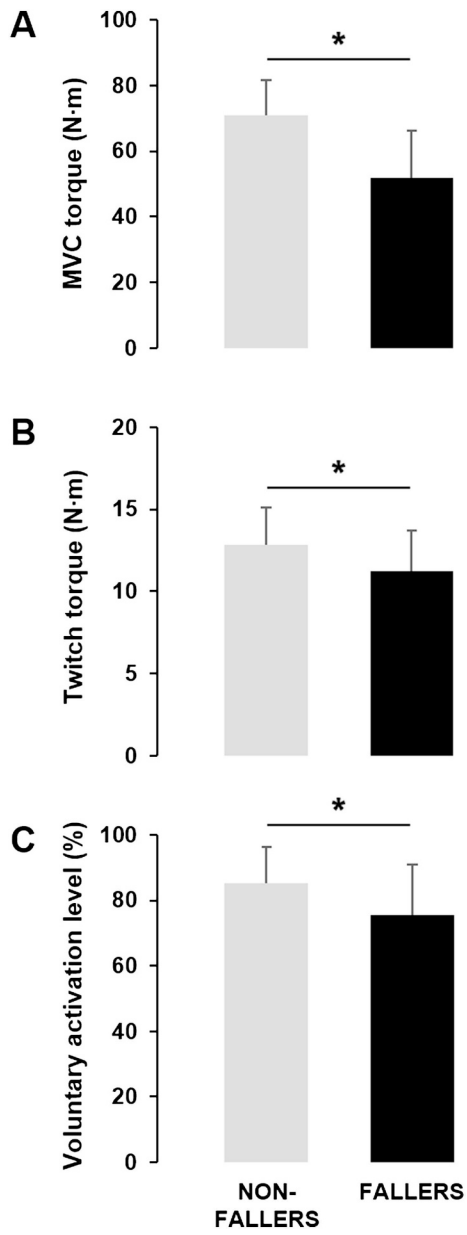


Fig. 3.