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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 perturbated/unperturbated 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 (~5% of the MVC torque in young adults, ~11% in elderly non-fallers and ~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 neural (reduction in VAL) and muscular (reduction in twitch torque amplitude) levels.

Table 1
Participants' characteristics.

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

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

2. Methods

2.1. Participants

Forty-eight volunteers aged 75–90 years participated in this experiment: 23 older non-fallers (mean age ± standard deviation [SD]: 83.3 ± 3.9 years; 6 men and 17 women) and 25 older fallers (84.0 ± 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/m^2, impaired cognitive status (MMSE ≤ 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