

Adaptations to long-term strength training of ankle joint muscles in old age

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Abstract The aim of this study was to enquire whether older adults, who continue plantar-flexion (PF) strength training for an additional 6-month period, would achieve further improvements in neuromuscular performance, in the ankle PFs, and in the antagonist dorsi-flexors (DFs). Twenty-three healthy older volunteers (mean age 77.4 ± 3.7 years) took part in this investigation and 12 of them followed a 1-year strength-training program. Both neural and muscular factors were examined during isometric maximal voluntary contraction (MVC) torques in ankle PF and DF pre-training, post 6 and post 12 months. The main finding was that 6 months of additional strength training of the PFs, beyond 6 months, allowed further improvements in neuromuscular performance at the ankle joint in older adults. Indeed, during the first 6 months of progressive resistance training, there was an increase in the PF MVC torque of 11.1 ± 19.9 N m, and then of 11.1 ± 17.9 N m in the last 6-month period. However, it was only after 1 year that there was an improvement in the evoked contraction at rest in PF (+8%). The strength training of the agonist PF muscles appeared to have an impact on the maximal resultant torque in DF. However, it appeared that this gain was first due to modifications occurring in the trained PFs muscles, then, it seemed that the motor drive of the DFs per se was altered. In conclusion, long-term strength training

of the PFs resulted in continued improvements in neuromuscular performance at the ankle joint in older adults, beyond the initial 6 months.

Keywords Aging · Agonist and antagonist muscles · Coactivation · Electrical stimulation · Electromyographic activity · Maximal voluntary contraction torque

Introduction

Aging is known to be associated with a substantial decline in neuromuscular performance, and this loss of strength occurs even in healthy aging. This decline is considered a major contributing factor to the loss of functional independence and frailty present in many older individuals (Bassey et al. 1992; Brown et al. 1995; Landers et al. 2001). Previous studies found a relevant decrease in the maximal voluntary contraction (MVC) torques produced by the ankle plantar-flexors (PFs) of older adults (Vandervoort and McComas 1986; Bemben et al. 1991; Morse et al. 2004; Simoneau et al. 2005). It has been established that resistance training programs resulted in notable increases in strength, even in older people (Frontera et al. 1988; Hakkinen et al. 2001; see Latham et al. 2004 for a systematic review). Indeed, when an individual performs strength training for several weeks, there is a quasi-systematic increase in the strength of the muscles that have been exercised. In addition, it appears that both intensity and duration have an effect on strength (Latham et al. 2004). Resistance training programs in older adults have varied considerably in length from just 2 weeks (Bemben and Murphy 2001; Connelly

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and Vandervoort 2000) to 2 years (McCartney et al. 1996; Porter et al. 2002; Morey et al. 1991; Kerr et al. 2001), with the mean gain in strength per week being approximately sevenfold greater following short-term (5%) than following long-term strength training (0.7%). On average, most resistance training studies lasted about 12 weeks (see Latham et al. 2004) so there is a limited amount of available information about the characteristics of the adaptations (neural or muscular) with prolonged training. In addition, less is known about the impact of strength training of agonist muscles on antagonist muscles. In a previous study, Simoneau et al. (2006) showed that a 6-month strength-training program of the PFs was very effective in improving strength in PF with a +0.95% mean strength gain per week, and it also induced a small but statistically significant impact on the antagonist muscles. It would thus be of interest to enquire whether continuing a 6-month strength-training program for older adults, in order to increase PF MVC torque, would allow further improvements in neuromuscular performance, and to know if there would be training-induced adaptations at the neural and/or muscular levels in the ankle PFs, and also in the antagonist dorsi-flexors (DFs). Detailed results for the first 6 months of training have been previously described (Simoneau et al. 2006).

Methods

Participants

Twenty-three healthy, community-dwelling older volunteers took part in this investigation. They were randomly assigned to either a training group ($n = 12$, five males and seven females, age 78.5 ± 2.9 year; height 1.60 ± 0.06 m; mass 65.5 ± 13.7 kg) or a control group ($n = 11$, six males and five females, age 76.2 ± 4.3 year; height 1.63 ± 0.09 m; mass 66.3 ± 11.4 kg). These older adults underwent a complete medical examination and only individuals free from muscular, neurological, cardiovascular, metabolic and inflammatory diseases took part in the present investigation. Only those individuals taking part in recreational, non-competitive, physical activities at a frequency of no more than twice a week, were admitted to the study. None of the participants had suffered a fall during the 2 years preceding the study. Written informed consent was obtained and all experimental procedures conformed to the standards set by the Declaration of Helsinki, and were approved by the local Committee on Human Research.

Strength-training protocol

The 12-month training program consisted of two sessions per week of supervised resistance training and one home-based session per week using elastic bands (Therabands™; blue band = extra heavy). The warm-up was in line with international recommendations and a position statement from the American College of Sports Medicine for safe exercise with older adults (American College of Sports Medicine 1998). It lasted 20 min and consisted of walking, marching, sidestepping, isolated mobility and supported stretches (held statically for 10 s). During the first six sessions, before the beginning of the study, participants were familiarized with the equipment and with the exercise technique. DFs per se were not trained directly. The training of the PF muscles involved bilateral movements, performed on a commercially available sitting calf-rise machine. This sitting calf-rise machine was chosen because for older individuals the sitting calf-rise machine was safer for the back than a standing calf-rise machine. For this exercise, participants plantar-flexed from a position of $\sim 20^\circ$ of DF (0° being perpendicularity of the tibia relative to the sole) to maximum PF ($\sim 30^\circ$). The individuals were instructed to perform the lifting of the weight (concentric action) in ~ 2 s and, immediately after, to lower the weight (eccentric action) in ~ 3 s. For safety reasons, the evaluation of the one repetition maximum (1 RM) (maximum load that can be lifted once only) in each subject was replaced by the evaluation of the 3 RM (maximum load that can be lifted three times only) (Welle et al. 1996; Tracy et al. 1999; Scaglioni et al. 2002; Reeves et al. 2005). The training protocol consisted, for the first 4 weeks, of three sets of ten repetitions with an initial load of ~ 50 – 55% of the 3 RM and was then increased to 75% of the 3 RM. The training load was increased every 2 weeks to coincide, as closely as possible, with 75% of the 3 RM. It should be noted that during 2 min rest sessions the participants carried out PF stretches. Subjects were individually supervised during program sessions at all times. For the home-based session, the band was placed around the end of the foot, with the ends of the band in the hands, the foot was stretched out until the knee was straight (not locked). Then subjects pressed against the band with the foot to point the foot forwards, and then slowly returned their foot to the starting position, using the whole range of motion at the ankle joint. Three sets of eight repetitions were performed. The control participants were asked to maintain their current physical activity levels and not to start strength training.

Mechanical and electromyographic recordings

Torque and electromyographic (EMG) data were recorded concurrently during maximal isometric PF and DF efforts. Strength was measured by using an isokinetic dynamometer (System 3; Biodex Medical Systems, Shirley, NY), which has been found to be both a valid and an accurate research tool (Taylor et al. 1991; Drouin et al. 2004). Subjects were supine with a knee angle of near 180° (full extension) and the ankle was placed in the neutral position: the footplate of the dynamometer perpendicular to the tibia. A supine position with leg extended was developed during testing to take into consideration that the PFs and DFs are used predominantly in weight bearing with the knee extended. Besides, Porter et al. (1997) showed that data obtained in such a position were in agreement with those obtained in a standing position. The right leg was placed horizontally, and the axis of the ankle joint was aligned with the center of rotation of the dynamometer shaft. To minimize trunk and hip movement during contractions, the waist was stabilized by means of a belt; arms were positioned across the chest. The right foot was attached to the dynamometer by means of the Biodex ankle attachment which was customized with a shoe bolted to the foot plate at the heel. The standard toe straps were used over the shoe. Torque signals obtained through the dynamometer were directly acquired by Tida 4.11 software (Tida, Heka Elektronik, Lambrecht/Pfaltz, Germany), with a sampling frequency of 2 kHz.

EMG activity from the soleus, gastrocnemius medialis, gastrocnemius lateralis and tibialis anterior muscles was recorded by means of two silver-chloride surface electrodes of 10-mm diameter (Controle Graphique Medical, Brie-Comte-Robert, France), with an inter-electrode (center-to-center) distance of 25 mm. Indeed, among the DFs, only the EMG activity of the tibialis anterior was recorded. Nevertheless, even if the DFs also included extensor hallucis longus, extensor digitorum longus and peroneus tertius, the tibialis anterior was regarded as the most powerful DF. Electrodes were placed following the European Recommendations for Surface ElectroMyoGraphy (Hermens et al. 2000). The ground electrode was attached in a central position on the same leg, between the gastrocnemii muscles. The positions of the electrodes were mapped at the time of the first session to be able to place the electrodes at exactly the same place during the two other sessions. Low impedance (< 5 k Ω) at the skin–electrode interface was obtained by shaving, abrading and cleaning the skin with an alcohol–ether–acetone mixture. EMG signals were amplified by a bandwidth frequency ranging from

15 Hz to 2 kHz and subsequently stored for off-line analysis.

Stimulation procedure

To stimulate the PFs, the posterior tibial nerve was stimulated using an adhesive electrode (10 mm diameter, Controle Graphique Medical, Brie-Comte-Robert, France) pressed into the popliteal fossa. The anode was a large rectangular electrode (10 cm \times 5 cm; Medcompex SA, Ecublens, Switzerland) placed on the anterior surface of the knee. To stimulate the DFs, the peroneal nerve was stimulated using an electrode, cathode and anode side by side, specifically placed just below the head of the fibula. The common peroneal nerve branches into the superficial and deep peroneal nerves. As the superficial peroneal nerve innervates peroneus longus and brevis muscles, we aimed to stimulate primarily the deep peroneal nerve that is more specifically localized in front of the fibula. Thus, care was taken to avoid activation of the peroneal muscles, and the absence of muscle activity was checked by palpation. Moreover, a way to know if data could have been affected by the activation of the peroneus muscles was to check if the peroneal nerve stimulation also induced a foot eversion before feet were fastened. The percutaneous electrical stimulus was a rectangular pulse of 1-ms duration for the tibial nerve and 0.5-ms width for the peroneal nerve, with a constant voltage of 400 V and an adjustable intensity delivered by a Digitimer stimulator (model DS7, Hertfordshire, England). Each participant was initially familiarized with several sub-maximal electrical stimuli. The current intensity was then progressively increased until maximal twitch torque and maximal compound muscle action potential (M-wave) amplitude were achieved. Once this optimal intensity was determined, it was then maintained for the entire session of electrical stimulation. Single stimulations were then delivered automatically by a digitimer triggered by commercially available software (Tida, Heka Elektronik, Lambrecht/Pfaltz, Germany).

Experimental procedures

All measurements were carried out at baseline (pre) and after the 12th month of the intervention period (post 12) for the training and control groups. The training group was also tested after 6 months of training (post 6). In order to standardize the tests, they were administered to all subjects between 2 and 6 p.m. Prior to performing MVCs, the responses to four single stimuli, each separated by a 5-s interval, were recorded, for the tibialis anterior and for the triceps surae muscles. Thereafter, the subjects performed 5–6-s MVCs in each condition

(PF and DF). A fourth MVC was performed if one of the previous attempts was not maximal (difference between the performances greater than 5% of the coefficient of variation). The trial resulting in the maximal torque developed was used for further analysis. During each maximal contraction, the subject was strongly encouraged by the experimenters and visual feedback of torque was provided by the Biodex monitor.

Data analysis

Concerning the electrically evoked stimulations, the average mechanical responses and EMG signals of the four single stimulations were considered. The following twitch contractile properties were computed: (a) peak torque (Pt), the highest value of twitch tension production; (b) time to peak torque (TPt), the time to twitch maximal torque, calculated from the onset of the mechanical signal and (c) half-relaxation time (HRT), the time needed to obtain half of the decline in twitch maximal torque. Peak-to-peak amplitude and peak-to-peak duration of soleus, gastrocnemius medialis, gastrocnemius lateralis and tibialis anterior muscles M-waves were calculated. For PF, the sum of the M-waves peak-to-peak amplitudes from the three muscles of the triceps surae has been used; as for the duration, the average of the M-waves of these three muscles was employed.

We also evaluated maximal muscular torques, coactivation and activity from the corresponding highest contractile force records. For voluntary torque testing, the root mean square (RMS) myoelectric activity of the soleus, gastrocnemius medialis, gastrocnemius lateralis and tibialis anterior muscles was calculated. During isometric activity, this RMS was measured over a 0.5-s period after the torque had reached a plateau. For PF, the RMS of the agonist muscle group corresponded to the sum of the RMS of gastrocnemii and soleus muscles. To reduce the differences in the EMG signals due to changes at the skin level, the RMS values were normalized to the amplitude of the M-wave of the session ($\text{RMS}/M_{\text{max}}$) (Duchateau et al. 2002; Marsh et al. 1981) to provide an indirect quantification of the maximal voluntary muscular activation. This normalization not only accounts for differences in electrode placement and electrical impedance, but also excludes all modifications induced at a peripheral level from the EMG values.

To evaluate the level of coactivation, the RMS data recorded from the tibialis anterior muscle during the PF action was divided by the corresponding RMS recorded during the DF action MVC and expressed as a percentage. In the same way, the RMS data recorded from the whole triceps surae muscles (gastrocnemii plus soleus muscles) during the DF action was divided

by the corresponding RMS recorded during the PF action MVC and expressed as a percentage (Hagood et al. 1990; Macaluso et al. 2002; Maganaris et al. 1998).

The neuromuscular efficiency (NME) was expressed as follows: $\text{NME} = \text{Pt}/M_{\text{max}}$.

Statistical analysis

All statistical tests were performed with Statistica software (version 6.1, StatSoft, Tulsa, Oklahoma, USA). Descriptive statistical methods, including means and their standard deviations (SDs) and standard errors (SEs) were calculated for each parameter. The data are presented as means \pm SD in the text and tables, and as means \pm SE in the figures.

For PF and DF, the potential modifications in MVC torques were analyzed by means of a two-way analysis of variance (group \times time, 2×2) with repeated measures on one factor (time: pre and post 12). For the training group, the changes in the mechanical and electrical parameters between baseline, 6 and 12 months were analyzed by means of a one-way analysis of variance with repeated measures on time. When a significant main effect was found, a least significant differences (LSD) Fisher post hoc test was used to identify the significant differences among the selected means.

For all analyses, the level of significance was established at $P < 0.05$.

Results

All the participants of the training group were able to successfully complete the whole training program without injury. No differences were found between the training group and the control group at baseline on any of the measured or calculated parameters (anthropometric characteristics, muscle strength, muscular and neural factors). The control group showed no modification for any analyzed data over the 12-month period. For instance, the PF MVC torque mean values were 75.3 ± 18.1 N m versus 75.3 ± 21.9 N m, pre and post 12, respectively; the DF MVC torque mean values were 32.8 ± 8.3 N m versus 32.5 ± 8.8 N m, pre and post 12, respectively.

Maximal force production

The average load for the 3 RM underwent a 55% increase during the 12 months of strength training.

There were significant improvements in isometric strength in both muscle groups at the ankle joint following 6 months of strength training, and then, only in

PF from the 6th to the 12th month of training (Fig. 1). Indeed, the mean MVC torques of the trained subjects increased in PF by 16.0% at post 6 and then by 13.8% at post 12 (69.4 ± 9.1 N m vs. 80.5 ± 17.1 N m vs. 91.6 ± 16.6 N m, $P = 0.036$ and $P = 0.036$, respectively). In DF, there were only improvements following the six first months (35.5 ± 10.4 N m vs. 37.8 ± 9.1 N m, $P = 0.024$) (Fig. 1b). The control group showed no modification after the 12-month period, either in PF (75.3 ± 18.1 N m vs. 75.3 ± 21.9 N m, pre and post 12 values, respectively) or in DF (32.8 ± 8.3 N m vs. 32.5 ± 8.8 N m, pre and post 12 values, respectively). Furthermore, the DF-to-PF MVC torque ratio significantly decreased in the training group after the 12-month period, from 0.52 to 0.40 ($P < 0.001$).

Muscular factors: contractile properties and M-waves

As for the amplitude of the mechanical twitch at rest (Pt), and the temporal characteristics (TPt, HRT) of PFs and DFs, there were no statistically significant changes (Tables 1, 2), except there was an augmentation of the triceps surae Pt from post 6 to post 12, increasing from 10.4 ± 3.3 to 12.3 ± 3.0 N m ($P = 0.005$). There were no significant effects of time on M-wave amplitude or duration, either in the triceps surae muscles or the tibialis anterior muscle (Tables 1, 2).

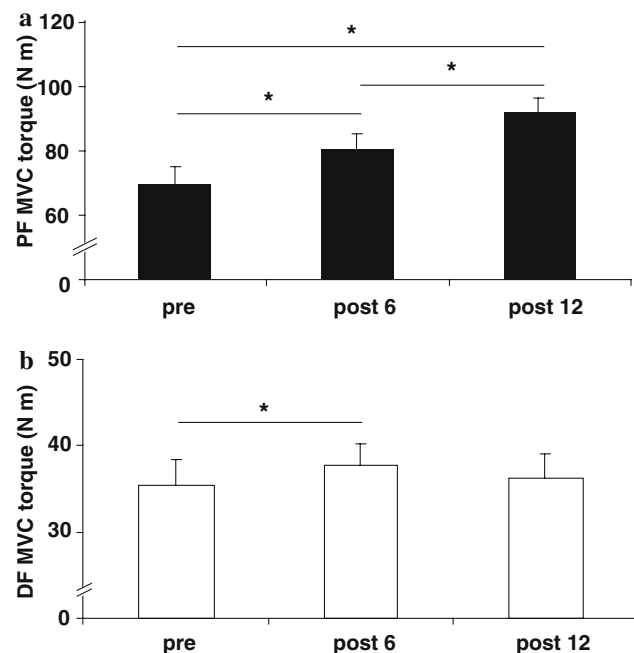


Fig. 1 Maximal voluntary contraction torques during isometric activity. **a** plantar-flexion (PF) and **b** dorsiflexion (DF), in older subjects, before, after 6 and 12 months of strength training. *Significant difference between values ($P < 0.05$)

Table 1 Contractile properties of the ankle plantar-flexor muscles in older adults (mean \pm SD), before, after 6 and 12 months of strength training

| | PF | | |
|--|-------------------|-------------------------|---------------------|
| | Pre | Post 6 | Post 12 |
| Twitch | | | |
| Pt (N m) | 11.4 ± 3.4 | 10.4 ± 3.3^a | 12.3 ± 3.0 |
| TPt (ms) | 121.8 ± 20.2 | 130.9 ± 20.7 | 120.3 ± 15.0 |
| HRT (ms) | 127.6 ± 21.7 | 128.3 ± 18.0 | 132.4 ± 27.5 |
| M-wave amplitude (mV) | 15.0 ± 7.0 | 17.8 ± 7.9 | 15.6 ± 7.0 |
| M-wave duration (ms) | 3.8 ± 1.4 | 3.9 ± 1.4 | 3.9 ± 0.9 |
| NME (Pt/M _{max}) | 0.89 ± 0.45 | 0.69 ± 0.45^a | 0.92 ± 0.47 |
| MVC | | | |
| RMS _{agonist} /M _{max} | 0.047 ± 0.022 | $0.056 \pm 0.027^{a,b}$ | 0.066 ± 0.026^c |

The M-wave amplitude is the sum of the three plantar-flexor muscles

PF plantar-flexion, Pt peak torque, TPt time to peak torque, HRT half-relaxation time, NME neuromuscular efficiency

^a Significant difference between post 6 and post 12 values

^b Significant difference between pre and post 6 values

^c Significant difference between pre and post 12 values

Table 2 Contractile properties of the ankle dorsiflexor muscles in older adults (mean \pm SD), before, after 6 and 12 months of strength training

| | DF | | |
|--|-------------------|---------------------|-------------------|
| | Pre | Post 6 | Post 12 |
| Twitch | | | |
| Pt (N m) | 3.0 ± 1.6 | 3.4 ± 1.5 | 2.9 ± 1.2 |
| TPt (ms) | 110.7 ± 15.5 | 113.1 ± 15.0 | 106.9 ± 20.6 |
| HRT (ms) | 99.0 ± 17.8 | 101.4 ± 17.4 | 96.1 ± 13.7 |
| M-wave amplitude (mV) | 3.3 ± 0.8 | 3.6 ± 1.1 | 3.6 ± 1.4 |
| M-wave duration (ms) | 6.2 ± 3.0 | 5.3 ± 2.1 | 5.2 ± 3.3 |
| NME (Pt/M _{max}) | 1.00 ± 0.62 | 1.04 ± 0.38 | 0.91 ± 0.51 |
| MVC | | | |
| RMS _{agonist} /M _{max} | 0.111 ± 0.012 | 0.097 ± 0.013^a | 0.116 ± 0.037 |

DF dorsiflexion, Pt peak torque, TPt time to peak torque, HRT half-relaxation time, NME neuromuscular efficiency

^a Significant difference between post 6 and post 12 values

Neural factors: EMG activity—activation level—coactivation level

For PF MVC, the RMS/M_{max} of the agonist muscle significantly increased in the training group during the whole training period ($P < 0.001$) (Table 1). For DF MVC, an augmentation of this electrical ratio was observed between post 6 and post 12 ($P = 0.019$) (Table 2).

The level of coactivation during PF was lower before than after 6 months for the trained older people ($P = 0.016$), and then, this coactivation decreased from post 6 to post 12 ($P = 0.019$) (Fig. 2a). In DF, the muscular coactivation of the training group significantly decreased ($P = 0.018$), and then remained stable (Fig. 2b).

Neuromuscular efficiency

The neuromuscular efficiency (NME) in PF increased from post 6 to post 12 with strength training ($P = 0.030$) (Table 1), while the NME in DF remained stable ($P > 0.05$) (Table 2).

Discussion

The main finding was that following long-term strength training of the PFs, beyond 6 months, allowed further improvements of the neuromuscular performances at the ankle joint in older adults.

Muscle strength

Long-term weight training proved to be a safe and well-tolerated mode of exercise for the older people.

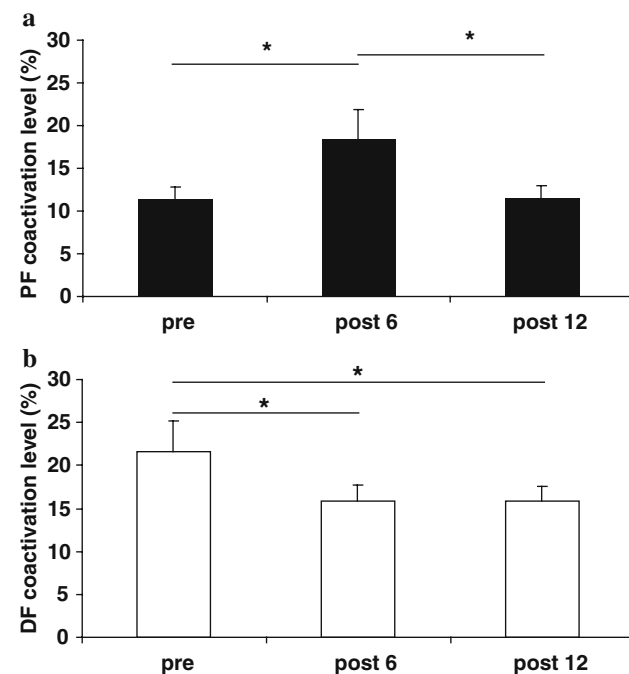


Fig. 2 Coactivation level during isometric maximal voluntary contraction torque in **a** plantar-flexion (PF) and **b** dorsiflexion (DF) in older subjects, before, after 6 and 12 months of strength training. *Significant difference between values ($P < 0.05$)

During the first 6 months of resistance training, there was an increase in the PF MVC torque of 16% and, interestingly, there was also a strength gain in DF (+6.5%). During this 1-year strength-training program, there was no evidence of a plateau in the strength gains of the trained PFs. Indeed, the proportion of the total change (over the entire 12-month intervention period) in each 6-month period was almost identical (16% vs. 14%). The fact that the strength continued to increase over the 12 months was important, as it suggested that long-term resistance training might help to thwart the reductions in strength that are commonly associated with aging. Given the fact that the knee joint was flexed during training whereas it was extended during testing, one can note that the increase in PF MVC torque after training should be mainly due to the adaptation of the soleus muscle. Surprisingly, the control group showed no MVC torque decline at the end of the 12-month period (75.3 ± 18.1 N m vs. 75.3 ± 21.9 N m, pre and post 12 values in PF, respectively, and 32.8 ± 2.5 N m vs. 32.5 ± 2.6 N m, pre and post 12 values in DF, respectively). The fact that there was no reduction after 1 year has already been reported, even after 2 years (McCartney et al. 1996). In DF, there were no longer strength gains after 6 months: the DF MVC torque remained stable from post 6 to post 12. As a consequence, the DF-to-PF MVC torque ratio kept on decreasing with training and was closer to the value of younger people (Bemben et al. 1991; Simoneau et al. 2005). As expected, these findings demonstrated that the neuromuscular system of older individuals could adapt to heavy-resistance exercise, and even to long-term training, as indicated by increases in strength, even after the first 6 months. Various factors could contribute to these strength gains following heavy-resistance training in older individuals and the two major mechanisms responsible for the adaptations to resistance training could be muscular and/or neural. In a previous study, we found that age-related strength decline in PF was primarily due to modifications at the muscle level (Simoneau et al. 2005).

Training-induced muscular adaptations

Changes in twitch contractile properties and in the associated M-wave characteristics reflect alterations of excitation–contraction coupling (Desmedt and Hainaut 1968). In the current study, the amplitude of the mechanical twitch at rest (Pt) and the temporal characteristics (TPt, HRT) of the PFs were not significantly changed after the first-half of the strength-training period. This absence of increase in the twitch amplitude

after 6 months corroborates the findings of Scaglioni et al. (2002) following a 16-week resistive program in a population of older men. However, these authors observed a 9% increase in the muscle cross-sectional area of the PFs, indicating that there were muscular adaptations without impact on the twitch amplitude. Nevertheless, the Pt significantly increased from post 6 to post 12, showing a long-term adaptation of this peripheral parameter altered by aging. In the present study, the maximal M-waves recorded from the triceps surae muscles, pre-training and at post 6 and post 12, showed no differences in terms of amplitude or in terms of conduction time. Thus, these observations suggest that there was no enhancement in muscle membrane excitability, so that the hypothesis of peripheral adaptations at the membrane level could be excluded (Pensini et al. 2002). Concerning the DFs, there were no significant modifications in the characteristics of either the mechanical twitch or the M-wave. However, an absence of change in twitch torque does not necessarily mean that muscular adaptations were totally absent (Scaglioni et al. 2002): only a tetanic contraction could have probed the intrinsic adaptations of the muscle. However, muscular adaptations alone could not explain the gains in DF MVC torque. These gains could be due to neural mechanisms acting on agonist and antagonist muscles.

Training-induced neural adaptations

In PF, in addition to the late increase in Pt, the strength gains could be explained by an augmentation in the RMS/M_{max} of the triceps surae muscles, throughout the training period. Thus, it appeared that neural adaptations were occurring during the whole year and not only at the beginning of the training. Unexpectedly, the level of coactivation in PF increased from pre to post 6 and then, decreased from post 6 to post 12. Nevertheless, the mechanical impact here might be negligible on the PF resultant torque (Simoneau et al. 2006). This first augmentation in coactivation was in agreement with the linear relationship that was found between coactivation intensity and developed torque (Simoneau et al. 2005). Besides, the observed decrease in coactivation from post 6 to post 12 was coupled with an increase in the EMG activity of the tibialis anterior muscle during DF MVC, so that the mechanical contribution of the latter muscle should be equivalent for the two periods.

In DF, from pre to post 6, the RMS/M_{max} of the tibialis anterior muscle remained constant. Nevertheless, even if no neural adaptations were observed on the most powerful DF muscle, a neural adaptation of the

synergists could not be excluded. Actually, the observed strength gain in DF could be associated to the decrease in the level of coactivation of the triceps surae muscles (Simoneau et al. 2006). Then, there was an increase in the EMG activity of the tibialis anterior muscle from post 6 to post 12, showing that antagonist adaptations occurred, but quite late; this result could be explained by the fact that the quantity of work for the DFs was rather small. From post 6 to post 12, despite this increase in the EMG activity of the tibialis anterior as agonist, there was surprisingly no increase in the DF MVC torque. It is worth noting that the measured torque is a resultant one: it corresponds to the sum of the participation of both agonist and antagonist muscles. As a consequence, if the DF MVC torque did not increase during this period, it would be due to an increase in the mechanical contribution of the antagonists: the PFs. Indeed, even if the coactivation of the PFs during DF remained similar, as the PF NME increased during this second training period, it meant that for an identical EMG activity, the PFs could generate higher torques at post 12 than at post 6. Thus, the mechanical contribution of the PFs during DF would increase from post 6 to post 12 and, as a consequence, it would thwart the increase in the DF agonist EMG activity, explaining why the resultant DF MVC torque did not increase during this second-half period of training.

In conclusion, beyond a 6-month strength-training period of the PFs, gains were still possible in older adults. Thus, extending this kind of training was successful. Moreover, it was only after 1 year that there was an improvement in the evoked contraction at rest (Pt) in PF. The strength training of the agonist PF muscles appeared to have an effect on the maximal resultant DF torque. However, it appeared that this gain was first due to modifications occurring in the principally trained muscles, then, in the end, it seemed that the motor drive of the antagonist muscles per se was altered, being nevertheless non-sufficient to induce a further strength gain because of the increase in the mechanical contribution of the PFs during the DF MVC. Given the findings of this study, following a long-term strength training of the PFs allowed further improvements in neuromuscular performance at the ankle joint in older adults. In addition, according to our findings, it is clear that the examination of both agonist and antagonist muscles of a joint is essential.

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