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# Neuromuscular adaptations to concurrent training in the elderly: effects of intrasession exercise sequence

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**Abstract** The aim of this study was investigate the effects of different intrasession exercise orders in the neuromuscular adaptations induced by concurrent training in elderly. Twenty-six healthy elderly men (64.7±4.1 years), were placed into two concurrent training groups: strength prior to (SE, $n=13$) or after (ES, $n=13$) endurance training. Subjects trained strength and endurance training during 12 weeks, three times per week performing both exercise types in the same training session. Upper and lower body one maximum repetition test (1RM) and lower-body isometric peak torque (PTiso) and rate of force development were evaluated as strength parameters. Upper and lower body muscle thickness (MT) was determined by ultrasonography. Lower-body maximal surface electromyographic activity of vastus lateralis and rectus femoris muscles (maximal electromyographic (EMG) amplitude) and neuromuscular economy (normalized EMG at 50 % of pretraining PTiso) were determined. Both SE and ES groups increased the upper- and lower-body 1RM, but the lower-body 1RM increases observed in the SE was higher than ES (35.1±12.8 vs. 21.9±10.6 %, respectively; $P<0.01$). Both SE and ES showed MT increases in all muscles evaluated, with no differences between groups. In addition, there were increases in the maximal EMG and neuromuscular economy of vastus lateralis in both SE and ES, but the neuromuscular economy of rectus femoris was improved only in SE ($P<0.001$). Performing strength prior to endurance exercise during concurrent training resulted in greater lower-body strength gains as well as greater changes in the neuromuscular economy (*rectus femoris*) in elderly.

**Keywords** Combined training · Electromiography · Muscle thickness · Aerobic exercise · Resistance exercise

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## Introduction

Biological aging is associated with declines in the muscle mass, strength performance, and cardiorespiratory fitness resulting in an impaired capacity of elderly performing daily activities (Izquierdo et al. 2001, 2003; Aagaard et al. 2010). To counteract this effect, a combination of strength and endurance training in elderly populations is the most effective strategy to improve both neuromuscular and cardiorespiratory functions and consequently to maintain the functional capacity during aging (Wood et al. 2001; Izquierdo et al. 2004; Cadore et al. 2011b). However, strength and endurance training have specific cardiovascular and neuromuscular adaptations that are opposite in nature. The primary adaptations to strength training include enhanced strength performance (García-Pallarés and Izquierdo 2011), muscle cell hypertrophy (Kraemer et al. 1995), and neural adaptations such as the increase in the maximal motor unit recruitment (Knight and Kamen 2001), maximal motor unit firing rate (Kamen and Knight 2004), as well as elevated spinal motorneuronal excitability and increased efferent motor drive (Aagaard et al. 2002a, b), with no changes in $VO_{2max}$. In contrast, endurance training induces central and peripheral adaptations that enhance $VO_{2max}$ and the ability of skeletal muscle to generate energy via oxidative metabolism with no increase in muscle strength or hypertrophy (Izquierdo et al. 2004).

Previous studies suggest that the simultaneous performance of both types of training (i.e., concurrent training) might reduce the strength development magnitude when compared with that observed due to strength training alone, and this phenomenon has been called the "interference effect" (Sale et al. 1990; Kraemer et al. 1995; Bell et al. 1997; Cadore et al. 2010; García-Pallarés and Izquierdo 2011).

A limited number of studies, however, have explored the neuromuscular adaptations related to concurrent strength and cardiovascular intervention in elderly populations (Wood et al. 2001; Izquierdo et al. 2004; Cadore et al. 2010; Holviala et al. 2010; Karavirta et al. 2011). Wood et al. (2001) demonstrated in elderly men that 12 weeks of concurrent training resulted in similar strength gains to those observed with strength training alone. However, the authors of that study used 50 % lower volume of strength training in the concurrent training group. Similarly, Izquierdo et al. (2004) observed no differences in strength gain between strength (twice weekly) and concurrent training (strength exercises on one day, cycle ergometer on the other). Studies that have used similar volumes of training between strength and concurrent groups in elderly men have shown no interference effect after 21 week or concurrent training (Holviala et al. 2010; Karavirta et al. 2009) whereas greater strength gains were reported after strength training alone (67 %) compared with the concurrent group (41 %) after 12-week concurrent intervention (Cadore et al. 2010). This controversial result may be related with the fact of performing endurance exercises immediately prior to strength exercises, which might have resulted in a peripheral fatigue that consequently reduced performance during strength training. In fact, it has been shown that aerobic exercise might acutely reduce strength performance (Lepers et al. 2001). If this were the case, the interference effect could be avoided by manipulating the intrasession exercise sequence.

Along with the scarce results regarding the influence of intrasession exercise sequence manipulation on concurrent strength and endurance adaptations, to the authors' best knowledge, there are no data regarding the effect of exercise order manipulation during concurrent training on the neural and muscle morphology adaptations in elderly subjects. Such data would give insight into possible mechanisms underlying the chronic negative influence of endurance training in strength training adaptation. Therefore, the purpose of the present study was to investigate the effects of different intrasession exercise orders during concurrent strength and endurance training on neuromuscular adaptations in the elderly. Our hypothesis was that performing strength exercise before endurance exercise would result in greater strength increases than in the opposite sequence (endurance strength).

## Methods

### Experimental design and approach to the problem

The physiological effects of different intrasession exercise sequences during concurrent training in the elderly were assessed with a strength and endurance training protocol that, in previous studies by our research group, have induced marked strength and cardiovascular gains in this population (Cadore et al. 2010, 2011b). Because the performance of the concurrent training caused an interference effect on strength adaptations, it was speculated that this effect was a consequence of the fatigue resulting from endurance exercise, which was always performed immediately before the strength exercise (Cadore et al. 2010). Thus, in the present study, we compared different intrasession exercise sequences during concurrent training in the same population (i.e., healthy elderly subjects). The subjects were evaluated using variables related to maximal strength, neuromuscular activity, and muscle thickness. The concurrent training programs lasted 12 weeks. However, to test the stability and reliability of the performance variables, some of the subjects were evaluated twice before the start of training (weeks −4 and 0), which served as a control period. We have previously tested the stability and reliability of these variables in elderly men using a larger number of subjects during a control period (Cadore et al. 2010, 2011a, b). Each specific test at pre- and post-intervention was overseen by the same investigator, who was blinded to the training group of the subjects, and was conducted on the same equipment with identical subject/equipment positioning. Each subject performed the tests at the same time of day throughout the study, and different tests were conducted on different days to avoid fatigue.

## Subjects

Twenty-six healthy elderly men (mean±SD: 64.7±4.1 years), who were not engaged in any regular and systematic training program in the previous 12 months, volunteered for the study after completing an ethical consent form. Some of the participants had little previous experience with resistance or aerobic exercise. The subjects volunteered for the present investigation following announcements in a widely read local newspaper. Subjects were carefully informed about the design of the study with special information given regarding the possible risks and discomfort related to the procedures. Subsequently, subjects were randomly selected and placed into two groups: strength training prior to endurance training (SE, $n$=13); and, endurance training prior to strength training (ES, $n$=13). Eight subjects (66.0±2.7 years) were evaluated twice before the start of training (weeks −4 and 0) and it served as control period. The study was conducted according to Declaration of Helsinki and was approved by Ethics Committee of Federal University of Rio Grande do Sul, Brazil.

Exclusion criteria included any history of neuromuscular, metabolic, hormonal, and cardiovascular diseases. Subjects were not taking any medication with influence on hormonal and neuromuscular metabolism and were advised to maintain their normal dietary intake throughout the study. Medical evaluations were performed using clinical anamnesis and effort electrocardiograph test, to ensure subject suitability for the testing procedure. The physical characteristics of subjects are shown in Table 1. Body mass and height were measured using an Asimed analog scale (resolution of 0.1 kg) and an Asimed stadiometer (resolution of 1 mm), respectively. Body composition was assessed using the skinfold technique. A seven-site skinfold equation was used to estimate body density (Jackson and Pollock 1978) and body fat was subsequently calculated using the Siri equation (Siri 1993).

## Maximal dynamic strength

Maximal strength was assessed using the one-repetition maximum test (1RM) on the bilateral elbow flexion and bilateral knee extension. The bilateral elbow flexion 1RM was performed with free weights and using a bar and the bilateral knee extension in an exercise machine (World-Esculptor, Porto Alegre, Brazil). One week prior to the test day, subjects were familiarized with all procedures in two sessions. On the test day, the subjects warmed up for 5 min on a cycle ergometer, stretched all major muscle groups, and performed specific movements for the exercise test. Each subject's maximal load was determined with no more than five attempts with a 4-min recovery between attempts. Performance time for each contraction (concentric and eccentric) was 2 s, controlled by an electronic metronome (Quartz, CA, USA). The test–retest reliability coefficient (intraclass correlation coefficient, ICC) was 0.99 for the knee extension and 0.95 for the elbow flexion.

## Isometric peak torque and rate of force development

Maximal isometric peak torque was obtained using and isokinetic dynamometer (Biodex, New York, USA). Subjects were positioned seated with their hips and thighs firmly strapped to the seat of the dynamometer, with the hip angle at 85°. After that, subjects warmed up for 10 knee extension/flexion repetitions

**Table 1** Physical characteristics before and after training; mean±SD

| | Strength–endurance group SE, $n$=13 | | Endurance–strength group ES, $n$=13 | |
|---|---|---|---|---|
| | Pre | Post | Pre | Post |
| Age (years) | 64.7±3.7 | 64.9±3.9 | 64.7±4.8 | 64.8±4.8 |
| Body mass (kg) | 79.7±10.5 | 79.5±9.5 | 83.3±13.4 | 82.6±13.3 |
| Height (cm) | 170.0±5.9 | 170.0±5.9 | 173.5±5.1 | 173.5±5.1 |
| % Fat mass | 27.3±3.7 | 25.6±3.3[a] | 28.1±3.0 | 26.8±3.4[a] |
| $VT_2$ (ml kg $min^{-1}$) | 19.7±3.9 | 20.5±3.2 | 19.9±4.9 | 20.0±4.7 |
| $VO_{2peak}$ (ml kg $min^{-1}$) | 27.4±6.1 | 29.5±6.6[a] | 26.6±6.9 | 28.8±6.5[a] |

[a] Significant difference from pretraining values ($P<0.001$)

at angular velocity of 90°$s^{-1}$, performing a submaximal effort. The dynamometer was connected to an A/D converter (Dataq Instruments Inc., Akron, OH, USA), which made it possible to quantify the torque exerted when each subject executed the knee extension at the determined angle. After having their right leg positioned by the evaluators at an angle of 120° in the knee extension (180° represented the full extension), the subjects were instructed to exert maximum strength possible as fast as was possible when extending or flexing the right knee. The subjects had three attempts at obtaining the maximum voluntary contraction (MVC) of the knee extensors and more three of the knee flexors, each lasting 5 s. After the MVCs, in order to evaluate the isometric neuromuscular economy, subjects had three 5-s attempts to exert 50 % of the pretraining isometric peak torque and maintain it for, at least, 3 s receiving a visual feedback in the computer that showed, in real-time, the force values. If the subjects had success in the first trial, the last two was not performed. The rest of the interval between each attempt of the protocol was 2 min. During all the maximum tests, the researchers provided verbal encouragement so that the subjects would feel motivated to produce their maximum force. The force–time curve was obtained using Biodex software with an acquisition rate of 2,000 Hz. Signal processing included filtering with a Butterworth low-pass filter of fourth order at a cutoff frequency of nine Hertz. Maximal peak torque was defined as the highest value of the torque (Newton meter) recorded during the unilateral knee extension and flexion. The isometric force–time analysis on the absolute scale included the maximal rate of force development (RFD; Newton per second), defined as the greatest increase in the force; and, the RFD at 100 ms, defined as the greatest increase in the force in the first period of 100 ms. The RFD variables were calculated from the force onset, which was considered the point that the force exceeded 2.5 times the standard deviations of the mean of the force signal at rest, and were determined using the MATLAB software. The test–retest reliability coefficients (ICC) were over 0.94 for all the variables in the isometric protocol.

## EMG measurements

During the isometric strength test, the maximal neuromuscular activity of agonist muscles was evaluated using surface electromyography (RMS values) in the vastus lateralis and rectus femoris, and the antagonist co-activation in the biceps femoris long head. Electrodes were positioned on the muscular belly in a bipolar configuration (20 mm interelectrode distance) in parallel with the orientation of the muscle fibers, according to Leis and Trapani (2000). Shaving and abrasion with alcohol were carried out on the muscular belly, as previously described by Häkkinen et al. (2003), in order to maintain the interelectrodes resistance above of 2,000 Ω. To ensure the same electrode position in subsequent tests, the right thigh of each subject was mapped for the position of the electrodes moles and small angiomas by marking on transparent paper (Narici et al. 1989). The ground electrode was fixed on the anterior crest of the tibia. The raw EMG signal was acquired simultaneously with the MVC using an eight-channel electromyograph (AMT-8, Bortec Biomedical Ltd., Canadá). The raw EMG was converted by an A/D converter DI-720 with 16-bits resolution (Dataq Instruments Inc. Akron, OH, USA), with a sampling frequency of 2,000 Hz per channel, connected to a PC. Following acquisition of the signal, the data were exported to the SAD32 software, where they were filtered using the Butterworth band-pass filter of fourth order, with a cutoff frequency between 20 and 500 Hz. After that, the EMG records were sliced exactly in 1 s when maximal value of stable force (1 second) was determined between the second and fourth second of the force–time curve, and the RMS values were calculated. The RMS values of the antagonist biceps femoris muscle were normalized by the maximum RMS values of this muscle, obtained during the highest MVC of isometric knee flexion at 100°.

After determination of maximal neuromuscular activity, submaximal neuromuscular activity was evaluated in order to determine the isometric neuromuscular economy. Thus, subjects performed the force trials corresponding to 50 % of pretraining MVC (described above). The apparatus and the collection and analysis procedures were the same used to determine the maximal EMG signal. After the training period, the submaximal neuromuscular activity was determined for the same absolute loads used in the pretraining evaluation. The submaximal RMS values were normalized using the maximum RMS values obtained during the MVC in each muscle. The test–retest reliability coefficient (ICC values) of the EMG measurements was over 0.85.

## Muscle thickness

The muscle thickness (MT) was measured using B-mode ultrasound (Philips, VMI, MG, Brazil). A 7.5-MHz scanning head was placed on the skin perpendicular to the tissue interface, the scanning head was coated with a water-soluble transmission gel to provide acoustic contact without depressing the dermal surface. The images were digitalized and after analyzed in software Image-J (National Institutes of Health, USA, version 1.37). The subcutaneous adipose tissue–muscle interface and the muscle–bone interface were identified, and the distance from the adipose tissue–muscle interface was defined as MT. The MT images were determined in the lower body muscles vastus lateralis (VL), vastus medialis (VM), vastus intermedius (VI), and rectus femoris (RF). The measurement for the VL was taken at midway between the lateral condyle of the femur and greater trochanter (Kumagai et al. 2000; Miyatani et al. 2002), whereas the measurement VM was taken at 30 % of the distance between the lateral condyle of the femur and the greater trochanter (Korhonen et al. 2009), yet the measurement for the VI and RF were measured as 60 % the distance from the greater trochanter to the lateral epicondyle and 3 cm lateral to the midline of the anterior thigh (Chilibeck et al. 2004). The sum of the four lower body muscles MT was considered as representative of quadríceps femoris (QF) muscle mass. In the upper body limbs, MT were obtained in the bíceps brachii (BB) and brachialis (BR) and the sum of the MT of these muscles was considered as representative of elbow flexors (EF) muscle mass. The site to EF measurement was at 40 % of the distance from the lateral epicondyle to the acromion process of the scapula, starting at the lateral epicondyle (Miyatani et al. 2002; Fukunaga et al. 2001). To ensure the same electrode position in subsequent tests, the right thigh of each subject was mapped for the position of the electrodes moles and small angiomas by marking on transparent paper (Narici et al. 1989). Subjects were evaluated in supine position, after 15-min resting and after 72 h without any vigorous physical activity. The MT test–retest reliability coefficients (ICC) were 0.92 for BB, 0.93 for BR, 0.94 for VL, 0.91 for VM, 0.92 for VI, and 0.95 for RF.

## Peak oxygen consumption and ventilatory threshold

Subjects performed an incremental test on a cycle ergometer (Cybex, USA) in order to determine the peak oxygen consumption ($VO_{2peak}$) heart rate ($HR_{VT}$) at ventilatory threshold ($VT_2$). They initially cycled with a 25 W load, which was progressively increased by 25 W every 2 min, while maintaining a cadence of 70–75 rpm, until exhaustion (Izquierdo et al. 2004). The test was halted when subjects were no longer able to maintain a cadence of over 70 rpm. All the incremental tests were conducted in the presence of a physician. The expired gas was analyzed using a metabolic cart (CPX/D, Medical Graphics Corporation, St. Paul, MN, USA) breath by breath. The $VT_2$ was determined using the ventilation curve corresponding to the point of exponential increase in the ventilation in relation to the load. In addition, to confirm the data, $VT_2$ was determined using the $CO_2$ ventilatory equivalent (Wasserman 1986). The maximum $VO_2$ value (milligram per kilogram per minute) obtained close to exhaustion was considered the $VO_{2peak}$. The maximum test was considered valid if at least two of the three listed criteria were met: (1) the maximum heart rate predicted by age was reached (220, age); (2) the impossibility of continuing to pedal at a minimum velocity of 70 rpm; and (3) an RER greater than 1.1 was obtained (Bell et al. 1997, 2000). Three experienced, independent physiologists determined the corresponding points. For the data analysis, the curves of the exhaled and inhaled gases were smoothed by visual analysis using the software Cardiorespiratory Diagnostic Software Breeze Ex version 3.06. The heart rate (HR) was measured using a Polar monitor (model FS1, Shangai, China). The test–retest reliability coefficients (ICC) were 0.88 for $VO_{2peak}$ and 0.85 for $VT_2$.

## Concurrent training programs

Participants of the study trained both strength and endurance training in the same session, three times a week, on nonconsecutive days. Training groups were differentiated by their intrasession concurrent strength and endurance training sequence. One group trained the strength training prior to SE, and another trained endurance prior to ES. Strength training was designed to improve muscular endurance in the first 4 weeks and subsequently to stimulate muscular hypertrophy and maximal strength gains. Before the start of the strength training, subjects completed two familiarization sessions to practice the exercises they would further perform during the training period. The strength and endurance training programs have been previously described (Cadore et al. 2010, 2011a). The individuals performed nine exercises (bench press, inclined leg-press, seated row, knee extension, inverse fly, leg curl, triceps curl, biceps curl, and abdominal exercises). In each session, subjects performed specific muscle stretching and a specific warm up, with one set of 25 repetitions with very light loads for the upper and lower body. During weeks 1 and 2, subjects performed two sets of 18–20 repetitions maximum (RM) in week 1 (i.e., the heaviest possible weight was used for the designated number of repetitions; mean±DP of relative load, 39.8±7.4 % of pretraining 1RM), progressing to 15–17 RM (week 3; 48.3±5.7 % of pretraining 1RM). In weeks 5–7, subjects performed two sets of 12–14 RM (64.1±8.7 % of pretraining 1RM), progressing to three sets of 8–10 RM (weeks 8–10) (81.3±12.3 % of pretraining 1RM), advancing to 6–8 RM (weeks 11–12; 93.1±14 % of pretraining 1RM). During the training program, the maximal training load of the knee extensors exercises in each mesocycle (i.e., 18–20, 15–17, 12–14, 8–10, and 6–8 RM) was recorded to allow future comparisons between groups. However, relative to 1RM loads were not controlled during the training program. In each set, the workload was adjusted when the repetitions performed were either above or below the repetitions established. All the sets were performed until failure. The recovery time between sets was 90–120 s. The strength training sessions lasted approximately 40 min.

The endurance training program was performed, using a cycle ergometer, at the intensity relative to the $HR_{VT}$ corresponding to the second $VT_2$. During the first 2 weeks, subjects cycled for 20 min at 80 % of $HR_{VT}$, progressing to 25 min at 85–90 % of $HR_{VT}$ in weeks 5–6. In the weeks 7–10, subjects cycled for 30 min at 95 % of $HR_{VT}$ and in the last 2 weeks of training, subjects performed six 4-min bouts at 100 % of $HR_{VT}$ (weeks 11–12), with 1 min of active recovery between bouts. The $VT_2$, used as a parameter to prescribe the intensity of endurance training, corresponded to 73.8±4.9 % of the $VO_{2peak}$. All the training sessions were carefully supervised by at least three experienced personal trainers.

## Statistical analysis

The SPSS statistical software package was used to analyze all data. Normal distribution and homogeneity parameters were checked with Shapiro–Wilk and Levene tests, respectively. Results are reported as mean±SD. Statistical comparisons in the control period (from weeks −4 to 0) were performed by using Student's *t* tests. The training-related effects were assessed using a two-way analysis of variance (ANOVA) with repeated measures (group×time). To verify changes in the training load peak, Bonferroni post hoc test was used after two-way ANOVA. Selected relative changes between groups were compared via one-way ANOVA. The sample size was calculated using the G POWER software (version 3.0.1) that determined that a sample of $n=13$ subjects, would provided a statistical power of over 0.85 in all variables. The retrospective statistical power provided by SPSS after analysis was 1.00 in all strength performance variables which a significant time–effect was observed and 0.8 for the significant time vs. group interaction results. Exceptions were observed in the RFD at 100 ms and maximal RFD, which the retrospective statistical power was 0.71 and 0.78, respectively. Furthermore, the retrospective statistical power in the EMG variables were 0.8 and 0.92 for the maximal EMG amplitude of VL and RF, respectively; and 1.0 and 0.85 for VL and and RF neuromuscular economy, respectively. Significance was accepted when $p<0.05$.

## Results

During the period control (i.e., between weeks −4 and 0), no changes were observed in the lower-body 1RM (63.9±10.3 vs. 64.1±10.2 kg), maximal neuromuscular activity of VL (0.180±0.075 vs. 0.197±0.094 V) and RF (0.121±0.081 vs. 0.161±0.010 V), as well as in the $\text{VO}_{2\text{peak}}$ (28.7±3.8 vs. 27.6±3.6 ml kg $\text{min}^{-1}$). There were no differences between groups before training in the body mass (kilogram), height (centimeter), age (years), and percent fat (percentage). After training, there was a significant decrease in the percent of body fat in both SE and ES (27.3±3.7 vs. 24.8±4.3 % and 28.1±2.9 vs. 26.8±3.4 %, respectively, $P<0.001$) with no differences between groups (Table 1). No changes were observed in the body mass after training.

### Training compliance and maximal training load of a specific training period (mesocycle)

There was no difference in the training compliance between SE and ES (94.8±4.3 vs. 97.2±2.9 %). During the different mesocycles, there was strong trend toward time vs. group interaction in the maximal training load relative to pretraining 1RM values in the knee extension exercise ($P=0.056$; Fig. 1) with the SE showing higher relative increases in this variable than ES during the strength training periodization [149.1±37.7 % (from 38.7±5 to 95±10 % of pretraining 1RM) vs. 132.9±32.2 % (from 36.2±10 to 82.9±8 % of pretraining 1RM), respectively].

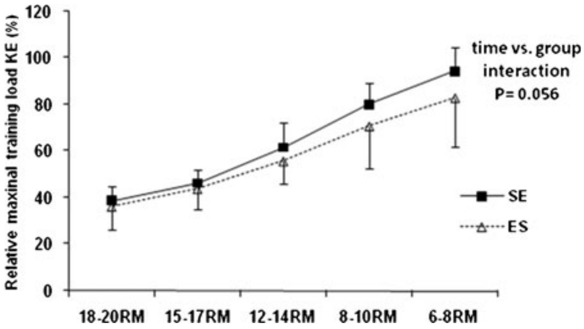

**Fig. 1** Mean±SD of maximal training load (percentage) relative to pretraining one maximum repetition maximum (1RM) values during different mesocycles. Tendency toward significant time vs. group interaction ($P=0.056$)

### Dynamic strength

At baseline, there were no differences between groups in the lower- and upper-body 1RM. After training, there was significant time vs. group interaction ($P<0.02$) in the lower-body 1RM. Both SE and ES increased the knee extensors 1RM values, but the increase observed in the SE was significantly higher than ES (35.1±12.8 vs. 21.9±10.6 %, respectively, $P<0.01$). In the upper-body 1RM, there were significant increases in both SE and ES (15.0±9.0 vs. 11.5±7.3 %, respectively, $P<0.001$), with no difference between groups (Fig. 2).

### Isometric peak torque and rate of force development

At baseline, there were no differences between groups in the isometric peak torque of knee extensors and flexors, knee extensors maximal RFD, or RFD at 100 ms. After training, there were increases in the knee extensors isometric peak torque in both SE and

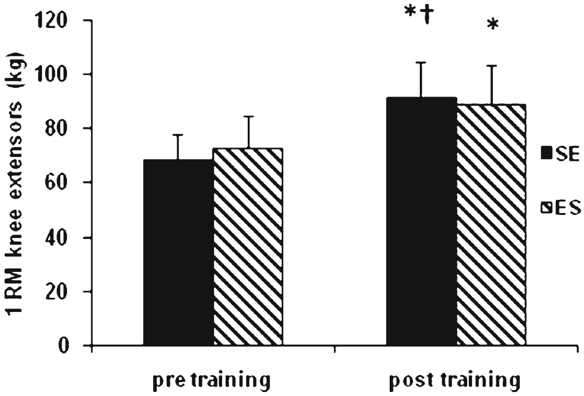

**Fig. 2** Mean±SD of lower-body one maximum repetition (1RM) values (kilogram), pre- and post-12 weeks of concurrent training. *SE* strength prior to endurance training, *ES* endurance prior to strength training. *$P<0.001$, significant difference from pretraining values. †$P<0.001$, significant time vs. group interaction

ES (8.0±7.1 vs. 5.7±9.6 %, respectively, $P<0.001$), with no difference between groups. In addition, knee flexors isometric peak torque increased in both SE and ES (7.8±8.7 vs. 7.9±7.7 %, respectively, $P<0.001$), with no difference between groups. There were increases in the knee extensors RFD at 100 ms in both SE and ES ($P<0.05$), as well as in the knee extensors maximal RFD in SE and ES groups ($P<0.001$), with no differences between groups (Table 2).

### Muscle thickness

At baseline, there were no differences between groups in the lower- (VL, RF, VM, VI, and QF sum) and upper-body muscle thickness (BB, BR, and EF sum; Table 3). After training, there was increases in the VL (SE, 7.3±4.6 %; ES, 7.5±5.3 %; $P<0.001$), VM (SE, 16.7±14.2 %; ES, 9.7±8.3 %; $P<0.001$), VI (SE, 9.4±8.7 %; ES, 12.1±9.3 %; $P<0.001$), and RF muscle thickness (SE, 3.5±3.2 %; ES, 6.4±3.8 %; $P<0.001$), with no differences between groups. In addition, there was increases in the QF sum (SE, 9.3±6.2 %; ES, 9.0±5.0 %; $P<0.001$), with no differences between groups (Fig. 3). In the upper-body muscle thickness, there was increases in the BB (SE, 4.6±3.7 %; ES, 3.3±1.9 %; $P<0.001$), BR (SE, 13.5±7.5 %; ES, 9.1±10.8 %; $P<0.001$), and EF sum (SE, 7.0±2.8 %; ES, 5.0±3.5 %; $P<0.001$). No differences between groups were observed in the upper-body muscle thickness variables.

### EMG measurements

At baseline, there were no differences between groups in the maximal neuromuscular activity (maximal EMG amplitude) of VL, RF, maximal coactivation of BF, as well neuromuscular economy of VL and RF. After training, there were significant increases in the maximal neuromuscular activity of VL (SE, 16.7±40.5 %; ES, 18.3±21.2 %; $P<0.05$; Fig. 4), as well as RF (SE, 22.5±23.6 %; ES, 14.1±26.2 %, $P<0.01$; Fig. 5), with no differences between groups. There were no changes in the coactivation of BF during the knee extensors MVC after training in any group (Table 3). After training, there was significant time vs. group interaction ($P<0.01$) in the RF neuromuscular economy. Changes were observed only in SE (−22.6±30.0 %, $P<0.01$), and this change was greater ($P<0.01$) than the observed in ES (1.5±24.0 %, $P=0.86$; Fig. 6). There were changes in the VL neuromuscular economy (SE, −16.9±12.7 %; ES, −12.5±15.4 %; $P<0.001$), with no differences between groups.

## Discussion

The primary finding of the present study was the greater lower-body strength gains observed when strength training was performed prior to endurance training (i.e., SE) compared with those observed when the endurance training was performed prior to strength training. Secondly, the greater strength gains in the SE sequence may be related with neural adaptations because only SE improved the rectus femoris neuromuscular economy. Furthermore, no differences were observed in the morphological adaptations between groups, which suggested that the intrasession exercise sequence influenced strength performance but not the magnitude of hypertrophy. These results suggest that

**Table 2** Strength performance before and after training: strength–endurance (SE) and endurance–strength (ES); mean±SD

| | Strength–endurance (SE, *n*=13) | | Endurance–strength (ES, *n*=13) | |
|---|---|---|---|---|
| | Pre-training | Post-training | Pre-training | Post-training |
| Upper-body 1RM (kg) | 27.0±2.2 | 31.3±3.7$^{***}$ | 26.2±4.2 | 29.1±4.4$^{***}$ |
| Lower-body 1RM (kg) | 68.1±9.8 | 91.5±12.7$^{***, ****}$ | 72.7±11.8 | 88.3±14.9$^{***}$ |
| KE isometric PT (Nm) | 229.8±27.8 | 247.3±26.9$^{***}$ | 238.6±38.6 | 250.2±34.3$^{***}$ |
| KF isometric PT (Nm) | 116.6±15.0 | 125.0±15.6$^{***}$ | 115.1±25.7 | 131.9±40.0$^{***}$ |
| KE RFD at 100 ms (Nm $s^{-1}$) | 490.6±354.0 | 620.0±366.8$^{*}$ | 428.7±320.0 | 652.5±459.5$^{*}$ |
| KE maximal RFD (Nm $s^{-1}$) | 773.7±354.4 | 879.7±434.9$^{**}$ | 757.7±324.5 | 1,007.2±515.9$^{**}$ |

*1RM* one maximum repetition, *KE* knee extensors, *KF* knee flexors, *PT* peak torque, *RFD* rate of force development

*$P<0.05$, **$P<0.01$, ***$P<0.001$, significant difference from pretraining values; ****$P<0.05$, significant time vs. group interaction

**Table 3** Muscle thickness, maximal neuromuscular activity and neuromuscular economy before and after training: strength–endurance (SE) and endurance–strength (ES); mean±SD

| | Strength–endurance (SE, *n*=13) | | Endurance–strength (ES, *n*=13) | |
|---|---|---|---|---|
| | Pretraining | Post-training | Pretraining | Post-training |
| VL muscle thickness (mm) | 19.8±2.7 | 21.3±3.2*** | 21.6±2.3 | 23.2±2.3*** |
| VM muscle thickness (mm) | 19.3±2.9 | 22.5±3.9*** | 19.4±4.7 | 21.2±5.1*** |
| VI muscle thickness (mm) | 14.3±3.4 | 15.6±3.5*** | 14.8±4.1 | 16.4±3.9*** |
| RF muscle thickness (mm) | 18.6±3.8 | 19.1±3.8*** | 17.6±3.6 | 19.0±3.4*** |
| QF muscle thickness (mm) | 72.0±8.6 | 78.5±8.7*** | 73.4±10.5 | 79.8±10.8*** |
| BB muscle thickness (mm) | 25.5±3.8 | 26.7±4.2*** | 25.9±4.2 | 26.7±4.0*** |
| BR muscle thickness (mm) | 9.4±1.9 | 10.7±2.2*** | 10.4±2.6 | 11.3±3.0*** |
| EF muscle thickness (mm) | 34.9±2.8 | 37.4±3.0*** | 36.3±4.6 | 38.1±4.4*** |
| Maximal NA VL (V) | 0.189±0.093 | 0.204±0.087* | 0.143±0.065 | 0.168±0.077* |
| Maximal NA RF (V) | 0.120±0.038 | 0.143±0.043** | 0.096±0.040 | 0.109±0.050** |
| Antagonist coactivation BF (%) | 21.4±11.4 | 19.8±10.1 | 24.2±10.7 | 27.3±18.3 |
| Neuromuscular economy VL (%) | 42.3±8.0 | 34.9±7.6*** | 44.2±8.9 | 38.4±9.3*** |
| Neuromuscular economy RF (%) | 41.9±11.9 | 31.1±11.8**, **** | 38.3±12.3 | 37.8±11.8 |

Maximal neuromuscular activity (NA) determined by maximal electromiographic signal amplitude

*VL* vastus lateralis, *VM* vastus medialis, *VI* vastus intermedius, *RF* rectus femoris, *BF* bíceps femoris

*$P<0.05$, **$P<0.01$, and ***$P<0.001$, significant difference from pretraining values; ****$P<0.05$, significant time vs. group interaction

performing strength training prior to endurance training optimizes strength gains in the elderly.

In the present study, both the ES and SE intervention groups showed strength gains (22 and 35 %, respectively) at a similar or greater magnitude compared with those observed in other studies that have investigated strength versus concurrent training adaptations in the elderly (20–41 %) (Wood et al. 2001; Izquierdo et al. 2004; Holviala et al. 2010, 2011; Karavirta et al. 2009, 2011). In Holviala et al. (2010), 21 weeks of strength or concurrent training resulted in similar strength gains in elderly men (20

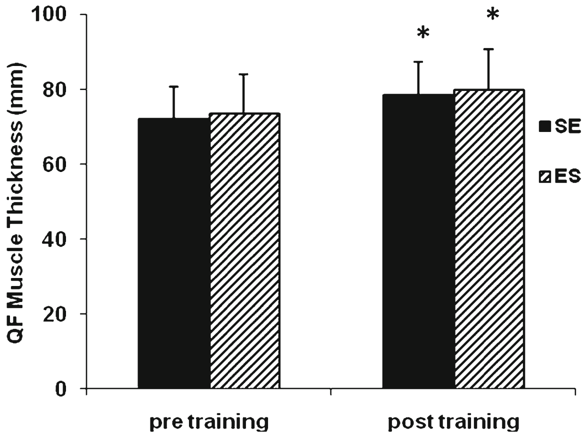

**Fig. 3** Mean±SD of the quadriceps femoris muscle thickness (millimeter) pre- and post-12 weeks of concurrent training. *SE* strength prior to endurance training, *ES* endurance prior to strength training. *$P<0.001$, significant difference from pretraining values

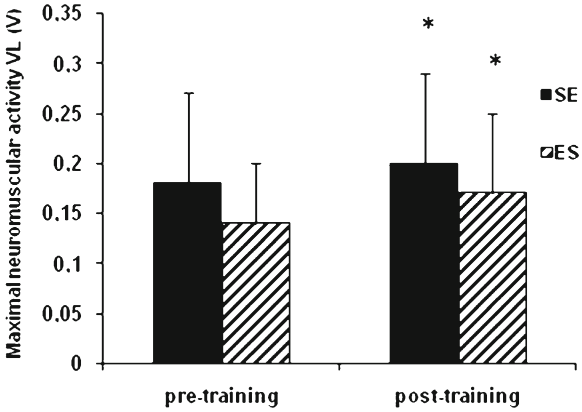

**Fig. 4** Mean±SD of maximal neuromuscular activity (maximal electromiographic amplitude) of vastus lateralis (RMS values) pre- and post-12 weeks of concurrent training. *SE* strength prior to endurance training, *ES* endurance prior to strength training. *$P<0.05$, significant difference from pretraining values

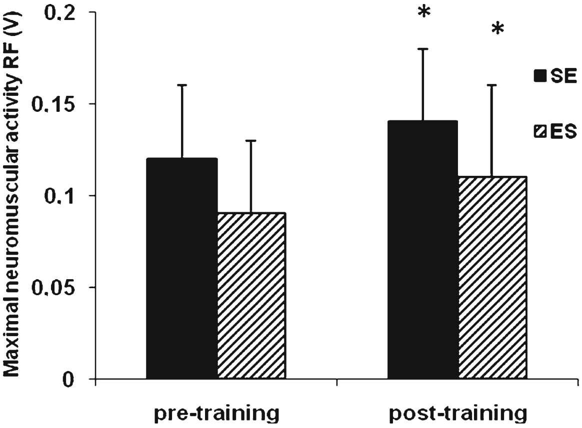

**Fig. 5** Mean±SD of maximal neuromuscular activity (maximal EMG amplitude) of rectus femoris (RMS values) pre- and post-12 weeks of concurrent training. *SE* strength prior to endurance training, *ES* endurance prior to strength training. *$P<0.05$, significant difference from pretraining values

and 21 %). In another study, Karavirta et al. (2011), using a similar strength training regime, demonstrated strength enhancements of similar magnitudes after 21 weeks of strength training alone or concurrent training (21–22 %). It is interesting to note that the same strength adaptations observed in the present study occurred in a shorter period of time than in the abovementioned studies (12 vs. 21 weeks; Holviala et al. 2010, 2011; Karavirta et al. 2009, 2011). These different time courses in strength development could be explained by the different weekly frequency of training performed. The subjects of the present study performed three training sessions per week, which is in contrast with the previous studies, which utilized two training sessions per week (Holviala et al. 2010, 2011; Karavirta et al. 2011). The increased number of training sessions in our study represents a 50 % higher volume of training. Thus, it is possible that the higher weekly volume performed in the present study might explain such neuromuscular adaptations as were observed here after only 12 weeks, even when performing endurance training immediately prior to strength training.

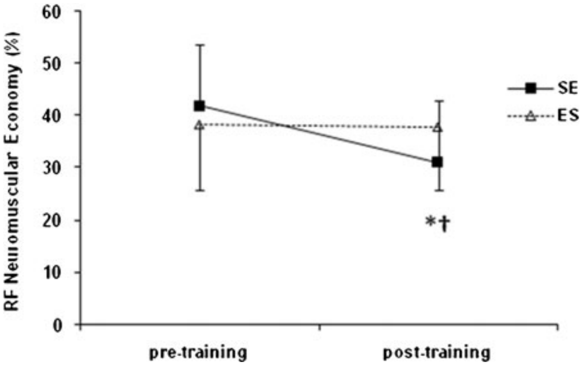

**Fig. 6** Mean±SD of neuromuscular economy (normalized EMG at 50 % of pretraining MVC) of rectus femoris before and after training in strength group (SG). *$P<0.01$, significant difference from pretraining values; †$P<0.01$, significant time vs. group interaction

A unique finding was that greater strength increases were observed in the group that performed strength training prior to endurance training. Few studies have investigated the effects of intrasession exercise sequence on the neuromuscular adaptations to concurrent training. In the study of Gravelle and Blessing (2000), which investigated young women, no significant differences were observed in the strength adaptations between groups that performed different exercise sequences. In another study, Chtara et al. (2008) observed an interference effect on the strength gains in young men after 12 weeks of concurrent training but no effect of different intrasession sequences (i.e., strength–endurance vs. endurance–strength). Using a concurrent training regime identical to the present study, Cadore et al. (2010) found that strength training alone resulted in a 50 % greater increase in knee extensor strength than concurrent training in a similar population (i.e., healthy untrained elderly people). In that study, because the endurance training was always performed immediately before strength training, it was hypothesized that the fatigue resulting from endurance exercise may have negatively affected the training-induced muscle strength gains. Therefore, the extent to which different intrasession exercise sequences (i.e., strength–endurance or endurance–strength) would result in different neuromuscular adaptations in the elderly was hypothesized. The results of the present study are in line with the results of Cadore et al. (2010) because in the present study, SE increased the maximal dynamic strength 50 % more than that observed after an ES order. A plausible explanation was that performing endurance training immediately prior to strength training might negatively influence the subsequent strength training performance. In this context, one may also suggest that the lower strength gains obtained after the ES training approach could be related in part to the fact that the ES group also achieved lower workloads in the training periodization (Fig. 1). It should also be noted that differences in the relative intensity of workloads between groups were more evident in the last two training cycles, when the volume per exercise during the strength training was between 10 and 6 RM, and the endurance intensity was close to $VT_2$.

In the present study, both groups increased the muscle thickness of the elbow flexor and knee extensor muscles. Some studies have shown that a high volume of concurrent training might impair the hypertrophy of type I fibers (Kraemer et al. 1995; Bell et al. 1997, 2000; Putman et al. 2004). Nevertheless, studies using imaging techniques to evaluate muscle hypertrophy have shown no differences in the magnitude of increase in muscle size between strength and concurrent groups in young (McCarthy et al. 2002; Häkkinen et al. 2003; Izquierdo et al. 2005), as well in elderly untrained subjects (Izquierdo et al. 2004; Sillampää et al. 2008; Karavirta et al. 2011). The present results are in agreement with those from previous studies that have found increases in the muscle thickness induced by strength training or concurrent training (Sillampää et al. 2008; Nogueira et al. 2009; Ahtiainen et al. 2010). Furthermore, it seems that performing endurance training before or after strength training in the same concurrent training session has no influence on the magnitude of the muscle hypertrophy induced by strength training. One might speculate that even performing strength training with a lower relative loading intensity (percent of 1RM), the use of maximal effort per set allows the ES group to stimulate its optimal contractile protein synthesis, which results in the same level of morphological adaptation. Indeed, it has been extensively shown in the literature that the optimal strength development stimulus is not necessarily the same as the optimal muscle hypertrophy stimulus (Schoenfeld 2010). It should be stated that potential differences in overall muscle size between ES and SE could be detected using imaging techniques with better spatial resolution (i.e., magnetic ressonance image and computadorized tomography).

Increases in the maximal EMG amplitude of the VL and RF muscles were observed in SE and ES, suggesting that both groups may be an optimal stimulus to enhance the neuromuscular activity (Häkkinen et al. 2003; Brentano et al. 2008). In contrast, performing strength training prior to endurance training resulted in a greater magnitude of neuromuscular economy (i.e., a reduction in the normalized EMG signal at the same absolute load) of the rectus femoris muscle in the SE group, whereas both groups improved the neuromuscular economy of vastus lateralis muscle. It could be speculated that the greater improvements in the neuromuscular economy in SE, together with the absence of differences in the morphological adaptations (i.e., muscle thickness) between groups, suggest that neural factors may help explain the different magnitude of strength gains, with the endurance training session performed immediately before strength exercises negatively influencing such adaptations. Impairments in the neural adaptations induced by concurrent training have been demonstrated by Häkkinen et al. (2003) and Cadore et al. (2010), who show that only strength training alone results in increases in rapid neural activation (Häkkinen et al. 2003) and maximal neuromuscular activity (Cadore et al. 2010) when compared with concurrent training. In addition, Cadore et al. (2010) have shown improvements in neuromuscular economy only in the elderly that performed strength training alone. However, caution is necessary in the interpretation of the present results because neuromuscular activity was evaluated isometrically and the different magnitude of strength gains was detected in a dynamic strength test (i.e., 1RM). Moreover, only one EMG parameter was more improved in SE than ES group. Thus, the interference of the intrasession exercise order in the neural adaptations as a mechanism to explain the different strength gains in the present study needs be further investigated. Furthermore, it is also possible that the greater magnitude of the neuromuscular economy enhancements observed in SE could be a consequence of the greater strength gains rather than a cause of those gains. An improved neuromuscular economy suggests that for the same pretraining load, subjects needed fewer motor units after training, being more economical at the neuromuscular level (Cadore et al. 2010, 2011a, b). Despite differences between groups, both SE and ES have improved the neuromuscular economy to some extent.

To conclude, the present data expand the knowledge of previous findings related to the interference effect observed during concurrent training in an elderly population. The intrasession exercise sequence had an influence on strength adaptations as observed in the greater strength increases when strength training was performed prior to endurance training (35 vs. 22 %). These differences might be related to the different training load peak achieved between groups, especially during the later phase of training, which the endurance training was performed close to the anaerobic ventilatory threshold. Furthermore, a different magnitude of neural adjustment might be suggested as a possible physiological explanation for these different strength adaptations because the neuromuscular economy was improved to a greater extent in the group that performed strength training prior to endurance training, whereas no differences between groups were observed in the maximal neuromuscular activity gains. Nevertheless, in the elderly, it is important to point out that the intrasession concurrent exercise sequence had no influence on muscle thickness gains. From a practical point of view, to optimize the strength gains in the elderly, the concurrent training prescription should include an intrasession exercise order of strength training prior to endurance training.

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