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STRENGTH AND ENDURANCE TRAINING IN ELDERLY MEN

Doctoral Thesis

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LIST OF PUBLICATIONS:

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SUMMARY

Aging is associated with declines in the muscle quality and quantity and strength performance, resulting in an impaired capacity of elderly performing daily activities. These changes include increases in the amount of adipose and connective tissue in the muscle, reductions in the number and size of muscle fibers, a reduction in the maximal voluntary agonist activation and an increase in the antagonist coactivation. In addition, a decline in cardiorespiratory capacity can be observed in elderly persons; this decline is primarily associated with a decrease in maximal heart output, changes in the arteriovenous oxygen difference and declines in neuromuscular function. The accumulation of connective and adipose tissue in the muscles can be assessed using the ultrasound imaging, whereby enhanced echo intensity represents changes caused by increased intramuscular connective and adipose tissue. Nevertheless, there are limited data regarding the association between echo intensity and strength performance, and no studies have investigated the relationship between echo intensity and other parameters related to physical fitness in the elderly, such as the endurance performance.

To counteract the declines in neuromuscular and cardiovascular performance associated with the aging, the concurrent strength and endurance training seems to be the most effective strategy. Notwithstanding, 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”. A limited number of studies, however, have explored the neuromuscular adaptations related to concurrent strength and cardiovascular intervention in elderly populations. Along with the scarce results regarding the neuromuscular adaptations to concurrent training in elderly, another aspect poorly investigated in elderly populations is the

influence of intra-session exercise sequence manipulation on concurrent strength and endurance adaptations.

To investigate the above mentioned issues, the present Thesis was composed by the following studies and respective purposes: Study 1: To investigate the relationships among echo intensity, neuromuscular and cardiorespiratory performance; Study 2: To investigate the neuromuscular and hormonal adaptations that occur in response to strength, endurance and concurrent training in elderly subjects; Study 3: To investigate the effects of different intra-session exercise orders during concurrent strength and endurance training on neuromuscular adaptations in the elderly.

In the study I, in order to investigate a possible relationship between echo intensity with strength development, as well with cardiorespiratory parameters in older men, physical evaluations were carried out using ergospirometry, dynamometry and ultrasonography in 31 elderly healthy men (64.7 ± 4.1 years). In the study II, in order to investigate the adaptations to strength, endurance and concurrent training, 23 healthy elderly men (65. ± 5.0 years) were divided in strength, concurrent and endurance training groups. The subjects were evaluated at -4 and 0 weeks before (control period) and 12 weeks after each specific training program. Subjects were tested using variables related to maximal strength, neuromuscular activity and serum hormonal concentrations. In the study III, the physiological effects of different intra-session exercise sequences during concurrent training in the elderly were assessed with a strength and endurance training protocol performed in the study 2. The healthy elderly men (64.7 ± 4.1 years) were evaluated using variables related to maximal strength, neuromuscular activity and muscle thickness.

The main findings of the study I were the associations found between muscle echo intensity with the neuromuscular and cardiorespiratory performance in elderly. In addition, the force per unit of muscle mass was associated with cardiovascular performance. In the study II, the main finding was the interference effect on the lower body-muscle strength gains observed in the concurrent group. In addition, this interference effect occurred together with the different variations in EMG measurements obtained among the groups. Moreover, measurement of hormonal concentrations did not suggest any evidence of increased catabolic state. The primary finding of the study III 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 (table 5). Secondly, the greater strength gains in the SE sequence may be related with neural adaptations because only SE improved the rectus femoris neuromuscular economy.

The conclusions of the present Doctoral Thesis were that: (I) The echo intensity measured using computer-aided grayscale analysis is an effective method for evaluating muscle quality that may contribute to future research on neuromuscular and cardiovascular function in the elderly (study I); (II) The differences in strength enhancement, resulting from strength and concurrent training suggests that endurance training performed simultaneously with strength training can negatively interfere in the strength gains in elderly men, when the same muscle group is activated in both types of training (study II); and, (III) To optimize the strength gains in the elderly, the concurrent training prescription should include an intra-session exercise order of strength training prior to endurance training (study III).

RESUMEN

Desde la segunda o tercera década de la vida, la capacidad funcional del sistema neuromuscular, cardiovascular y respiratorio del ser humano comienza a disminuir de modo progresivo. Estos cambios incluyen un aumento en la cantidad de tejido adiposo y conjuntivo en el músculo, una reducción en el número y tamaño de fibras musculares, así como una reducción en la activación agonista voluntaria máxima y un aumento en la coactivación antagonista. Además, en personas mayores, se observa una disminución en la capacidad cardiovascular asociada con una disminución en la frecuencia cardiaca, cambios en la diferencia arterio-venosa de oxígeno y caídas en la función neuromuscular. La acumulación de tejido conjuntivo y adiposo en los músculos, puede ser evaluada a través de la ultrasonografía o ecografía. Un incremento en la intensidad de la señal ultrasonográfica representa cambios generados por un aumento del contenido conjuntivo y adiposo intramuscular. Sin embargo, existen datos limitados acerca de la asociación de la intensidad de la señal ultrasonográfica con la producción de fuerza, y ningún estudio ha investigado la relación entre la intensidad de la señal con otros parámetros relacionados con la capacidad física, como la respuesta cardiovascular.

Para reducir la disminución en la respuesta neuromuscular y cardiovascular asociada al envejecimiento, el entrenamiento concurrente de fuerza y resistencia cardiovascular parece ser la estrategia más efectiva. Sin embargo, estudios previos sugieren que el entrenamiento concurrente resulta en menores mejoras de la fuerza si es comparado con el entrenamiento sólo de fuerza. Éste fenómeno es conocido como “el efecto de interferencia”. No obstante, el número de estudios que ha explorado las adaptaciones neuromusculares tras un entrenamiento concurrente de fuerza y resistencia cardiovascular en poblaciones ancianas, es muy reducido. Otro aspecto del

entrenamiento concurrente no investigado en personas mayores, es la influencia del orden de los entrenamientos de fuerza y resistencia cardiovascular en una misma sesión, sobre las adaptaciones al entrenamiento.

Con el propósito de examinar estas cuestiones, la presente tesis doctoral estuvo conformada por tres estudios de investigación experimental y un estudio de revisión con los siguientes objetivos: Estudio I: Investigar la asociación entre la intensidad de la señal ultrasonográfica con el desempeño neuromuscular y cardiovascular en ancianos; Estudio II: Investigar las adaptaciones neuromusculares y hormonales en respuesta al entrenamiento de fuerza, entrenamiento de resistencia cardiovascular y entrenamiento concurrente en ancianos; Estudio III: Investigar los efectos de diferentes órdenes de ejecución de ejercicios de fuerza y resistencia cardiovascular durante el entrenamiento concurrente, en las adaptaciones neuromusculares en ancianos.

En el Estudio I, se examinó la posible asociación entre la intensidad de la señal ultrasonográfica con la producción de fuerza y las variables cardiorespiratorias. En este estudio se realizaron diferentes evaluaciones físicas (ergoespirometría, dinamometría y ultrasonografía) a 31 hombres ancianos sanos (64,7 ± 4,1 años). En el Estudio II, se examinó las adaptaciones a los entrenamientos de fuerza, resistencia cardiovascular y entrenamiento concurrente en 23 ancianos sanos (65 ± 5 años) que divididos en 3 grupos de entrenamiento (fuerza, resistencia cardiovascular y concurrente). Los sujetos fueron evaluados en las semanas -4 y 0 antes del inicio del entrenamiento (periodo control) y después de 12 semanas de entrenamiento. Las variables evaluadas estaban relacionadas con la fuerza máxima, actividad neuromuscular y concentraciones hormonales. En el Estudio III, se evaluaron los efectos fisiológicos de diferentes secuencias de ejercicios de fuerza y resistencia cardiovascular durante un entrenamiento concurrente en ancianos. Los entrenamientos de fuerza y resistencia cardiovascular utilizados fueron similares a los utilizados en el estudio II. Asimismo, los sujetos, hombres ancianos sanos (64,7 ± 4,0 años), fueron evaluados utilizando variables relacionadas con la fuerza máxima, actividad muscular y grosor muscular.

Los principales resultados del estudio 1 fueron las asociaciones encontradas entre la intensidad de la señal ultrasonográfica muscular con la respuesta neuromuscular y cardiovascular en personas mayores. Además, la fuerza por unidad de masa muscular se asoció con la respuesta cardiovascular. En el estudio 2, el principal resultado fue el efecto de interferencia observado en la mejora de la fuerza muscular de miembros inferiores en el grupo de entrenamiento concurrente. Este efecto de interferencia ocurrió en paralelo con diferentes cambios en las medidas de EMG obtenidas entre los grupos. Por otra parte, las concentraciones hormonales no sugirieron ninguna evidencia de un aumento en el estado catabólico. El principal resultado del estudio 3 fue que las mejoras de fuerza de miembros inferiores fueron mayores cuando el entrenamiento de fuerza fue realizado antes del entrenamiento de resistencia cardiovascular (grupo SE), comparadas con las observadas en el grupo que ejecutó el orden inverso de entrenamiento (resistencia - fuerza). Estas mayores mejoras en la fuerza, pueden estar relacionadas con adaptaciones neurales, ya que solamente el grupo SE aumentó la eficiencia neuromuscular del músculo recto femoral.

Las principales conclusiones de la presente Tesis Doctoral son: (I) La intensidad de la señal ultrasonográfica utilizando el análisis de la escala de grises es un método efectivo para evaluar la calidad muscular. Este método puede proporcionar información útil en futuras investigaciones de la función neuromuscular y cardiovascular en ancianos (Estudio I). (II) Las diferencias en la mejora de la fuerza resultantes de los entrenamientos de fuerza y entrenamiento concurrente, sugieren que el entrenamiento de resistencia cardiovascular ejecutado simultáneamente con el entrenamiento de fuerza puede interferir negativamente en la mejora de fuerza en hombres mayores, cuando el mismo grupo muscular es activado en los dos tipos de entrenamiento (Estudio II); y, (III) Para optimizar la mejora de la fuerza en mayores, el entrenamiento concurrente deberá ser planificado de forma que el entrenamiento de fuerza sea ejecutado antes del entrenamiento de resistencia cardiovascular (Estudio III).

CONTENTS

LIST OF FIGURES AND TABLES:

LIST OF ABBREVIATIONS

%	Percentual
%MVC	Percentual of maximum voluntary contraction
%EMG	Percentual of maximal neuromuscular activity
COR	Cortisol
MVC	Maximum voluntary contraction
EMG	electromiography signal
HR	Heart rate
$HR_{máx}$	maximal heart rate
HR_{VT}	Heart rate at the second ventilatory threshold
SG	Strength training group
EG	Endurance training group
CG	Concurrent training group
SE	Strength-endurance training group
ES	Endurance-strength training group
RM	Repetitions maximum
1 RM	One repetitions maximum
RMS	Root Mean Square
FT	Free testosterone
TT	Total testosterone
TT/COR	Total Testosterone to cortisol ratio
FT/COR	FreeTestosterone to cortisol ratio
RFD	Rate of force development
A.U.	Arbitrary units
VE	Ventilation
VO_2	Oxigen uptake
VO_{2peak}	Peak of Oxigen uptake
$VO_{2máx}$	Maximal Oxigen uptake
$W_{máx}$	Maximal workload at cycle ergometer
VT_1	First ventilatory threshold
VT_2	Second ventilatory threshold
W_{VT1}	Workload at first ventilatory threshold
W_{VT2}	Workload at second ventilatory threshold

A/D	Analog to digital converter
ICC	Reliability coefficients
EI	Echo intensity
MT	Muscle thickness
VL	Vastus lateralis
VM	Vastus medialis
VI	Vastus intermedius
RF	Rectus femoris
BF	Bíceps femoris
QF	Quadríceps femoris
EF	Elbow flexors
BB	Bíceps brachii
BR	Brachialis
PT_{iso}	Isometric peak torque

1. Neuromuscular and cardiovascular function: Age and training effects

1.1. Effects of aging on neuromuscular and cardiovascular function:

Biological aging is associated with declines in the muscle quality and quantity and strength performance, resulting in an impaired capacity of elderly performing daily activities (Izquierdo et al. 2001; 2003; Aagard et al. 2010). These changes include increases in the amount of adipose and connective tissue in the muscle (Seene et al. 2011), reductions in the number and size of muscle fibers (Larsson et al. 1978; Lexell et al. 1988; Lynch et al. 1999), a reduction in the maximal voluntary agonist activation and an increase in the antagonist coactivation (Izquierdo et al. 1999a; Klein et al. 2001; Suetta et al. 2004). In addition, a decline in cardiorespiratory capacity can be observed in elderly persons; this decline is primarily associated with a decrease in maximal heart output, changes in the arteriovenous oxygen difference (Izquierdo et al. 2001) and declines in neuromuscular function (Izquierdo et al. 2001, 2003; Cadore et al. 2011a).

1.2. Relationship between muscle quality and echo intensity determined by ultrasonography:

The accumulation of connective and adipose tissue in the muscles, i.e., changes in muscle quality, can be assessed using the non-invasive, easily accessible and safe method of ultrasound imaging, whereby enhanced echo intensity represents changes caused by increased intramuscular connective and adipose tissue (Pillen et al. 2009; Fukumoto et al. 2011). Evidence suggests that ultrasonography can detect structural muscle changes caused by impaired neuromuscular function. Indeed, it has been shown that elderly populations present greater gray scale values when compared with young populations (Arts et al. 2010), and this changes have been associated with enhanced intramuscular adipose tissue (Kent-Braun et al. 2000; Arts et al. 2010; Fukumoto et al. 2011).

Although impairments in the neuromuscular and cardiovascular function may occur in parallel with increases in the gray scale values in elderly, studies investigating the relationship between echo intensity and physical fitness parameters in this population are scarce. Sipilä and Suominen (1991, 1994) showed that the echo intensity of the quadriceps femoris was associated with knee extensor strength in an elderly population. Unfortunately, their results were based on echo intensity values generated by visual scoring, which did not control for operator-induced error. In another study using computer-aided grayscale analysis, Fukumoto et al. (2011) observed negative correlations between grayscale values and isometric strength in elderly men, suggesting that the subjects with greater adipose and connective tissue, i.e., those with greater echo intensity values, had lower strength performance. Nevertheless, there are limited data regarding the association between echo intensity and strength performance, and no studies have investigated the relationship between echo intensity and other parameters related to physical fitness in the elderly, such as neuromuscular and endurance performance. In addition to neuromuscular function, cardiorespiratory fitness has been associated with functional capacity in elderly populations. In this context, it would be interesting to determine the association between the muscle echo intensity and cardiovascular fitness.

1.3. Concurrent strength and endurance training:

To counteract the declines in the muscle quality and cardiovascular performance associated with the aging process, 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 different 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; 2002b), 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).

1.4. Concurrent training in elderly populations:

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). In these two studies involving elderly subjects, the volume of training performed was lower in the concurrent training groups (Wood et al. 2001; Izquierdo et al. 2004). Thus, it is not known whether interference would have occurred if these two studies had used similar volumes for strength training in the concurrent groups as they used in the strength training alone groups. However, it is possible that even by performing a greater volume of concurrent training, the large trainability of untrained elderly subjects may lead to similar strength enhancements induced by concurrent and strength training with no presence of interference effect in this population (Karavirta et al. 2009).

1.5. Effects of intra-session exercise order during the concurrent training:

Along with the scarce results regarding the neuromuscular adaptations to concurrent training in elderly, another aspect poorly investigated in elderly populations is the influence of intra-session exercise sequence manipulation on concurrent strength and endurance adaptations. In fact, even in young populations, few studies have investigated the effects of intra-session 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 intra-session sequences (i.e., strength-endurance vs. endurance-strength). However, there are no data regarding the effect of exercise order manipulation during concurrent training on the neural and muscle morphology adaptations in elderly subjects and such data would have a great practical applications in the concurrent training prescription in elderly, as well as would give insight into possible mechanisms underlying the chronic negative influence of endurance training in strength training adaptation.

Given the relevance of the neuromuscular and cardiovascular performance to the functional capacity in elderly and the few data regarding the neuromuscular adaptations to concurrent training in elderly, the present doctoral thesis has the following hypothesis:

2. HYPOTHESIS:

H_1. The echo intensity would be associated with several parameters of neuromuscular and cardiorespiratory performance (study I).

H_2. Due to the large trainability of older subjects, no differences between strength and concurrent training would be found. However, if the interference effect is observed, we speculate that neural and endocrine mechanisms could help to explain this possible effect (study II).

H_3. In the case of occurrence of interference effect in the experiment 2, our third hypothesis was that performing strength exercise before endurance exercise would result in greater strength increases than in the opposite sequence (endurance-strength) (study III).

To test the abovementioned hypothesis, we conducted three experiments with the following objectives:

3. OBJECTIVES:

O_1. To investigate the relationships among echo intensity, neuromuscular and cardiorespiratory performance (study I).

O_2. To investigate the neuromuscular and hormonal adaptations that occur in response to strength, endurance and concurrent training in elderly subjects (study II).

O_3. To investigate the effects of different intra-session exercise orders during concurrent strength and endurance training on neuromuscular adaptations in the elderly (study III).

4. METHODS

4.1. Study I.

4.1.1. Subjects and Experimental design:

Healthy elderly men aged 60 years or older, who were not engaged in any regular and systematic training program in the previous 12 months, volunteered for the studies after completing an ethical consent form. The subjects volunteered for the investigations following announcements in a widely read local newspaper. Subjects were carefully informed about the design of the studies with special information given regarding the possible risks and discomfort related to the procedures. The studies were conducted according to Declaration of Helsinki and was approved by the local ethics committee. 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. Medical evaluations were performed using clinical anamnesis and effort electrocardiograph test, to ensure subject suitability for the testing procedure

In order to investigate a possible relationship between echo intensity with strength development, as well with cardiorespiratory parameters in older men, physical evaluations were carried out using ergospirometry, dynamometry and ultrasonography. For this purpose, the participants in the present study attended the Laboratory on several different occasions, since the evaluations of echo intensity, isometric and isokinetic torque and aerobic capacity were made on separate days. By measuring and correlating all these variables, we attempted to get insight regarding the relationship among them in elderly, since physiological concepts might explain possible correlations. Prior to data collection, the participants took part in a familiarization session for each test. Thirty-one healthy elderly men (Mean ± SD: 64.7 ± 4.1 years) volunteered for this study.

4.1.2. Isometric and isokinetic peak torque:

Maximal isometric and isokinetic peak torque were 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 at angular velocity of $90°\cdot s^{-1}$, performing a submaximal effort. The dynamometer was connected to an A/D converter (Dataq Instruments Inc. Akron, Ohio-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 dynamometer 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 the right knee. The subjects had three attempts at obtaining the maximum voluntary contraction (MVC) of the knee extensors, each lasting five seconds, and an additional contraction was obtained if a torque variation higher than 10% was observed between consecutive contractions. In the last part of the protocol, subjects performed five dynamic repetitions of concentric knee extensions/flexions at 60, 180 and $360°\cdot s^{-1}$, in order to obtain the isokinetic peak torque in each angular velocity. The rest interval between each attempt of the protocol was two-minutes. 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 and analyzed using Biodex software. Signal processing included filtering with a Butterworth low-pass filter at a cut-off frequency of nine Hertz. Maximal peak torque was defined as the highest value of the torque ($N\cdot m$) recorded during the unilateral knee extension. The test-retest reliability coefficients (ICC) were over 0.94 for all the variables in the isometric and isokinetic protocol.

4.1.3. Echo Intensity and Muscle Thickness:

The echo intensity (EI) and 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. Subjects were evaluated in supine position, after 15 minutes resting and after 72 hours without any vigorous physical activity. The EI was determined by gray-scales analysis using the standard histogram function in Image-J (National institute of health, USA, version 1.37). A region of interest was select in rectus femoris as much of the muscle was possible without any bone or surrounding fascia. For echo intensity analysis the depth setting was fixed at 5 cm. When this setting was insufficient to display the entire muscle, only the superficial part of the muscle was used for EI analyses. The EI in region of interest was expressed in values between 0 and 256 (0: Black; 256: White).

The MT images were determined in the lower-body muscles vastus lateralis (VL), vastus medialis (VM), vastus intermedius (VM), rectus femoris (RF) (figure 1). The measurement for the VL was taken at midway between the lateral condyle of the femur and greater trochanter (Kumagai et al. 2000), 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. The images were digitalized and after analyzed in software Image-J (National institute 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 same investigator made all measurements of EI and MT. Force per unit of active muscle mass was calculated from the quotient between the maximal isometric torque (PT_{iso}) of the right leg and the sum of the muscle thickness (MT) of the muscles of quadríceps femoris (QF) adjusted by allometric scaling (i.e. F α $m^{2/3}$) (Jaric et al. 2002). The QF MT was composed by the VL, RF, VM, and VI MT. Thus, force per unit of muscle mass was calculated following the formula: $MQ = PT_{iso}$ (N·m) of the right leg / MT QF_{sum} of (VL + VM + VI + RF) $(mm)^{0,67}$. The MT test-retest reliability coefficients (ICC) were 0.94 for VL, 0.91 for VM, 0.92 for VI and 0.95 for RF.

Fig. 1: Ultrasonographic image of quadriceps femoris.

4.1.4. Cardiovascular performance:

Subjects performed an incremental test on a cycle ergometer (Cybex, USA) in order to determine the peak oxygen uptake (VO_{2peak}), the first (VT_1) and second (VT_2) ventilatory thresholds, maximal workload ($W_{máx}$) and the workloads at VT_1 (W_{VT1}) and VT_2 (W_{VT2}) (figure 2). They initially cycled with a 25W load, which was progressively increased by 25W every two minutes, while maintaining a cadence of 70-75 rpm, until exhaustion (Izquierdo et al. 2003). 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) breath by breath. The VT_1 and VT_2 were determined using the ventilation curve corresponding to the points of exponential increase in the ventilation in relation to the load (Cadore et al. 2011a, 2011b). In addition, to confirm the data, VT_2 was determined using the CO_2 ventilatory equivalent (VE/VCO_2) (Wasserman 1986). The maximum VO_2 value ($ml.kg^{-1}.min^{-1}$) obtained close to exhaustion was considered the VO_{2peak}. The W_{max} (watts) was calculated using the formula: W_{max}=

$W_{com}+(t/180)\cdot\Delta W$, which W_{com} is the load at the last stage completed, t is the time at the last incomplete stage and ΔW is the load increment in the last stage (25 watts) (Izquierdo et al. 2001, 2003). The maximum test was considered valid if at least 2 of the 3 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. 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, CHI). The test-retest reliability coefficients (ICC) were 0.88 to VO_{2peak} and $W_{máx}$, as well 0.85 to VT_1 and VT_2.

Fig.2. Maximal incremental test and metabolic cart.

4.1.5. Statistical analysis:

Normal distribution parameters were checked with Shapiro-Wilk test. The Pearson product moment correlation test was used to investigate possible associations between the parametric parameters analyzed. In the non-parametric data, Spearman correlation test was used. Significance was accepted as $P < 0.05$ and the analysis were made in SSPS version 18.0.

4.2. STUDY II.

4.2.1. Subjects and Experimental Design:

Twenty-nine healthy elderly men (Mean ± SD: 65±5 years; age range: 61 - 70 years) volunteered for the study. Subsequently, subjects were randomly selected and placed into three groups: strength training (SG, n=10); endurance training (EG, n=9); and, concurrent training (CG, n=10). Three participants dropped out after the control period and another three dropped out during the training period. At the end of the study, the number of subjects in each group was: SG=8; EG=7; and, CG=8.

In order to investigate the adaptations to strength, endurance and concurrent training, subjects were evaluated using variables related to maximal strength, neuromuscular activity and serum hormonal concentrations. The investigations of electromiographic signal (EMG) and hormonal parameters provided insights about possible mechanisms involved with training adaptations and interference effect. The total duration of the present study was 16 weeks, in which the subjects were tested at -4 and 0 weeks before (control period) and 12 weeks after each specific training program. Thus, all the tests were performed three times during the investigation and the first and second pre training measures (control period) were used to determine the stability and reliability of the variables. Each subject performed the tests at the same time of day throughout the period of the study and the different tests were conducted on different days to avoid fatigue.

4.2.2. Maximal dynamic strength:

Maximal strength was assessed using the one-repetition maximum test (1-RM) on the bench press and bilateral knee extension (figure 3). One week prior to the test day, subjects were familiarized with all procedures. On the test day, the subjects warmed up for five minutes 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 four-minute recovery between attempts. Performance time for each contraction (concentric and eccentric) was two seconds, controlled by an electronic metronome (Quartz, CA, USA). The test-retest reliability coefficient (ICC) was 0.99 for both exercises.

Fig. 3. Lower-body maximal dynamic strength test (1RM).

4.2.3. Maximal isometric strength:

In order to obtain the maximal isometric strength, the subjects warmed up for five minutes on a cycle ergometer and were then positioned on knee extension exercise machine (Taurus, Porto Alegre, Brazil), fitted with a load cell coupled to the cable that displaced the load. The load cell was connected to an A/D converter (Miotec, Porto Alegre, Brazil), which made it possible to quantify the traction exerted when each subject executed the knee extension at the determined angle. The subjects were positioned seated with the hip at a 110° angle, strapped to the machine at the waist. After having their right leg positioned by the evaluators at an angle of 110° in the knee extension (180° represented the full extension), the subjects were instructed to exert maximum strength possible when extending the right knee. The subjects had three attempts at obtaining the maximum voluntary contraction (MVC), each lasting five seconds, with a three-minute rest interval between each attempt. During this test, the researchers provided verbal encouragement so that the subjects would feel motivated to produce their maximum strength. The force-time curve was obtained using Miograph software (Miotec), with an acquisition rate of 2000 Hz and later analyzed using SAD32 software. Signal processing included filtering with a Butterworth low-pass filter at a cut-off frequency of nine Hertz. Later, in order to determine the highest MVC, a one-second slice was made in the plateau of force, between the 2nd and 4th second of the force-time curve. The test-retest reliability coefficient (ICC) was 0.94 for MVC.

4.2.4. EMG Measurements:

During the isometric strength test, the maximal muscular activation 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 (2001). 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 2000 Ω (figure 4). 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 a four-channel electromyograph (Miotool, Porto Alegre, Brazil), with a sampling frequency of 2000 Hz per channel, connected to a personal computer (Dell Vostro 1000, São Paulo, Brazil). Following acquisition of the signal, the data were exported to the SAD32 software, where they were filtered using the Butterworth band-pass filter, with a cut-off frequency of between 20 and 500 Hz. After that, the EMG records were sliced exactly in the 1 second when the MVC was determined in the force-time curve and the root mean square (RMS) values were calculated. The RMS values of biceps femoris were normalized by the maximum RMS values of this muscle, obtained during the MVC of knee flexion at 90°.

After determination of maximal muscular activation, submaximal muscular activation was evaluated in order to determine the isometric neuromuscular economy. Thus, subjects randomly performed the strength trials corresponding to 40, 60 and 80% of pre training MVC. In this protocol, subjects were asked to maintain the specific force value for three seconds, receiving a visual feed-back in the computer that showed, in real-time, the strength values. One trial was performed for each intensity, with 5-minute rest between trials. The apparatus and the collection and analysis procedures were the same used to determine the maximal EMG signal. After the training period, the submaximal muscular activation was determined for the same absolute loads used in the pre-training 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.

Fig. 4. Skin preparation and electrodes inter-resistance control.

4.2.5. Blood collection and analysis:

Blood was obtained from the subjects between 8:00 and 8:30 a.m., after eight hours of sleep, 12 hours fasting and two days with no exercise. The time of blood collection was chosen due to its use in many studies conducted with these procedures for the control of the circadian hormonal range (Kraemer et al. 1995; Izquierdo et al. 2001; Cadore et al. 2008a, 2008b). Subjects sat in a slightly reclined position during 15 min then 10 ml of blood was drawn from an antecubital vein. After collection, the blood was maintained at ambient temperature for 45 min and then centrifuged for ten minutes at 2.000 rpm. The serum was then removed and frozen at -20ºC for later analysis. With this blood sample, resting concentrations of total testosterone (TT) (MP Medicals, Ohio, USA) and free testosterone (FT) (Diagnostic Systems Lab, Webster, USA) and cortisol (COR) (MP Medicals, Ohio, USA) were determined in duplicate, using radioimmunoassay kits. From these values it was possible to calculate the TT/COR ratio. To eliminate interassay variance, all samples were analyzed within the same assay batch, and all intra-assay variances were ≤ 6.3%. Antibody sensitivities were 0.2 ng/ml for TT, 0.2 pg/ml for FT, 0.05 ug/dl for COR. The test-retest reliability coefficient (ICC) were 0.85 for COR, 0.94 for TT and TL.

4.2.6. Strength training:

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 individuals in the SG performed nine exercises (inclined leg-press, knee extension, leg curl, bench press, lat pull down, seated row, triceps curl, biceps curl and abdominal exercises) three times a week on non-consecutive days. 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 one to seven, subjects performed two sets of 18-20 repetitions maximum (RM) in week 1, progressing to 12-14 RM (week 5). In weeks eight to 12, subjects performed three sets of 12-14 RM (week 8), advancing to 6-8 RM (week 11). During the training program, all the sets were performed until failure. In each set the workload was adjusted when the repetitions performed were either above or below the repetitions established. The recovery time between sets was 90 to 120 seconds. The whole strength training periodization is shown in the Table 1. All the training sessions were carefully supervised by at least two experienced personal trainers.

4.2.7. Endurance training:

Participants in the EG trained three times a week, on non-consecutive days, using a cycle ergometer, at the intensity relative to the heart rate (HR_{VT}) corresponding to the second ventilatory threshold (VT_2). In each session, subjects performed a warm up lasting five minutes at comfortable cadence. During the first two weeks, subjects cycled for 20 minutes at 80% of HR_{VT}, progressing to six four minute bouts at 100% of HR_{VT} (weeks 11-12), with one minute of active recovery between bouts. The VT_2, used as a parameter to prescribe the intensity of endurance training, corresponded to 79.6 ± 5% of the VO_{2peak}. The Cardiorespiratory parameters were measured similar as described in study 1. The whole endurance training periodization is shown in the Table 1.

Table 1: Complete strength and endurance training periodization

Strength training				Endurance training		
Week	Sessions	Sets	Repetitions	Week	Volume	Intensity
1	3	2	18 - 20 RM	1	20 min	80 % HR_{VT}
2	3	2	18 – 20 RM	2	20 min	80 % HR_{VT}
3	3	2	15 – 17 RM	3	20 min	85 % HR_{VT}
4	3	2	15 – 17 RM	4	25 min	85 % HR_{VT}
5	3	2	12 – 14 RM	5	25 min	85 % HR_{VT}
6	3	2	12 – 14 RM	6	25 min	90 % HR_{VT}
7	3	2	12 – 14 RM	7	30 min	90 % HR_{VT}
8	3	3	8 – 10 RM	8	30 min	90 % HR_{VT}
9	3	3	8 – 10 RM	9	30 min	95 % HR_{VT}
10	3	3	8 – 10 RM	10	30 min	95 % HR_{VT}
11	3	3	6 – 8 RM	11	6 x 4 min / 1 min resting	100 % HR_{VT}
12	3	3	6 – 8 RM	12	6 x 4 min / 1 min resting	100 % HR_{VT}

RM: maximum repetitions; HR_{VT}: heart rate at ventilatory threshold; min, minutes.

4.2.8. Concurrent training:

Participants in the CG performed the combined volume of both the SG and EG training. During all sessions, strength exercises were preceded by endurance exercise. This order of exercise was chosen to investigate the effects of aerobic training preceding strength training due to the possible fatigue effects of aerobic training, especially when performed on a cycle ergometer [28]. The CG training sessions lasted approximately 70 minutes.

4.2.9. Statistical Analysis

Statistical comparisons in the control period (from week –4 to week 0) were performed by using Student's paired t-tests. The training-related effects were assessed using a two-way Analysis of Variance (ANOVA) with repeated measures (group x time). When a significant F value was achieved, Bonferroni post-hoc procedures were used to locate the pair wise differences. Selected relative changes between groups were compared via one-way ANOVA. Significance was accepted when $p < 0.05$.

4.3. STUDY III.

4.3.1. Subjects and Experimental Design:

Twenty six healthy elderly men (Mean ± SD: 64.7 ± 4.1 years) volunteered for the study. 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 physiological effects of different intra-session exercise sequences during concurrent training in the elderly were assessed with a strength and endurance training protocol performed in the study II. 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. 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.

4.3.2. Maximal dynamic strength:

Maximal strength was assessed using the one-repetition maximum test (1-RM) on the bilateral elbow flexion and bilateral knee extension with similar procedures as described in the study II.

4.3.3. Isometric peak torque and rate of force development:

Maximal isometric peak torque were 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 at angular velocity of $90°\cdot s^{-1}$, performing a submaximal effort. The dynamometer was connected to an A/D converter (Dataq Instruments Inc. Akron, Ohio-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 five seconds. After the MVCs, in order to evaluate the isometric neuromuscular economy, subjects had three 5-s attempts to exert 50% of the pre training isometric peak torque and maintain it for, at least, three seconds receiving a visual feed-back 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 interval between each attempt of the protocol was two-minutes. 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 2000 Hz. Signal processing included filtering with a Butterworth low-pass filter of 4^{th} order at a cut-off frequency of nine Hertz. Maximal peak torque was defined as the highest value of the torque ($N \cdot m$) 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) ($N{*}s^{-1}$), defined as the greatest increase in the force; and, the RFD at 100ms, defined as the greatest increase in the force in the first period of 100ms. 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.

4.3.4. 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 positioning and repositioning, skin preparation, interelectrodes resistance, ground electrode and filtering and analysis procedures were done as described in the study 2. The raw EMG signal was acquired simultaneously with the MVC using a 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, Ohio-USA), with a sampling frequency of 2000 Hz per channel, connected to a PC computer.

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 pre training 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 pre-training 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.

4.3.5. Muscle Thickness:

The muscle thickness (MT) was measured with similar apparatus and procedures as described in the study 1. In addition to the right knee extensor, the MT of upper-body limbs 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 (Miatany et al. 2000; Fukunaga et al. 2001).

4.3.6. Concurrent training programs:

Participants of the study trained both strength and endurance training in the same session (figure 5), three times a week, on non-consecutive days, with the same strength and endurance training periodization described in the study II. Training groups were differentiated by their intra-session concurrent strength and endurance training sequence. One group trained the strength training prior to endurance training (SE), and another trained endurance prior to strength training (ES). During the strength 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, the relative to 1 RM 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 and all the sets were performed until failure.

Fig. 5. Concurrent strength and endurance training.

4.3.7. Statistical Analysis:

Statistical comparisons in the control period (from week –4 to week 0) were performed by using Student's paired t-tests. The training-related effects were assessed using a two-way Analysis of Variance (ANOVA) with repeated measures (group x 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. Significance was accepted when $p<0.05$.

5. RESULTS AND DISCUSSION

5.1. STUDY I.

The main findings of the study 1 were the associations found between muscle echo intensity with the neuromuscular (figure 6) and cardiorespiratory (figure 7) performance in elderly (table 2 and 3). In addition, the force per unit of muscle mass was associated with cardiovascular performance, suggesting that this parameter is an optimal neuromuscular factor associated with endurance performance in this population (figure 8 and table 3). Moreover, our results showed that the isokinetic peak torques obtained at higher velocities (180 and 360$^{\circ\cdot s^{-1}}$) were more closely associated with endurance performance in elderly subjects (table 3). The present results suggest that the echo intensity measured using computer-aided grayscale analysis is a low-cost, easily accessible and safe method for evaluating muscle quality that may contribute to further studies of neuromuscular and cardiovascular function in the elderly.

Table 2: Correlation coefficients between echo intensity, muscle thickness and strength performance:

	Isometric PT (N·m)	PT 60$^{\circ \cdot s^{-1}}$ (N·m)	PT 180$^{\circ \cdot s^{-1}}$ (N·m)	PT 360$^{\circ \cdot s^{-1}}$ (N·m)
Echo intensity (A.u.)	-0.51**	-0.48**	-0.64***	-0.61***
VI MT (mm)	0.42*	0.53**	0.51**	0.52**
VM MT (mm)	0.42*	0.55***	0.62***	0.60***
QF MT (mm)	0.43*	0.57***	0.63***	0.61***

PT, peak torque; MT, muscle thickness; VI, vastus intermedius; VM, vastus medialis; QF, quadriceps femoris. Significant correlations: *(P <0.05); **(P <0.01); and, ***(P <0.001).

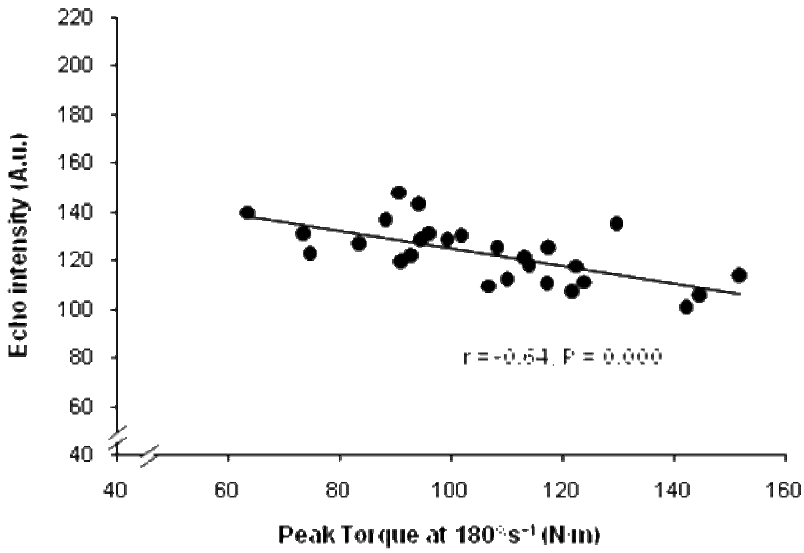

Fig. 6. Relationship between rectus femoris echo intensity (A.u.) and knee extensors peak torque at 180°.s-1 (N.m).

Table 3: Correlation coefficients between echo intensity, strength and cardiovascular performance:

	VO_{2peak}	$W_{máx}$	VT_1	VT_2	W_{VT1}	W_{VT2}
Echo intensity (A.u.)	0.08	-0.29	0.14	0.05	-0.46*	-0.50**
Torque per unit of muscle mass	0.60***	0.30	0.52**	0.60***	0.38*	0.40*
Isometric PT (N·m)	0.23	0.38*	0.25	0.32	0.40*	0.41*
PT $60^{o.s-1}$ (N·m)	0.14	0.40*	0.20	0.21	0.38*	0.52**
PT $180^{o.s-1}$ (N·m)	0.14	0.47**	0.10	0.18	0.41*	0.64***
PT $360^{o.s-1}$ (N·m)	0.12	0.46**	0.04	0.13	0.35	0.67***

Torque per unit of muscle mass ($Nm \cdot mm^{-0.67}$); PT, peak torque; VO_{2peak}, peak oxigen uptake ($ml \cdot kg \cdot min^{-1}$); $W_{máx}$, maximal workload (W); VT_1 and VT_2, ventilatory thresholds ($ml \cdot kg \cdot min^{-1}$); W_{VT1} and W_{VT2}, workloads at ventilatory thresholds (W). Significant correlations: *(P <0.05); **(P <0.01); and, ***(P <0.001).

The results regarding the association between echo intensity and cardiovascular performance suggest that the connective and adipose tissue accumulation reported by the grayscale analysis may also influence cardiorespiratory capacity. A possible explanation for these results may be the aging-related increase in the amount of intramuscular connective tissue that is associated with a decreased number of capillaries and results in greater isolation of each capillary from the adjacent muscle fiber, which disturbs the blood supply of the muscle fibers (Tyml and Costello 2001; Egginton and Gaffney 2010). Since the muscle capilarization is an important factor to the cardiorespiratory capacity, this deleterious process associated with lower muscle quality may also impair cardiorespiratory capacity. It should be highlighted that the workloads performed at the aerobic and anaerobic thresholds are markers of economy of movement (Izquierdo et al. 2001, 2003; Cadore et al. 2011a; 2012a), and these endurance parameters are associated with the capacity to perform daily activities in the elderly (Hartman et al. 2007).

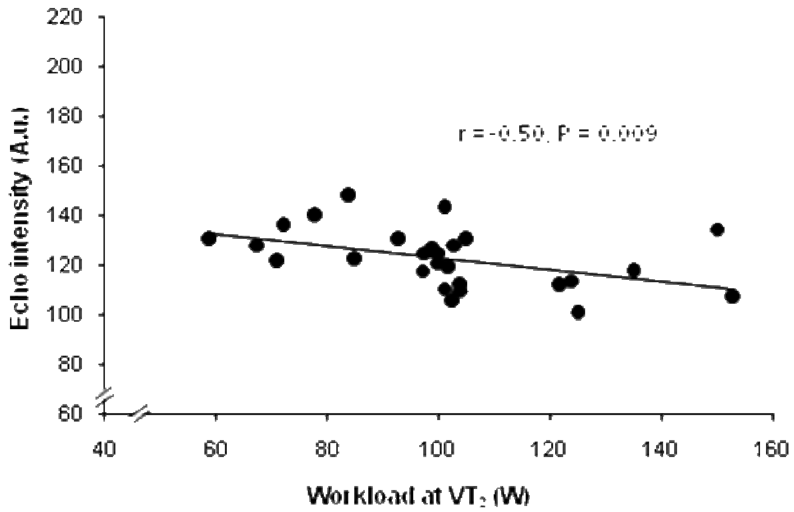

Fig. 7. Relationship between rectus femoris echo intensity (A.u.) and workload at the second ventilatory threshold (VT2) (watts).

Similar to the relationship observed between echo intensity and cardiorespiratory fitness, significant negative relationships were observed between echo intensity and muscle strength. In agreement with the present results, Fukumoto et al. (2011) have shown a negative correlation between quadriceps echo intensity and isometric muscle strength (r = -0.40, P<0.01) using grayscale analysis. The present results expand the data regarding the association between muscle echo intensity and strength performance in the elderly because a relationship was also observed with explosive performance (r=-0.64 to -0.67, P<0.001). Thus, the negative association between echo intensity and strength reinforces the idea that not only muscle size but also muscle quality, i.e., the amount of connective and adipose tissue in the muscle, is associated with high-speed isokinetic performance.

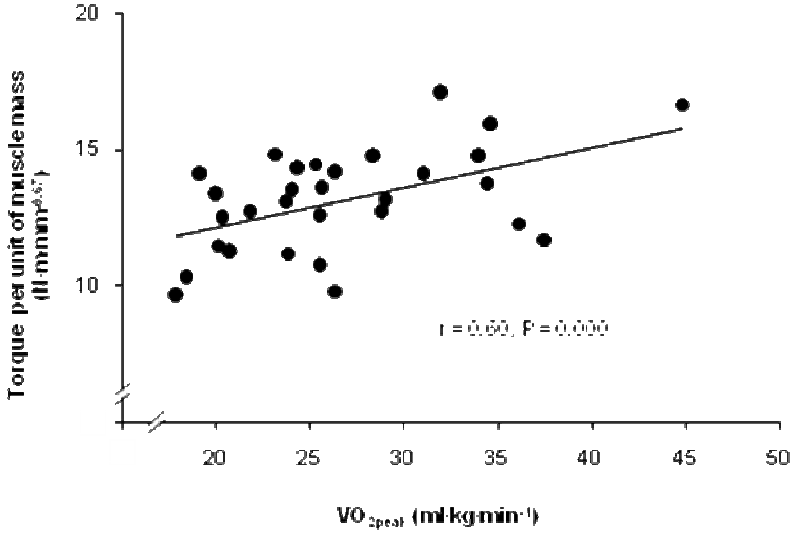

Fig. 8. Relationship between torque per unit of muscle mass (Nm.mm-0.67) and peak oxygen uptake (ml.kg.min-1).

Although the force per unit of muscle mass has previously been associated with functional capacity (Misic et al. 2007; Korhonen et al. 2009; Granacher et al. 2010), a unique finding of the present study was the association between this neuromuscular parameter and cardiovascular function in the elderly. Some studies have shown positive correlations between strength variables and cardiorespiratory fitness (Izquierdo et al. 2001, 2003; Brentano et al. 2008; Cadore et al. 2011). In a study by Izquierdo et al. (2001), the maximal and submaximal aerobic capacity of elderly subjects were positively related to maximal strength and power values of the lower limbs ($r=0.44$ to 0.56, $P<0.05$ to 0.01). In another study, Izquierdo et al. (2003) also showed that strength training combining slow and explosive contractions significantly improved the submaximal and maximal endurance capacity in elderly subjects. Interestingly, in the present study, the isometric peak torque and the muscle thickness measures QF, VI, VM, VL and RF were not associated with the aerobic variables VO_{2peak}, VT_1 and VT_2. Thus, because the force per unit of muscle mass provides an estimation of the contribution of neural factors associated with force production (Tracy et al. 1999; Frontera et al. 2000; Reeves et al. 2004; Narici et al. 2005; Cadore et al. 2011a), our results suggest that neural factors, such as maximal recruitment capacity and firing rate (Häkkinen et al. 2000, 2001), have more influence on cardiorespiratory fitness in the elderly than morphological factors such as muscle thickness.

5.2. STUDY II.

The main finding of the present study was the presence of an interference effect on the gains in lower body-muscle strength observed in the concurrent group, which was not seen in the upper-body strength measurements in the same group (figure 9). In addition, this interference effect occurred together with the different variations in EMG measurements obtained for the groups (figure 10 and 11). Moreover, measurement of hormonal concentrations did not suggest any evidence of increased catabolic state (table 4).

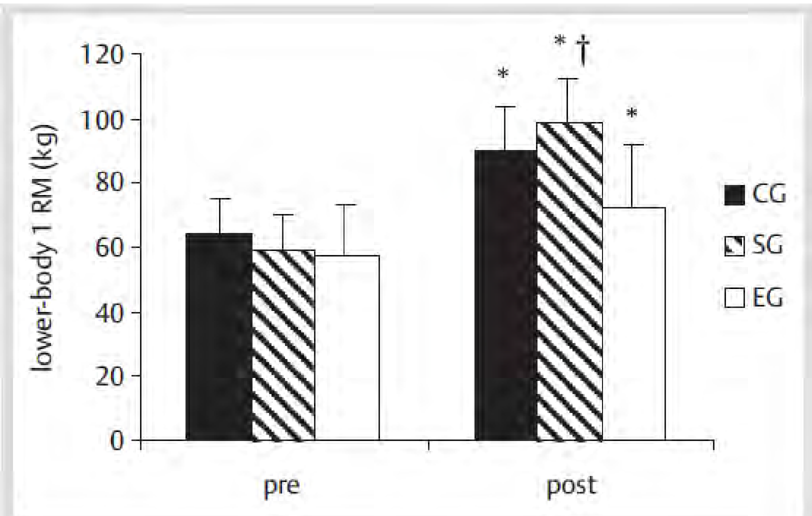

*Fig. 9. Lower-body 1 RM values (kg) before and after 12 weeks of training. CG, concurrent group; SG, strength group; EG, endurance group. *Significant difference from pre training values (P <0.01). † Significant time vs. group interaction.*

A possible cause of the interference effect observed in the present investigation may be the type of endurance exercise performed (cycle ergometer) (Leveritt and Abernethy 1999; De Souza et al. 2007) and the timing of its execution, immediately before the strength exercises, since it has been demonstrated that a cycle ergometer exercise session can induce an acute decrease in lower-body force development due to the local fatigue (Sale et al. 1990; Leveritt and Abernethy 1999). Possibly, there was concurrent recruitment of motor units used in both types of training, resulting in lower gains in dynamic strength in the CG. This would seem to be supported by the fact that the EG experienced a gain in dynamic strength (24.7%). Some authors have reported improvements in lower-body strength in response to endurance training performed on a cycle ergometer when performed in combination with strength training (Izquierdo et al. 2004, 2005), as well as small enhances when it is performed alone (Van Zant and Bouillon 2007). The same effects are not observed when aerobic training consists of running or jogging (Kraemer et al. 1995; Millet et al. 2002). Thus, this would seem to suggest that the recruitment of high threshold motor units, responsible for higher force production, in the endurance training, especially at intensities near VT_2, resulted in increased muscle strength in the EG, with local fatigue in these motor units, which led to decreased strength performance in the CG.

Although it has been suggested that the neural component of force production may be related to the occurrence of an interference effect (Nader 2006), few studies have compared the adaptations of the EMG signal arising from strength and concurrent training (McCarthy et al. 2002; Häkkinen et al. 2003) and no study has reported differences in the adaptations in maximal RMS values after training (strength vs. concurrent). In the present study, significant increases in the amplitude of the EMG signal from the vastus lateralis and rectus femoris were observed in the SG after 12 weeks of training, while no modifications were observed in the CG and EG.

Our results are in accordance with the studies from Häkkinen et al. (1998, 2000), which found a significant increase in the amplitude of the EMG signal after strength training. Furthermore, in the present study, the subjects in the SG experienced a significant decrease in muscle activation for the same absolute load (percent of MVC before training) on the vastus lateralis (40, 60 and 80%) and rectus femoris (60 and 80%), suggesting that for the same load, subjects needed fewer motor units after training, which is more economical at the neuromuscular level. The absence of similar adaptations in the CG suggests that the interference effect observed in the present study may be related with neural adaptations to strength training, with the endurance training session performed immediately before strength exercises negatively influencing such adaptations. In fact, a study by Lepers et al. (2001), demonstrated that 30 minutes at 80% of maximal aerobic power resulted in decreases in isometric and concentric force, as well as decreases in the maximal EMG:M wave ratio, which suggests a central fatigue mechanism, indicating a reduction in the number of motor units recruited and/or lower firing rate during maximal effort. Thus, the fatigue imposed by endurance training may have prevented the neuromuscular system from developing the maximal capacity of voluntary recruitment of motor units and increases in the firing rate in the CG, resulting in lower strength development when compared to the SG.

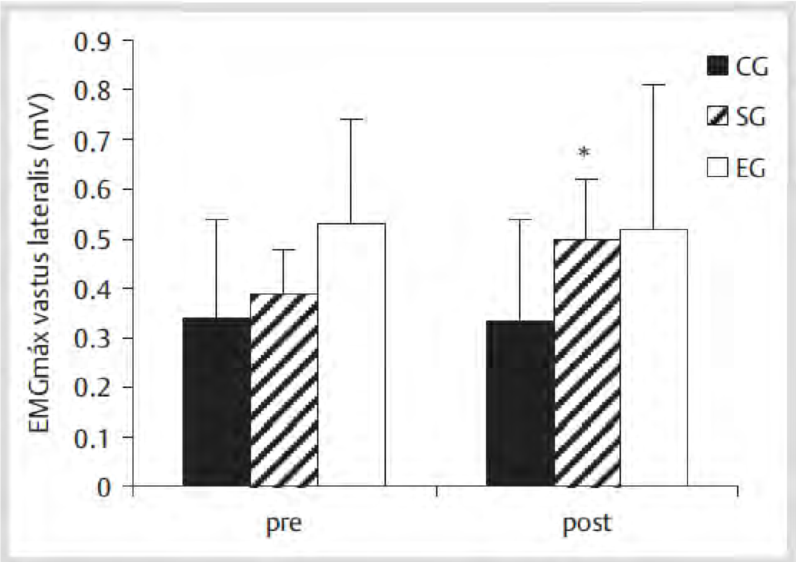

*Fig. 10: Maximal EMG activity of vastus lateralis (RMS values) before and after 12 weeks of training. CG, concurrent group; SG, strength group; EG, endurance group. *Significant difference from pre training values (P <0.05).*

It has been suggested that modifications to the balance between anabolic (i.e. testosterone) and catabolic hormones (i.e. cortisol) may play a role in the interference effect seen in concurrent training, when such an effect is accompanied by increases in basal cortisol (Kraemer et al. 1995; Bell et al. 1997, 2000). However, there were no significant modifications to basal hormones in the CG (table 4), indicating these subjects experienced no chronic catabolic state, and, consequently, the absence of any relationship between hormonal status and the strength gains found in the present study.

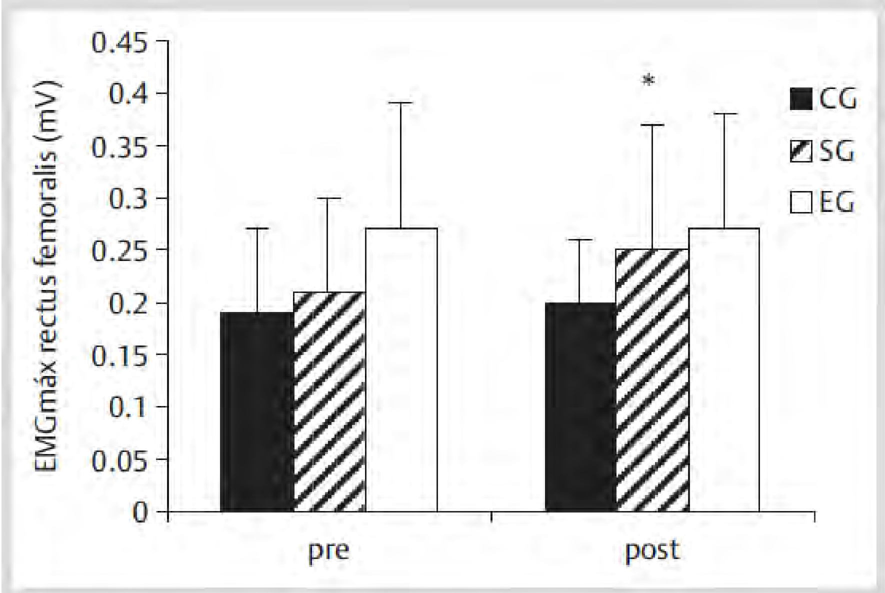

*Fig. 11: Maximal EMG activity of rectus femoralis (RMS values) before and after 12 weeks of training. CG, concurrent group; SG, strength group; EG, endurance group. *Significant difference from pre training values (P <0.05).*

Table 4: Resting hormonal concentrations before and after training. Mean ± SD.

	Concurrent training		Strength training		Endurance training	
	CG, n = 8		SG, n = 8		EG, n = 7	
	Pre	Post	Pre	Post	Pre	Post
TT (ng/mL)	3.35 ± 0.72	3.36 ± 1.5	3.6 ± 0.46	3.3 ± 0.53	3.7 ± 1.5	3.35 ± 1.6
FT (pg/mL)	9.84 ± 1.8	7.26 ± 3.16	10.1 ± 1.7	9.1 ± 1.35	9.7 ± 2.8	7.9 ± 3.0*
COR (mg/dL)	26.44 ± 2.6	27.2 ± 1.97	24.24 ± 2.4	24.7 ± 3.8	27.8 ± 3.0	24.5 ± 2.0
TT/COR (A.U.)	0.13 ± 0.03	0.11 ± 0.06	0.15 ± 0.03	0.14 ± 0.04	0.14 ± 0.06	0.14 ± 0.07
FT/COR (A.U.)	0.38 ± 0.09	0.27 ± 0.11	0.42 ± 0.09	0.4 ± 0.01	0.35 ± 0.12	0.33 ± 0.15

TT, total testosterone; FT, free testosterone; COR, cortisol; A.U., arbitrary units. *Significant difference from pre training values P < 0.05.

5.3. STUDY III.

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 (figure 12 and table 5). Secondly, the greater strength gains in the SE sequence may be related with neural adaptations because only SE improved the rectus femoris neuromuscular economy (figure 15 and table 6). Furthermore, no differences were observed in the morphological adaptations between groups, which suggested that the intra-session exercise sequence influenced strength performance but not the magnitude of hypertrophy (figure 14 and table 6). These results suggest that performing strength training prior to endurance training optimizes strength gains in the elderly.

Table 5: 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 (N·m)	229.8 ± 27.8	247.3 ± 26.9***	238.6 ± 38.6	250.2 ± 34.3***
KF Isometric PT (N·m)	116.6 ± 15.0	125.0 ± 15.6***	115.1 ± 25.7	131.9 ± 40.0***
KE RFD at 100ms ($N·m·s^{-1}$)	490.6 ± 354.0	620.0 ± 366.8*	428.7 ± 320.0	652.5 ± 459.5*
KE Maximal RFD ($N·m·s^{-1}$)	773.7 ± 354.4	879.7 ± 434.9**	757.7 ± 324.5	1007.2 ± 515.9**

1RM, one maximum repetition; KE, knee extensors; KF, knee flexors; PT, peak torque; RFD, rate of force development. Significant difference from pre training values *(P <0.05), **(P <0.01), and ***(P <0.001). †Significant time vs. group interaction (P<0.05).

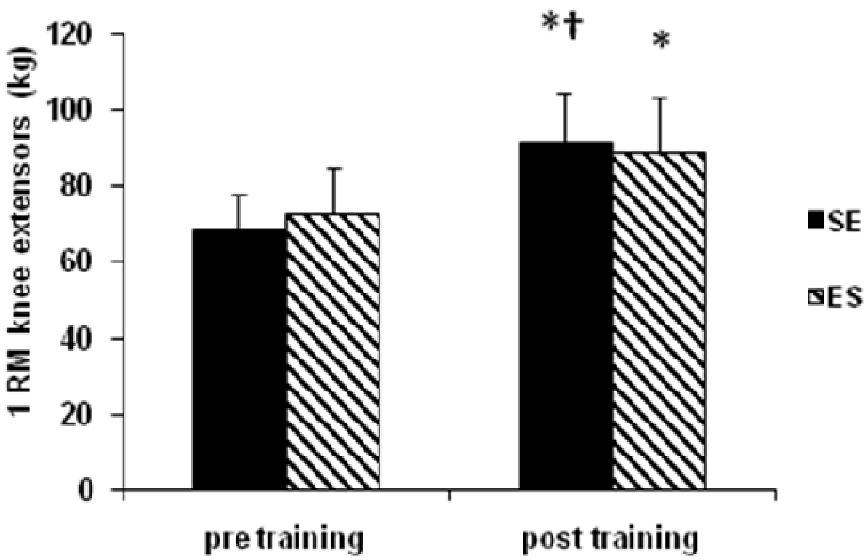

*Fig. 12: Mean ± SD of lower-body one maximum repetition (1RM) values (kg), pre and post 12 weeks of concurrent training. SE, strength prior to endurance training; ES, endurance prior to strength training. *Significant difference from pre training values (P<0.001). †Significant time vs. group interaction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

Few studies have investigated the effects of intra-session exercise sequence on the neuromuscular adaptations to concurrent training (Gravelle and Blessing 2000; Chtara et al. 2008). 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 intra-session 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 (figure 13). 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.

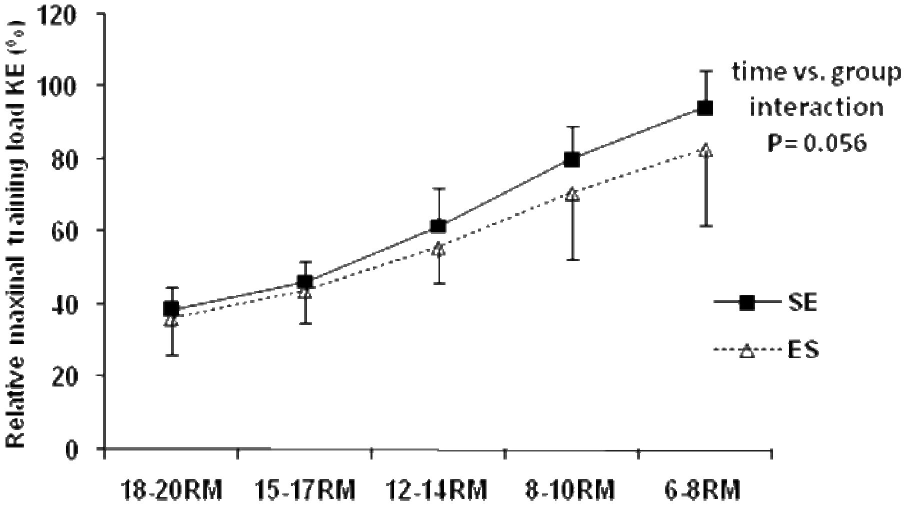

Fig. 13: Mean ± SD of maximal training load (%) relative to pre training one maximum repetition maximum (1RM) values during different mesocycles. Tendency toward significant time vs. group interaction (P=0.056).

Table 6: 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)	
	Pre-training	Post-training	Pre-training	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

VL, vastus lateralis; VM, vastus medialis; VI, vastus intermedius; RF, rectus femoris; BF, bíceps femoris. Maximal neuromuscular activity (NA) determined by maximal electromiographic signal amplitude. Significant difference from pre training values: *(P <0.05), **(P <0.01), and ***(P <0.001). †Significant time vs. group interaction (P<0.05).

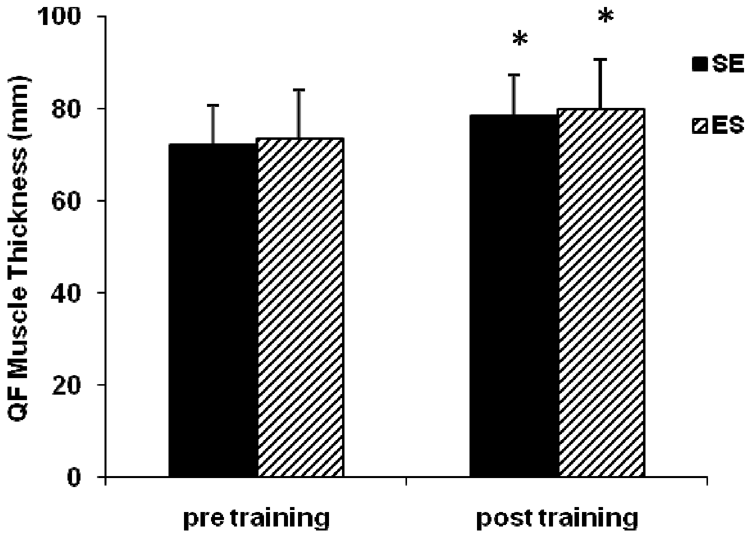

*Fig. 14: Mean ± SD of the quadriceps femoris muscle thickness (mm) pre and post 12 weeks of concurrent training. SE, strength prior to endurance training; ES, endurance prior to strength training. *Significant difference from pre training values (P<0.001).*

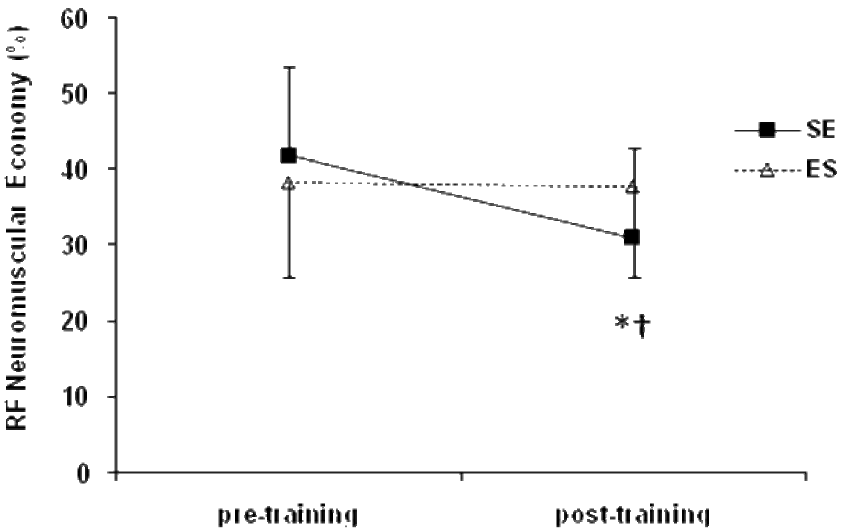

*Fig. 15: Neuromuscular economy (normalized EMG at 50% of pre-training MVC) of rectus femoris. SE, strength prior to endurance training; ES, endurance prior to strength training. *Significant difference from pre training values (P <0.01). †Significant time vs. group interaction (P<0.01).*

6. CONCLUSIONS

1. The echo intensity measured using computer-aided grayscale analysis is a low cost, easily accessible and safe method for evaluating muscle quality that may contribute to future research on neuromuscular and cardiovascular function in the elderly (study I).

2. The force per unit of muscle mass was more strongly associated with cardiovascular performance than strength or muscle thickness, which suggests that neural factors associated with strength development are related to cardiorespiratory performance in older subjects (study II).

3. The differences in strength enhancement, resulting from strength and concurrent training suggests that endurance training performed simultaneously with strength training can negatively interfere in the strength gains in elderly men, when the same muscle group is activated in both types of training (study II).

4. According to the mechanisms investigated, interference to neural adaptations seems to explain, at least in part, the interference effect seen in the concurrent strength and endurance training program (study II).

5. The hormonal concentrations measured failed to suggest any increased catabolic state, reinforcing the hypothesis of a local neuromuscular and not a systemic interference effect, at least with the volume used in the present study (study II).

6. The data of the study III expand the knowledge of our previous findings related to the interference effect observed during concurrent training in an elderly population. The intra-session 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%) (study III).

7. 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 (study III).

8. 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 (study III).

9. The intra-session concurrent exercise sequence had no influence on muscle thickness gains in the elderly (study III).

10. From a practical point of view, to optimize the strength gains in the elderly, the concurrent training prescription should include an intra-session exercise order of strength training prior to endurance training (study III).

7. LISTA DE ARTÍCULOS CIENTÍFICOS:

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Echo intensity is associated with skeletal muscle power and cardiovascular performance in elderly men

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ABSTRACT

The purpose of the present study was to investigate the relationship between echo intensity, neuromuscular and cardiorespiratory performances in the elderly. Thirty-one healthy elderly men (65.5 ± 5.0) participated in this study. Echo intensity of rectus femoris and quadriceps femoris muscle thicknesses was determined by ultrasound images. Lower-body isometric and isokinetic peak torques (60, 180 and $360^{\circ.s-1}$), as well as rate of force development were evaluated as strength parameters. In addition, torque per unit of muscle mass was evaluated by the quotient between isometric peak torque of the knee extensors and the quadriceps femoris muscle thickness. The peak oxygen uptake (VO_{2peak}), maximum aerobic workload ($W_{máx}$), absolute (VT_1 and VT_2) ventilatory thresholds, as well as workloads at VT_1 and VT_2 (W_{VT1} and W_{VT2}) were evaluated during a maximal incremental test on a cycle ergometer. There were significant negative correlations between the individual values of echo intensity with the corresponding individual values of isometric and isokinetic peak torques (60, 180 and $360^{\circ.s-1}$) ($r = -0.48$ to $r = -0.64$; $P < 0.05$), as well as with W_{VT1} ($r = -0.46$) and W_{VT2} ($r = -0.50$) ($P < 0.05$). In addition, significant positive correlations were observed between torque per unit of muscle mass and cardiovascular parameters ($r = 0.52$ to $r = 0.60$; $P < 0.001$). The present results suggest that the echo intensity analysis using computer-aided gray-scale analysis is a low cost, easily accessible, and a safe method to evaluate the muscle quality, and may contribute to the research of neuromuscular and cardiovascular performances in the elderly.

1. Introduction

The aging process leads to changes in muscle quality and quantity, e.g., sarcopenia (Visvanathan and Chapman, 2010). These changes include increases in the amount of adipose and connective tissues in the muscle (Seene et al., 2012), reductions in the number and size of muscle fibers (Larsson et al., 1978; Lexell et al., 1988; Lynch et al., 1999), a reduction in the maximal voluntary agonist activation and an increase in the antagonist coactivation (Izquierdo et al., 1999; Klein et al., 2001; Suetta et al., 2004). These physiological factors result in impairments in muscle strength, power and functional capacity (Izquierdo et al., 1999, 2001, 2003). In addition, a decline in cardiorespiratory capacity can be observed in elderly persons; this decline is primarily associated with a decrease in maximal heart output, changes in the arteriovenous oxygen difference (Izquierdo et al., 2001) and declines in neuromuscular function (Izquierdo et al., 2001, 2003; Cadore et al., 2011a).

The accumulation of connective and adipose tissues in the muscles, i.e., changes in muscle quality, can be assessed using computed tomography imaging which shows a reduced attenuation coefficient due to augmented fat infiltration (Goodpaster et al., 2000). Muscle quality can also be assessed using the non-invasive, easily accessible and safe method of ultrasound imaging, whereby enhanced echo intensity represents changes caused by increased intramuscular connective and adipose tissues (Pillen et al., 2009; Fukumoto et al., 2012). Evidence suggests that ultrasonography can detect structural muscle changes caused by impaired neuromuscular function. Indeed, it has been shown that elderly populations present greater gray scale values when compared with young populations (Arts et al., 2010), and these changes have been associated with enhanced intramuscular adipose tissue (Kent-Braun et al., 2000; Arts et al., 2010; Fukumoto et al., 2012).

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Although impairments in the neuromuscular and cardiovascular functions may occur in parallel with increases in the gray scale values in the elderly, studies investigating the relationship between echo intensity and physical fitness parameters in this population are scarce. Sipilä and Suominen (1991, 1994) showed that the echo intensity of the quadriceps femoris was associated with knee extensor strength in an elderly population. Unfortunately, their results were based on echo intensity values generated by visual scoring, which did not control operator-induced error. In another study using computer-aided grayscale analysis, Fukumoto et al. (2012) observed negative correlations between grayscale values and isometric strength in elderly men, suggesting that the subjects with greater adipose and connective tissues, i.e., those with greater echo intensity values, had lower strength performance. Nevertheless, there are limited data regarding the association between echo intensity and strength performance, and no studies have investigated the relationship between echo intensity and other parameters related to physical fitness in the elderly, such as neuromuscular and endurance performances. In addition to neuromuscular function, cardiorespiratory fitness has been associated with functional capacity in elderly populations. In this context, it would be interesting to determine the association between the muscle echo intensity and cardiovascular fitness.

Given the relevance of the neuromuscular and cardiovascular performances to the functional capacity in the elderly, to investigate the relationship between echo intensity and these functional parameters may help to justify the use of the non-invasive and safe method of ultrasound imaging to evaluate the muscle quality in the elderly. Thus, the purpose of the present study was to investigate the relationships among echo intensity, neuromuscular and cardiorespiratory performances. Our hypothesis was that the echo intensity would be associated with several parameters of neuromuscular and cardiorespiratory performances.

2. Methods

2.1. Experimental design

In order to investigate a possible relationship between echo intensity with strength development, as well as with cardiorespiratory parameters in older men, physical evaluations were carried out using ergospirometry, dynamometry and ultrasonography. For this purpose, the participants in the present study attended the Laboratory on several different occasions, since the evaluations of echo intensity, isometric and isokinetic torques and aerobic capacity were made on separate days. By measuring and correlating all these variables, we attempted to get an insight regarding the relationship among them in the elderly, since physiological concepts might explain possible correlations. Prior to data collection, the participants took part in a familiarization session for each test. The ambient conditions were kept constant during all tests (temperature: 22–24 °C).

2.2. Subjects

Thirty-one healthy elderly men (mean ± SD: 64.7 ± 4.1 years), who were not engaged in any regular and systematic training programs in the previous 12 months, volunteered for the study after completing an ethical consent form. 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. The study was conducted according to the Declaration of Helsinki and was approved by the 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 metabolisms. Medical evaluations were performed using clinical anamnesis and effort electrocardiograph test (ECG), 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).

2.3. Isometric and isokinetic peak torques

Maximal isometric and isokinetic peak torques were obtained using an isokinetic dynamometer (Biodex, New York, USA). Subjects were positioned and 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 at angular velocity of $90°.s^{-1}$, performing a submaximal effort. The dynamometer was connected to an A/D converter (Dataq Instruments Inc. Akron, Ohio—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 dynamometer at an angle of 120° in the knee extension (180° represented the full extension), the subjects were instructed to exert maximum strength possible and as fast as possible when extending the right knee. The subjects had three attempts at obtaining the maximum voluntary contraction (MVC) of the knee extensors, each lasting 5 s, and an additional contraction was obtained if a torque variation higher than 10% was observed between consecutive contractions (Cadore et al., 2012b). In the last part of the protocol, subjects performed five dynamic repetitions of concentric knee extensions/flexions at 60, 180 and $360°.s^{-1}$, in order to obtain the isokinetic peak torque in each angular velocity. The rest 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 and analyzed using Biodex software. Signal processing included filtering with a Butterworth low-pass filter of 4th order at a cut-off frequency of 9 Hz. Maximal peak torque was defined as the highest value of the torque (N.m) recorded during the unilateral knee extension. The test–retest reliability coefficients (ICC) were over 0.94 for all the variables in the isometric and isokinetic protocols.

2.4. Echo intensity and muscle thickness

The echo intensity (EI) and muscle thickness (MT) were 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. Subjects were evaluated in supine position, after 15 min resting and after 72 h without any vigorous physical activity. The EI was determined by gray-scale analysis using the standard histogram function in

Table 1
Values are mean ± SD of physical characteristics, strength, echo intensity, cardiorespiratory and muscle thickness.

Variables	Mean ± SD
Age (years)	65.5 ± 5.0
Height (cm)	172.2 ± 5.8
Body mass (kg)	81.8 ± 12.0
Fat mass (%)	27.4 ± 3.0
Echo intensity (A.u.)	126.5 ± 22.9

Image-J (National Institute of Health, USA, version 1.37). A region of interest was selected in rectus femoris as much of the muscle was possible without any bone or surrounding fascia. For echo intensity analysis the depth setting was fixed at 5 cm. When this setting was insufficient to display the entire muscle, only the superficial part of the muscle was used for EI analyses. The EI in the region of interest was expressed in values between 0 and 256 (0: black; 256: white).

The MT images were determined in the lower-body muscles vastus lateralis (VL), vastus medialis (VM), vastus intermedius (VM), 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), 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 was measured as 60% of 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 the quadríceps femoris (QF) muscle mass. The images were digitalized and after they were analyzed in software Image-J (National Institute 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 same investigator made all measurements of EI and MT. Force per unit of active muscle mass was calculated from the quotient between the maximal isometric torque (PT_{iso}) of the right leg and the sum of the muscle thickness (MT) of the muscles of quadríceps femoris (QF) adjusted by allometric scaling (i.e. $F \alpha m^{2/3}$) (Jaric et al., 2002). The QF MT was composed by the VL, RF, VM, and VI MT. Thus, the force per unit of muscle mass was calculated following the formula: $MQ = PT_{iso}$ (N.m) of the right leg/MT QF_{sum} of $(VL + VM + VI + RF)\ (mm)^{0.67}$. The MT test–retest reliability coefficients (ICC) were 0.94 for VL, 0.91 for VM, 0.92 for VI and 0.95 for RF.

2.5. Cardiovascular performance

Subjects performed an incremental test on a cycle ergometer (Cybex, USA) in order to determine the peak oxygen uptake (VO_{2peak}), the first (VT_1) and second (VT_2) ventilatory thresholds, maximal workload ($W_{máx}$) and the workloads at VT_1 (W_{VT1}) and VT_2 (W_{VT2}). 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., 2003). 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) breath by breath. The VT_1 and VT_2 were determined using the ventilation curve corresponding to the points of exponential increase in the ventilation in relation to the load (Cadore et al., 2011a, 2011b). In addition, to confirm the data, VT_2 was determined using the CO_2 ventilatory equivalent (VE/VCO_2) (Wasserman, 1986). The maximum VO_2 value (ml.kg^{-1}.min^{-1}) obtained close to exhaustion was considered the VO_{2peak}. The W_{max} (watts) was calculated using the formula: $W_{max} = W_{com} + (t/180).\Delta W$, in which W_{com} is the load at the last stage completed, t is the time at the last incomplete stage and ΔW is the load increment in the last stage (25 W) (Izquierdo et al., 2001, 2003). The maximum test was considered valid if at least 2 of the 3 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. 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, CHI). The test–retest reliability coefficients (ICC) were 0.88 to VO_{2peak} and $W_{máx}$, as well as 0.85 to VT_1 and VT_2.

2.6. Statistical analysis

Normal distribution parameters were checked with Shapiro–Wilk test. Descriptive results are reported as mean ± SD. The Pearson product moment correlation test was used to investigate possible associations between the parametric parameters analyzed. In the non-parametric data, Spearman correlation test was used. Significance was accepted as $P<0.05$ and the analysis were made in SSPS version 18.0.

3. Results

Tables 1 and 2 show the physical characteristics, echo intensity, muscle isometric and isokinetic strengths, as well as cardiovascular values of the participants.

3.1. Relationships between echo intensity, strength and cardiovascular performance

Significant negative correlations were observed between the individual values of rectus femoris echo intensity and the corresponding individual values of isometric peak torque and isokinetic peak torque at $60°.s^{-1}$, $180°.s^{-1}$ and $360°.s^{-1}$ (range from $r = -0.48$ to $r = -0.64$; $P<0.05$) (Table 3 and Fig. 1). In addition, significant negative correlations were observed between rectus femoris echo intensity and the workload at VT_1 (W_{VT1}) ($r = -0.46$, $P = 0.013$), and the workload at VT_2 (W_{VT2}) ($r = -0.50$, $P = 0.009$) (Table 4 and Fig. 2).

3.2. Relationships between muscle mass, strength and cardiovascular performance

Significant correlations were observed between individual values of muscle thickness and the corresponding values of isometric and isokinetic peak torques (range from $r = 0.44$ to $r = 0.62$, $P<0.001$ to $P<0.05$) (Table 3). No significant correlations were found between any muscle thickness measure (i.e., VL, VM, VI, RF and QF) with any cardiorespiratory parameter (Table 3).

3.3. Relationships between strength and cardiovascular performance

Significant correlations were observed between the individual values of the force per unit of muscle mass and cardiovascular values (range from $r = 0.52$ to $r = 0.60$; $P<0.001$ to P) (Table 3 and Fig. 3). In addition, significant correlations were observed between the

Table 2
Values are mean ± SD of strength, cardiorespiratory and muscle thickness.

Variables	Mean ± SD
Isometric PT (N.m)	231.1 ± 34.1
Isokinetic PT $60°.s^{-1}$ (N.m)	169.5 ± 31.7
Isokinetic PT $180°.s^{-1}$ (N.m)	107.6 ± 21.3
Isokinetic PT $360°.s^{-1}$ (N.m)	77.0 ± 13.1
Torque per unit of muscle mass (Nm.mm$^{-0.67}$)	13.1 ± 1.8
VL muscle thickness (mm)	20.6 ± 2.7
VM muscle thickness (mm)	19.3 ± 3.8
VI muscle thickness (mm)	14.2 ± 3.5
RF muscle thickness (mm)	18.4 ± 3.6
QF muscle thickness (mm)	72.6 ± 9.0
VO_{2peak} (ml.kg.min^{-1})	26.7 ± 6.3
$W_{máx}$ (W)	122.6 ± 23.7
VT_1 (ml.kg.min^{-1})	14.2 ± 2.7
VT_2 (ml.kg.min^{-1})	20.2 ± 4.6
W_{VT1} (W)	61.2 ± 13.0
W_{VT2} (W)	101.7 ± 19.6

PT, peak torque; VL, vastus lateralis; VM, vastus medialis; VI, vastus intermedius; RF, rectus femoris; QF, quadriceps femoris; VO_{2peak}, Peak oxigen uptake; $W_{máx}$, maximal workload; VT_1 and VT_2, ventilatory thresholds; W_{VT1} and W_{VT2}, workloads at VT_1 and VT_2.

Table 3
Correlation coefficients between echo intensity, muscle thickness and strength performance.

	Isometric PT (N.m)	PT 60°.s−1 (N.m)	PT 180°.s−1 (N.m)	PT 360°.s−1 (N.m)
Echo intensity (A.u.)	−0.51**	−0.48**	−0.64***	−0.67***
VI MT (mm)	0.42*	0.53**	0.51**	0.52**
VM MT (mm)	0.42*	0.55***	0.62***	0.60***
QF MT (mm)	0.43*	0.57***	0.63***	0.61***

PT, peak torque; MT, muscle thickness; VI, vastus intermedius; VM, vastus medialis; QF, quadriceps femoris. Significant correlations: *(P<0.05); **(P<0.01); and, ***(P<0.001).

Table 4
Correlation coefficients between echo intensity, strength and cardiovascular performance.

	VO_{2peak}	$W_{máx}$	VT_1	VT_2	W_{VT1}	W_{VT2}
Echo intensity (A.u.)	0.08	−0.29	0.14	0.05	−0.46*	−0.50**
Torque per unit of muscle mass	0.60***	0.30	0.52**	0.60***	0.38*	0.40*
Isometric PT (N.m)	0.23	0.38*	0.25	0.32	0.40*	0.41*
PT 60°.s−1 (N.m)	0.14	0.40*	0.20	0.21	0.38*	0.52**
PT 180°.s−1 (N.m)	0.14	0.47**	0.10	0.18	0.41*	0.64***
PT 360°.s−1 (N.m)	0.12	0.46**	0.04	0.13	0.35	0.67***

Torque per unit of muscle mass ($Nm.mm^{-0.67}$); PT, peak torque; VO_{2peak}, peak oxigen uptake ($ml.kg.min^{-1}$); $W_{máx}$, maximal workload (W); VT_1 and VT_2, ventilatory thresholds ($ml.kg.min^{-1}$); W_{VT1} and W_{VT2}, workloads at ventilatory thresholds (W). Significant correlations: *(P<0.05); **(P<0.01); and, ***(P<0.001).

individual values of cardiovascular performance and the corresponding values of isometric and isokinetic torques (range from r = 0.38 to r = 0.67; P<0.001–0.05) (Table 4).

4. Discussion

A unique finding of the present study was the associations found between muscle echo intensity with the neuromuscular and cardiorespiratory performances in the elderly. In addition, the force per unit of muscle mass was associated with cardiovascular performance, suggesting that this parameter is an optimal neuromuscular factor associated with endurance performance in this population. Moreover, our results showed that the isokinetic peak torques obtained at higher velocities (180 and 360°.s−1) were more closely associated with endurance performance in elderly subjects. The present results suggest that the echo intensity measured using computer-aided grayscale analysis is a low-cost, easily accessible and a safe method for evaluating muscle quality that may contribute to further studies of neuromuscular and cardiovascular functions in the elderly.

In addition to the limited data regarding the association between echo intensity and strength performance, to the best of the authors' knowledge, no studies have investigated the relationship between echo intensity and cardiorespiratory fitness in elderly men. A unique finding of the present study was the negative associations found between rectus femoris echo intensity and the workloads at the ventilatory thresholds. These results suggest that the connective and adipose tissue accumulation reported by the grayscale analysis may also influence cardiorespiratory capacity. A possible explanation for these results may be the aging-related increase in the amount of intramuscular connective tissue that is associated with a decreased number of capillaries and results in greater isolation of each capillary from the adjacent muscle fiber, which disturbs the blood supply of the muscle fibers (Tyml and Mathieu-Costello, 2001; Egginton and Gaffney, 2010). Since the muscle capillarization is an important factor to the cardiorespiratory capacity, this deleterious process associated with lower muscle quality may also impair cardiorespiratory capacity. It should be highlighted that the workloads performed at the aerobic and anaerobic thresholds are markers of economy of movement (Izquierdo et al., 2001, 2003; Cadore et al., 2011a, 2012a), and these endurance parameters are associated with the capacity to perform daily activities in the elderly (Hartman et al., 2007).

Similar to the relationship observed between echo intensity and cardiorespiratory fitness, significant negative relationships were observed between echo intensity and muscle strength. In agreement with the present results, Fukumoto et al. (2012) have shown a negative correlation between quadriceps echo intensity and isometric muscle strength (r = −0.40, P<0.01) using grayscale analysis. However, despite their interesting result, their study only evaluated elderly women, and only one strength variable was measured. The present results expand the data regarding the association between muscle echo intensity and strength performance in the elderly because a relationship was also observed with explosive performance (r = −0.64 to −0.67, P<0.001). Thus, the negative association between echo intensity and strength reinforces the idea that not only muscle size but also muscle quality, i.e., the amount of connective and adipose tissues in the muscle, is associated with high-speed isokinetic performance.

In the present study, positive associations were observed between the force per unit of muscle mass and VO_{2peak}, VT_1 and VT_2. Although the force per unit of muscle mass has previously been associated with functional capacity (Misic and Evans, 2007; Korhonen et al., 2009; Granacher et al., 2010), a unique finding of the present study was the association between this neuromuscular parameter and cardiovascular function in the elderly. Some studies have shown positive correlations between strength variables and cardiorespiratory fitness (Izquierdo et al., 2001, 2003; Brentano et al., 2008; Cadore et al., 2011a). Interestingly, in the present study, the isometric peak torque and the muscle thickness measures QF, VI, VM, VL and RF were not associated with the aerobic variables VO_{2peak}, VT_1 and VT_2. Thus, because the force per unit of muscle mass provides an estimation of

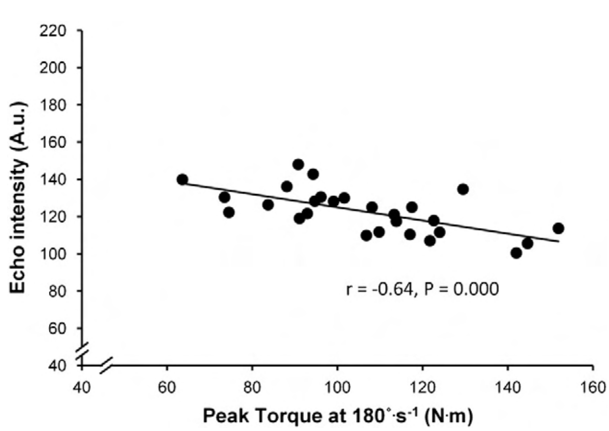

Fig. 1. Relationship between rectus femoris echo intensity (A.u.) and knee extensors peak torque at 180°.s−1 (N.m).

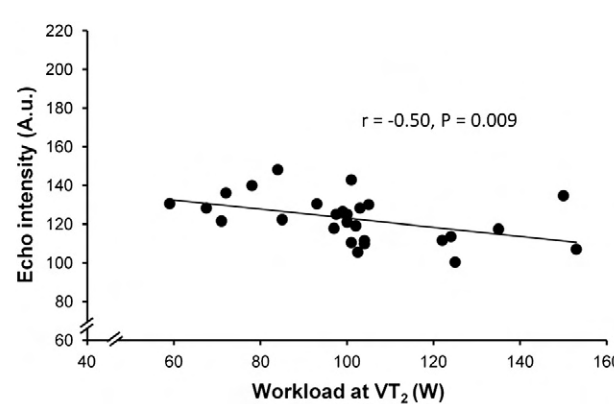

Fig. 2. Relationship between rectus femoris echo intensity (A.u.) and workload at the second ventilatory threshold (VT_2) (watts).

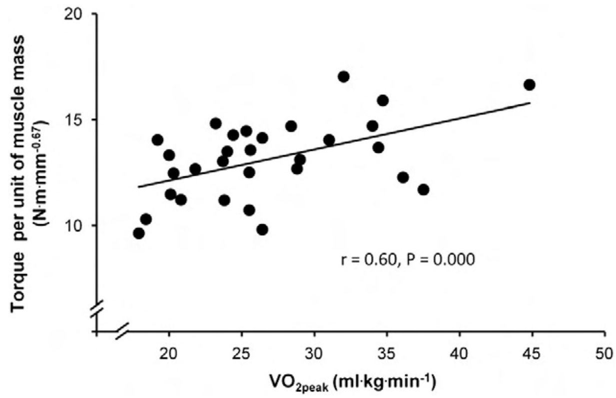

Fig. 3. Relationship between torque per unit of muscle mass (Nm.mm$^{-0.67}$) and peak oxygen uptake (ml.kg.min^{-1}).

the contribution of neural factors associated with force production (Tracy et al., 1999; Frontera et al., 2000; Reeves et al., 2004; Narici et al., 2005; Cadore et al., 2011a), our results suggest that neural factors, such as maximal recruitment capacity and firing rate (Häkkinen et al., 2000, 2001), have more influence on cardiorespiratory fitness in the elderly than morphological factors such as muscle thickness. In fact, aerobic capacity has previously been associated with neural parameters such as neuromuscular economy in the elderly (Cadore et al., 2011b) and rapid neural activation in young athletes (Nummela et al., 2006).

Another interesting finding of the present study is the greater associations observed between W_{VT2} and the isokinetic peak torque at the velocities of 180 and 360°.s^{-1} ($r = 0.64$ and 0.67, respectively) compared with the association observed between W_{VT2} and peak torque at 60°.s^{-1} ($r = 0.54$). In a study by Izquierdo et al. (2001), the maximal and submaximal aerobic capacities of elderly subjects were positively related to maximal strength and power values of the lower limbs ($r = 0.44$ to 0.56, $P < 0.05$ to 0.01). In another study, Izquierdo et al. (2003) also showed that strength training combining slow and explosive contractions significantly improved the submaximal and maximal endurance capacities in elderly subjects. Our results reinforce the idea that reduced cardiorespiratory capacity during aging may also be related to declines in neuromuscular function (Izquierdo et al., 2001, 2003; Cadore et al., 2011a). Our results also suggest that cardiorespiratory capacity in the elderly may be more enhanced by strength training aimed at developing explosive strength. Furthermore, it has been shown that explosive strength training enhances functional capacity in elderly subjects (Pereira et al., 2012; Reid and Fielding, 2012). Taken together, these results suggest that explosive strength training may improve several health parameters in the elderly, such as strength performance, functional capacity and cardiorespiratory fitness.

A possible limitation of the present study is that the ultrasound imaging does not allow the identification of what kind of intramuscular factor, such as adipose or connective tissue may contribute more to the echo intensity values. However, the association observed between echo intensity with neuromuscular and cardiovascular performance suggests that the gray scale analysis of ultrasound imaging may be an easy and non-invasive technic to investigate the effects of long-term strength and endurance trainings in the muscle quality in the elderly.

To conclude, our results expand the data regarding the association between muscle echo intensity and physical fitness in elderly subjects. In the present study, echo intensity was associated with several parameters of neuromuscular and cardiorespiratory performances in this population. The present results suggest that the echo intensity measured using computer-aided grayscale analysis is a low cost, easily accessible and a safe method for evaluating muscle quality that may contribute to future research on neuromuscular and cardiovascular functions in the elderly. Thus, our results have an important clinical application, since the echo intensity evaluated by grayscale analysis may be suggested as a useful tool to investigate the effects of strength and endurance trainings in the muscle quality in the elderly. Furthermore, the force per unit of muscle mass was more strongly associated with cardiovascular performance than strength or muscle thickness, which suggests that neural factors associated with strength development are related to cardiorespiratory performance in older subjects. In addition, the peak torque at higher velocities (180 and 360°.s^{-1}) was more closely associated with cardiorespiratory fitness than the peak torque at a lower velocity (60°.s^{-1}). From a practical point of view, the present results suggest that strength training aimed at developing explosive force production may also improve cardiorespiratory performance in the elderly.

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Physiological Effects of Concurrent Training in Elderly Men

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Key words
- physical training
- neural adaptations
- serum hormones
- strength development

Abstract

The aim of the present study was to investigate the effects of concurrent strength and endurance training on neuromuscular and hormonal parameters in elderly men. 23 healthy men (65 ± 4 years) were randomly assigned to 1 of 3 groups: concurrent (CG, n = 8), strength (SG, n = 8) or endurance group (EG, n = 7). The programs consisted, of strength training, endurance training on a cycle ergometer or a combination of both in the same session 3 times per week over a duration of 12 weeks. Subjects were evaluated on parameters related to muscle strength, muscle activation and serum hormones. There were significant increases in lower-body strength in all groups ($P < 0.05$), with higher increases in SG (67%) than CG (41%) and both were higher than EG (25%) ($p < 0.01$). Only SG and CG increased upper-body strength ($p < 0.01$), with no significant difference between the 2 groups. Furthermore, there were significant decreases in free testosterone in EG after training. Significant increases in isometric strength and maximal muscle activation ($p < 0.05$) as well as decreases in the submaximal muscle activation to the same load, were only seen in SG ($p < 0.05$). The present results suggest that the interference effect observed due to concurrent strength and endurance training could be related to impairment of neural adaptations.

Introduction

Biological aging is associated with a decline in the capacity to develop force and power [24], reduced cardiorespiratory fitness [19] and consequently decreased functional capacity, especially after the decade of life between 60 and 70 [10, 12]. To counteract this, several studies have shown that strength training improves both strength and power during aging [13–15] and that endurance training also enhances aerobic fitness in this population [21, 23]. In view of this, the prescription of both endurance and strength training is fundamental to improve functional capacity in elderly populations [2].

The combination of strength and endurance training (i.e., concurrent training) has been widely investigated [8, 23, 31, 37]. These studies have shown that combining endurance and strength training, specifically when high volumes, intensity and/or frequencies are employed, may inversely affect the gains observed during strength and power training (i.e., interference effect) [7, 25, 36]. However, few studies have investigated the interference effects in elderly subjects. Wood et al. [40], investigating elderly men, demonstrated that 12 weeks of concurrent training resulted in similar strength gains to those observed with strength training alone. However, the authors used 50% lower volume of strength training in the concurrent training group [40]. Similarly, Izquierdo et al. [20] observed no differences between strength (twice weekly) and concurrent training (strength exercises on 1 day, cycle ergometer on the other) in the strength gains. In these 2 studies involving elderly subjects, the volume of training performed was lower in the concurrent training groups [20, 40]. Thus, it is not known whether interference would have occurred if these 2 studies had used similar volumes for strength training in the concurrent groups as they used in the strength training alone groups. However, it is possible that even by performing a higher volume of concurrent training, the large trainability of untrained elderly subjects may lead to similar strength enhancements induced by concurrent and strength training with no presence of interference effect in this population [23].

Several mechanisms have been suggested as being responsible for the interference of endurance exercise on strength gains resulting from

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resistance training. These include negative effects on neural adaptations [15], low glycogen content resulting in chronic catabolic state [4,25]; and, interference on the hypertrophy of type I fibers [3,35]. However, there is a lack of evidence of interference on the neural component of strength development when evaluated by electromyography (EMG) measurements [15,31]. Häkkinen et al. [15] have shown that only the strength group enhanced fast muscular activation (500 ms) after training compared with concurrent group. In another study, McCarthy et al. [31] did not find any differences between strength and concurrent groups in the magnitude of neural adaptations (maximal EMG amplitude) after training. Nevertheless, no interference effect on maximal strength was observed in these studies [5,31], and a question that arises is: could the neural component explain the interference effect, in the presence of this phenomenon?

The chronic catabolic state has been investigated using resting serum hormonal concentrations (i.e., testosterone, cortisol) such as anabolism/catabolism markers during the training period. In fact, studies investigating both strength and concurrent training modalities have demonstrated that when high training volume is performed, different hormonal modifications may ensue [5,25]. Besides this possibility, the influence of the reduction in testosterone on the strength decline during aging [12] provides the rationale for conducting research in this area. Likewise, these endocrine adjustments have yet to be investigated in older populations performing concurrent training.

Therefore, the aim of the present study was to investigate the neuromuscular and hormonal adaptations that occur in response to strength, endurance and concurrent training in elderly subjects. Our hypothesis was that, due to the large trainability of older subjects, no differences between strength and concurrent training would be found. However, if the interference effect was observed, we speculated that neural and endocrine mechanisms could help to explain this possible effect.

Methods

Experimental design

In order to investigate the adaptations to strength, endurance and concurrent training, subjects were evaluated using variables related to maximal strength, muscular activation and serum hormonal concentrations. The investigations of electromiographic signal (EMG) and hormonal parameters would provide insights about possible mechanisms involved with training adaptations or even an interference effect. The total duration of the present study was 16 weeks, in which the subjects were tested at −4 and 0 weeks before (control period) and 12 weeks after each specific training program. Thus, all the tests were performed 3 times during the investigation and the first and second pre training measures (control period) were used to determine the stability and reliability of the variables. Each subject performed the tests at the same time of day throughout the period of the study and the different tests were conducted on different days to avoid fatigue. At each point of evaluation (control, pre and post training), subjects completed all the tests in 1 week.

Subjects

29 healthy elderly men (Mean ± SD: 65 ± 5 years; age range: 61–70 years), who had not been engaged in any regular and systematic training program in the previous 12 months, volunteered for the study after completing an ethical consent form. The subjects volunteered for the present investigation following announcements in a widely read local newspaper. After that, 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 3 groups: strength training (SG, n = 10); endurance training (EG, n = 9); and, concurrent training (CG, n = 10). 3 participants dropped out after the control period and another 3 dropped out during the training period. 4 of them due to professional problems and the other 2 moved to another city. At the end of the study, the number of subjects in each group was: SG = 8; EG = 7; and, CG = 8. The study was conducted according to the ethical standards of the International Journal of Sports Medicine described by Harriss and Atkinson [17], 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 (ECG), to ensure subject suitability for the testing procedure. The physical characteristics of subjects are shown in the ▶ **Table 1**.

Body composition

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. The same technician obtained all anthropometric measurements on the right side of the subject's body. Skinfold thickness was obtained with a Cescorf skinfold caliper. A 7-site skinfold equation was used to estimate body density [22] and body fat was subsequently calculated using the Siri equation [18].

Table 1 Physical characteristics before and after training. Mean ± SD.

	Concurrent training CG, n = 8		**Strength training SG, n = 8**		**Endurance training EG, n = 7**	
	pre	**post**	**pre**	**post**	**pre**	**post**
age (years)	66.8 ± 4.8	67.6 ± 5.3	64.0 ± 3.5	64.3 ± 3.7	64.4 ± 3.5	64.4 ± 3.5
body mass (kg)	85.3 ± 11.9	89.7 ± 10.7	80.8 ± 12.2	80.8 ± 12.0	79.1 ± 13.9	78.0 ± 12.4
height (cm)	176.6 ± 4.8	176.6 ± 4.8	173.4 ± 6.2	173.4 ± 6.2	173.0 ± 8.9	173.1 ± 8.8
% fat mass	26.2 ± 3.9	28.8 ± 2.9	27.3 ± 2.7	27.9 ± 2.8	28.9 ± 4.5	27.1 ± 5.0
fat mass (kg)	22.7 ± 6.3	25.1 ± 5.7	22.2 ± 5.0	25.6 ± 6.0	23.0 ± 5.6	21.4 ± 5.9
VO_{2peak} ($ml \cdot kg^{-1} \cdot min^{-1}$)	27.0 ± 3.7	32.9 ± 2.7*	27.3 ± 4.3	28.3 ± 4.1	24.7 ± 7.1	29.7 ± 2.6*

* Significant difference from pre training values ($P < 0.05$)

Maximal dynamic strength

Maximal strength was assessed using the 1-repetition maximum test (1-RM) on the bench press and bilateral knee extension. 1 week prior to the test day, subjects were familiarized with all procedures. 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 5 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 (ICC) was 0.99 for both exercises.

Maximal isometric strength

In order to obtain the maximal isometric strength, the subjects warmed up for 5 min on a cycle ergometer and were then positioned on knee extension exercise machine (Taurus, Porto Alegre, Brazil), fitted with a load cell coupled to the cable that displaced the load. The load cell was connected to an A/D converter (Miotec, Porto Alegre, Brazil), which made it possible to quantify the traction exerted when each subject executed the knee extension at the determined angle. The subjects were positioned seated with the hip at a 110° angle, strapped to the machine at the waist. After having their right leg positioned by the evaluators at an angle of 110° in the knee extension (180° represented the full extension), the subjects were instructed to exert maximum strength possible when extending the right knee. The subjects had 3 attempts at obtaining the maximum voluntary contraction (MVC), each lasting 5 s, with a 3-min rest interval between each attempt. During this test, the researchers provided verbal encouragement so that the subjects would feel motivated to produce their maximum strength. The force-time curve was obtained using Miograph software (Miotec), with an acquisition rate of 2 000 Hz and later analyzed using SAD32 software. Signal processing included filtering with a Butterworth low-pass filter at a cut-off frequency of 9 Hz. Later, in order to determine the highest MVC, a 1-s slice was made in the plateau of force, between the 2nd and 4th second of the force-time curve. The test-retest reliability coefficient (ICC) was 0.94 for MVC

EMG measurements

During the isometric strength test, the maximal muscular activation 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 [27]. Shaving and abrasion with alcohol were carried out on the muscular belly, as previously described by Häkkinen et al. [15], in order to maintain the interelectrodes resistance above 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 [34]. The ground electrode was fixed on the anterior crest of the tibia. The raw EMG signal was acquired simultaneously with the MVC using a 4-channel electromyograph (Miotool, Porto Alegre, Brazil), with a sampling frequency of 2 000 Hz per channel, connected to a personal computer (Dell Vostro 1 000, São Paulo, Brazil). Following acquisition of the signal, the data were exported to the SAD32 software, where they were filtered using the Butterworth band-pass filter, with a cut-off frequency of between 20 and 500 Hz. After that, the EMG records were sliced exactly in the 1 s when the MVC was determined in the force-time curve and the root mean square (RMS) values were calculated. The RMS values of biceps femoris were normalized by the maximum RMS values of this muscle, obtained during the MVC of knee flexion at 90°.

After determination of maximal muscular activation, submaximal muscular activation was evaluated in order to determine the isometric neuromuscular economy. Thus, subjects randomly performed the strength trials corresponding to 40, 60 and 80% of pre training MVC. In this protocol, subjects were asked to maintain the specific force value for 3 s, receiving a visual feedback in the computer that showed, in real-time, the strength values. 1 trial was performed for each intensity, with 5-min rest between trials. The apparatus and the collection and analysis procedures were the same used to determine the maximal EMG signal. After the training period, the submaximal muscular activation was determined for the same absolute loads used in the pre-training 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.

Blood collection and analysis

Blood was obtained from the subjects between 8:00 and 8:30 a.m., after 8 h of sleep, 12 h fasting and 2 days with no exercise. The time of blood collection was chosen due to its use in many studies conducted with these procedures for the control of the circadian hormonal range [6,12]. Subjects sat in a slightly reclined position for 15 min after which 10 ml of blood was drawn from an antecubital vein. After collection, the blood was maintained at ambient temperature for 45 min and then centrifuged for 10 min at 2 000 rpm. The serum was then removed and frozen at −20 °C for later analysis. With this blood sample, resting concentrations of total testosterone (TT) (MP Medicals, Ohio, USA) and free testosterone (FT) (Diagnostic Systems Lab, Webster, USA) and cortisol (COR) (MP Medicals, Ohio, USA) were determined in duplicate, using radioimmunoassay kits. From these values it was possible to calculate the TT/COR ratio. To eliminate interassay variance, all samples were analyzed within the same assay batch, and all intra-assay variances were ≤6.3%. Antibody sensitivities were 0.2 ng/ml for TT, 0.2 pg/ml for FT, 0.05 ug/dl for COR. The test-retest reliability coefficients (ICC) were 0.85 for COR, 0.94 for TT and TL.

Ventilatory threshold and correspondent heart rate

Subjects performed an incremental test on a cycle ergometer (Cybex, USA) in order to determine the heart rate (HR_{VT}) at ventilatory threshold (VT_2). They initially cycled with a 25W load, which was progressively increased by 25W every 3 min, while maintaining a cadence of 70–75 rpm, until exhaustion. 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) 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 [16]. In addition, to confirm the data, VT_2 was determined using the CO_2 ventilatory equivalent (VE/VCO_2). The maximum VO_2 value ($ml{*}kg^{-1}{*}min^{-1}$) obtained close to exhaustion was consid-

Table 2 Complete strength and endurance training periodization.

Strength training				Endurance training		
Week	Sessions	Sets	Repetitions	Week	Volume	Intensity
1	3	2	18–20 RM	1	20 min	80% HR_{VT}
2	2	2	18–20 RM	2	20 min	80% HR_{VT}
3	3	2	15–17 RM	3	20 min	85% HR_{VT}
4	3	2	15–17 RM	4	25 min	85% HR_{VT}
5	3	2	12–14 RM	5	25 min	85% HR_{VT}
6	3	2	12–14 RM	6	25 min	90% HR_{VT}
7	3	2	12–14 RM	7	30 min	90% HR_{VT}
8	3	3	8–10 RM	8	30 min	90% HR_{VT}
9	3	3	8–10 RM	9	30 min	95% HR_{VT}
10	3	3	8–10 RM	10	30 min	95% HR_{VT}
11	3	3	6–8 RM	11	6×4 min/1 min resting	100% HR_{VT}
12	3	3	6–8 RM	12	6×4 min/1 min resting	100% HR_{VT}

RM: maximum repetitions; HR_{VT}: heart rate at ventilatory threshold; min, minutes

ered the Peak Oxygen Uptake (VO_{2peak}). 3 experienced, independent physiologists determined the corresponding points. For the data analysis, the curves of the exhaled and inhaled gases were smoothed using the "median five of seven" method provided by the *Cardiorespiratory Diagnostic Software Breeze Ex* version 3.06. The HR was measured using a Polar monitor (model FS1, Shangai, CHI). The test-retest reliability coefficient (ICC) was 0.83.

Strength training

The strength-training program 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 2 familiarization sessions to practice the exercises they would further perform during the training period. The individuals in the SG performed 9 exercises (inclined leg-press, knee extension, leg curl, bench press, lat pull down, seated row, triceps curl, biceps curl and abdominal exercises) 3 times a week on non-consecutive days. 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 1–7, subjects performed 2 sets of 18–20 repetitions maximum (RM) in week 1 (i.e., the heaviest possible weight was used for the designated number of repetitions) [36], progressing to 12–14 RM (week 5). In weeks 8–12, subjects performed 3 sets of 12–14 RM (week 8), advancing to 6–8 RM (week 11). During the training program, although the exact percent of 1 RM in each set was not controlled, all the sets were performed until failure [25,36]. In each set the workload was adjusted when the repetitions performed were either above or below the repetitions established. The recovery time between sets was 90–120 s. The SG training sessions lasted approximately 40 min. The whole strength training periodization is shown in the ▶ **Table 2**. All the training sessions were carefully supervised by at least 2 experienced personal trainers.

Endurance training

Participants in the EG trained 3 times a week, on non-consecutive days, using a cycle ergometer, at the intensity relative to the heart rate (HR_{VT}) corresponding to the second ventilatory threshold (VT_2). In each session, subjects performed a warm up lasting 5 min at comfortable cadence. During the first 2 weeks, subjects cycled for 20 min at 80% of HR_{VT}, progressing to 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 79.6 ± 5% of the VO_{2peak}. The whole endurance training periodization is shown in ▶ **Table 2**.

Concurrent training

Participants in the CG performed the combined volume of both the SG and EG training. During all sessions, strength exercises were preceded by endurance exercise. This order of exercise was chosen to investigate the effects of aerobic training preceding strength training due to the possible fatigue effects of aerobic training, especially when performed on a cycle ergometer [28]. The CG training sessions lasted approximately 70 min.

Statistical analysis

The SPSS statistical software package was used to analyze all data. Results are reported as mean ± SD. Statistical comparisons in the control period (from week −4 to week 0) were performed by using Student's paired *t*-tests. The training-related effects were assessed using a 2-way Analysis of Variance (ANOVA) with repeated measures (group x time). When a significant *F* value was achieved, Bonferroni *post-hoc* procedures were used to locate the pairwise differences. Selected relative changes between groups were compared via 1-way ANOVA. Significance was accepted when $p < 0.05$.

Results

All subjects performed at least 85% of training with no difference between groups in the number of sessions performed (CG and SG: 32 of 36 and EG 33 of 36 sessions). The results are shown as Mean ± SD. There were no differences between the groups in terms of the variables studied before the start of the training. After the control period, there were no significant differences in dynamic and isometric strength, EMG parameters and hormonal concentrations in all the groups (▶ **Table 3**). There were no significant differences in the body composition or body mass after training (▶ **Table 1**). There were significant increases in the VO_{2peak} in the EG (20.4 ± 10.6%) and CG (22 ± 10%) ($p < 0.05$), and no modification was seen in the SG (5.7 ± 7%) (▶ **Table 1**).
After the training period, a significant interaction was observed (time vs. group) on lower body 1 RM values ($p < 0.001$). Post hoc tests demonstrated that all groups increased the lower-body dynamic strength (▶ **Fig. 1**), but the increase in SG (67.6 ± 17.1%) was significantly higher than CG (41.3 ± 8.2%) and EG (24.7 ± 8%) and CG significantly higher than EG ($p < 0.001$). After training,

Table 3 Pre and post control period values (−4 and 0 weeks).

	Concurrent training CG, n=8		Strength training SG, n=8		Endurance training EG, n=7	
	Week −4	**Week 0**	**Week −4**	**Week 0**	**Week −4**	**Week 0**
LB 1 RM (kg)	65.1±9.4	64.3±11.8	55.6±6.7	58.3±10.2	54.4±18.6	54.4±18.6
UB 1 RM (kg)	43.1±4.9	43.1±4.9	35.1±4.5	38.3±4.8	37.8±14.6	39.2±15.4
MVC (kg)	42.0±7.1	43.2±8.9	42.8±6.3	44.1±10	40.6±13.6	43.3±15.6
EMG VL (mV)	0.322±0.2	0.343±0.22	0.314±0.13	0.399±0.2	0.436±0.16	0.484±0.22
EMG RF (mV)	0.160±0.05	0.188±0.08	0.177±0.08	0.210±0.09	0.245±0.14	0.243±0.13
EMG BF (%)	24.7±18.5	23.3±14.0	21.3±6.9	24.3±9.5	33.6±23.3	33.9±15.0
TT (ng/mL)	3.35±0.72	3.35±0.72	3.6±0.46	3.6±0.46	3.7±1.5	3.7±1.5
FT (pg/mL)	9.84±1.8	9.84±1.8	10.1±1.7	10.1±1.7	9.7±2.8	9.7±2.8
COR (mg/dL)	26.44±2.6	26.44±2.6	24.24±2.4	24.24±2.4	27.8±3.0	27.8±3.0
TT/COR (A.U.)	0.13±0.03	0.13±0.03	0.15±0.03	0.15±0.03	0.14±0.06	0.14±0.06
FT/COR (A.U.)	0.38±0.09	0.38±0.09	0.42±0.09	0.42±0.09	0.35±0.12	0.35±0.12

LB and UB 1 RM, lower and upper-body dynamic strength; MVC, maximal voluntary contraction; EMG VL, RF and BF, maximal muscular activation of vastus lateralis, rectus femoris and coactivation of biceps femoris; TT, total testosterone; FT, free testosterone; COR, cortisol; A.U., arbitrary units. No significant differences after control period

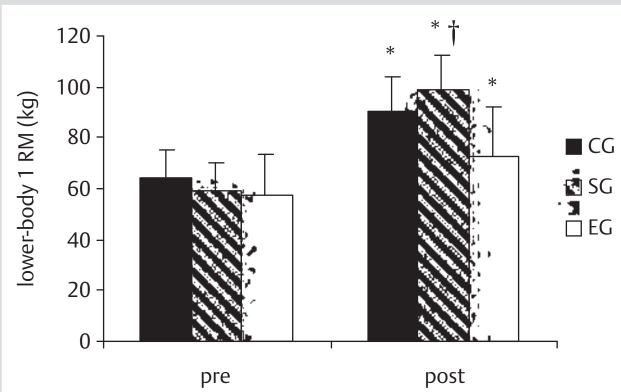

Fig. 1 Lower-body 1 RM values (kg) before and after 12 weeks of training. CG, concurrent group; SG, strength group; EG, endurance group. * Significant difference from pre training values (P<0.01). † Significant difference from EG.

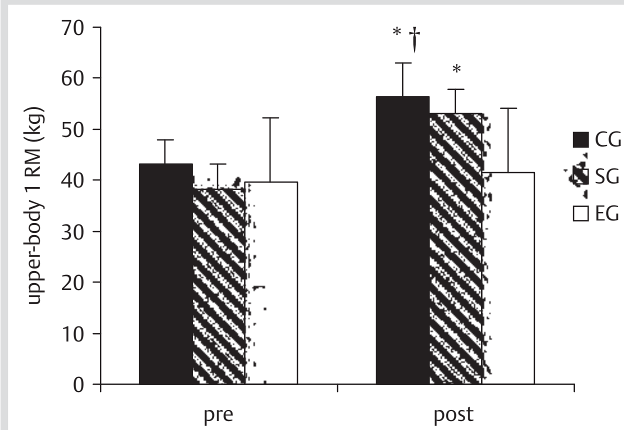

Fig. 2 Upper-body 1 RM values (kg) before and after 12 weeks of training. CG, concurrent group; SG, strength group; EG, endurance group. * Significant difference from pre training values (P<0.01). † Significant difference from EG.

the absolute values of lower-body dynamic strength were higher in SG compared with EG ($p<0.01$) (Fig. 1). In the bench press 1 RM values, there were significant increases in SG and CG (33.7±8.1 and 32.6±10.8%, respectively, ($p<0.001$), without difference in the magnitude, which both increased upper-body strength more than EG ($p<0.001$). After training the absolute values of upper-body dynamic strength were higher in CG compared with EG ($p<0.01$) (Fig. 2). A significant interaction (time vs. group) was observed in the isometric strength. There was significant increase only in SG (13.3±13%) ($P<0.02$) and no significant modifications were observed in the other groups.

Regarding the maximal muscular activation (EMG), a significant interaction (time vs. group) was observed ($p<0.05$). There was a significant increase in the RMS values of vastus lateralis (Fig. 3) and rectus femoris (Fig. 4) during the MVC only in SG ($p<0.05$). The percent increase in maximal activation of vastus lateralis was significantly higher in SG (32.7±24.7%) compared to CG (1.1±2%) and EG (0.6±1.2%) ($p<0.05$). Regarding submaximal activation, significant decreases in the normalized electric activity of vastus lateralis were only seen in SG at 40, 60 and 80% of MVC (Fig. 5), rectus femoris at 60 and 80% of MVC (Fig. 6) and biceps femoris antagonist co-activation at 80% of MVC (Table 4).

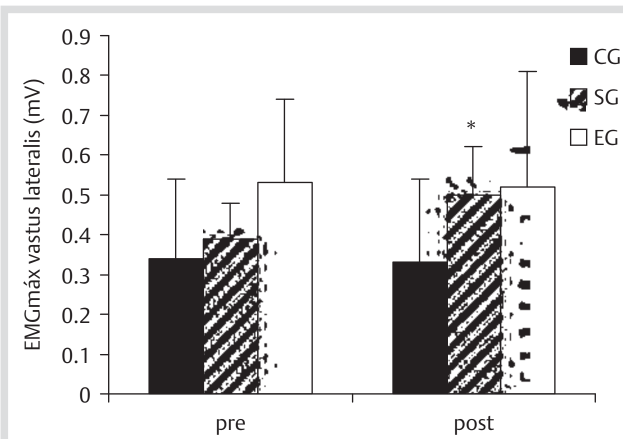

Fig. 3 Maximal EMG activity of vastus lateralis (RMS values) before and after 12 weeks of training. CG, concurrent group; SG, strength group; EG, endurance group. * Significant difference from pre training values (P<0.05).

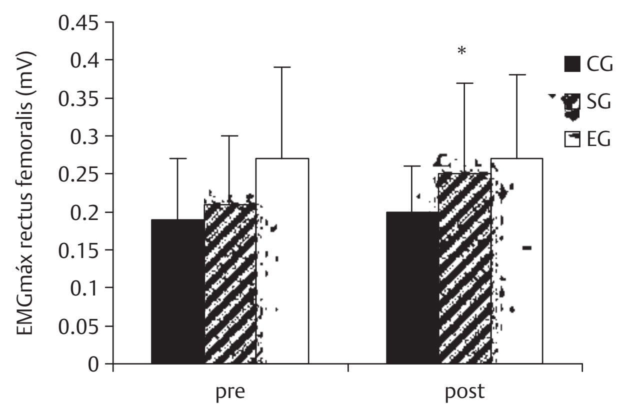

Fig. 4 Maximal EMG activity of rectus femoralis (RMS values) before and after 12 weeks of training. CG, concurrent group; SG, strength group; EG, endurance group. * Significant difference from pre training values (P<0.05).

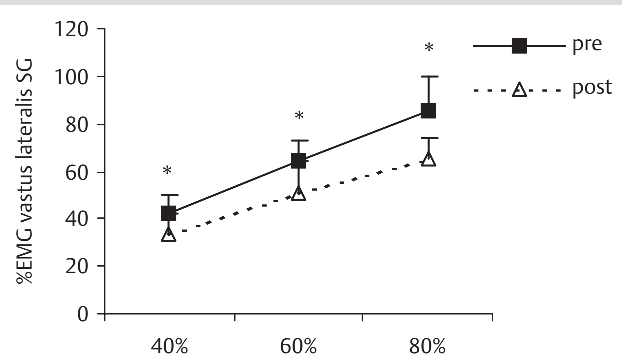

Fig. 5 Isometric neuromuscular economy (normalized EMG) vastus lateralis during different percent of pre-training MVC before and after training in strength group (SG). * Significant difference from pre training values (P<0.05).

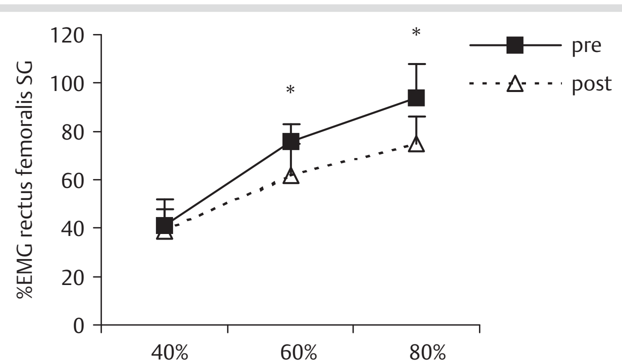

Fig. 6 Isometric neuromuscular economy (normalized EMG) of rectus femoralis during different percent of pre-training MVC before and after training in strength group (SG). * Significant difference from pre training values (P<0.05).

In the present study, there were no significant interactions (time vs. group) for TT, FT, COR, TT/COR and FT/COR ratios (◉ **Table 5**). There was a significant decrease in the FT concentrations after 12 weeks of training in EG ($p<0.05$), as well as a decreased FT approaching significance in CG ($P=0.068$), and decreased TT ($p=0.06$) and COR ($p=0.052$) approaching significance in EG. In addition, significant correlations between the increases in strength with the mean of TT ($r=0.94$; $p<0.01$) and the mean of TT:COR ratio along the study ($r=0.93$; $p<0.01$) were only seen in EG.

Discussion

The main finding of the present study was the presence of an interference effect on the gains in lower body-muscle strength observed in the concurrent group, which was not seen in the upper-body strength measurements in the same group. In addition, this interference effect occurred together with the different variations in EMG measurements obtained for the groups. Moreover, measurement of hormonal concentrations did not suggest any evidence of increased catabolic state. Furthermore, there was a significant relationship between strength improvements and basal testosterone and TT:COR ratio in the endurance group. Thus, the first hypothesis was rejected since our results showed an interference effect in the elderly subjects. Moreover, our second hypothesis was confirmed, since the maximal EMG adaptation was higher after training in SG, suggesting that the neural component may help to explain the interference phenomenon.

Few studies have investigated concurrent training in elderly subjects, and, until now, no interference effect has been observed in this population [20, 23, 40]. In a study from Wood et al. [40], similar strength gains were observed in a comparison between strength and concurrent training after 12 weeks, 3 times a week, but with the concurrent group performing 50% less strength training volume (single set) compared to the strength group (2 sets). In another study, Izquierdo et al. [20] observed no interference effect when comparing 16 weeks of concurrent training with each modality performed once a week, and strength training twice a week (both 3–5 sets). Using the same volume in the concurrent and strength groups (3 sets), Karavirta et al. [23] showed that after 21 weeks of training, strength gains were the same in both groups. In the present study, although an interference effect was observed in the CG, this group had a similar or greater magnitude of strength gains after concurrent training (41%) in relation to the results of the above mentioned studies (21–44%), even though the number of training sessions were similar to those in the studies by Wood et al. [40], Izquierdo et al. [20] and Karavirta et al. [23] (36, 32 and 42 sessions respectively). These discrepancies could be explained by different initial levels of physical fitness among the subjects [1]. It is possible that by being less physically fit at the start of the training period, the sedentary elderly in the present study were able to obtain greater strength gains while, on the other hand, they were more susceptible to the interference effect when the endurance exercise was added.

Another possible cause of the interference effect observed in the present investigation may be the type of endurance exercise performed (cycle ergometer) [9, 28] and the timing of its execution, immediately before the strength exercises, since it has been demonstrated that a cycle ergometer exercise session can induce an acute decrease in lower-body force development due to the local fatigue [29, 36]. Possibly, there was concurrent recruitment of motor units used in both types of training, resulting in lower gains in dynamic strength in the CG. This would seem to be supported by the fact that the EG experienced a gain in dynamic strength (24.7%). Some authors have reported only a small improvement in lower-body strength in response to endurance

Table 4 Submaximal muscular activation values before and after training.

	Concurrent training CG, n=8		Strength training SG, n=8		Endurance training EG, n=7	
	Pre	Post	Pre	Post	Pre	Post
EMG VL 40 (%)	43.6±10.7	38.9±11.1	42.0±7.9	33.8±7.6*	38.0±6.5	33.5±5.2
EMG VL 60 (%)	60.8±16.4	58.0±11.6	63.9±9.3	50.7±13.4*	54.0±7.5	51.6±11.1
EMG VL 80 (%)	87.0±17.4	75.9±7.8	85.6±14.4	65.3±8.7*	91.6±19.1	73.5±14.5
EMG RF 40 (%)	37.7±15.0	41.5±12.1	41.4±7.4	38.6±13.1	48.3±9.7	45.4±9.0
EMG RF 60 (%)	60.3±27.9	61.1±10.7	76.3±7.3	61.8±12.5*	66.7±13.5	64.8±15.1
EMG RF 80 (%)	81.0±32.1	71.2±11.1	94.7±14.3	75.0±10.6*	93.4±17.8	81.0±14.0
EMG BF 40 (%)	15.5±7.9	14.5±13.5	11.9±5.8	8.7±5.4*	23.9±11.6	20.4±17.3
EMG BF 60 (%)	23.7±12.8	20.2±17.5	16.9±9.1	16.7±14.1	33.4±16.7	27.0±22.2
EMG BF 80 (%)	31.8±17.5	25.4±22.5	21.2±9.1	15.9±7.0*	50.6±35.2	36.7±32.1

EMG VL, RF and BF, Submaximal muscular activation of vastus lateralis, rectus femoris and coactivation of biceps femoris at 40, 60 and 80% of maximal voluntary contraction values. * Significant difference from pre training values ($P<0.01$)

Table 5 Resting hormonal concentrations before and after training. Mean±SD.

	Concurrent training CG, n=8		Strength training SG, n=8		Endurance training EG, n=7	
	Pre	Post	Pre	Post	Pre	Post
TT (ng/mL)	3.35±0.72	3.36±1.5	3.6±0.46	3.3±0.53	3.7±1.5	3.35±1.6
FT (pg/mL)	9.84±1.8	7.26±3.16	10.1±1.7	9.1±1.35	9.7±2.8	7.9±3.0*
COR (mg/dL)	26.44±2.6	27.2±1.97	24.24±2.4	24.7±3.8	27.8±3.0	24.5±2.0
TT/COR (A.U.)	0.13±0.03	0.11±0.06	0.15±0.03	0.14±0.04	0.14±0.06	0.14±0.07
FT/COR (A.U.)	0.38±0.09	0.27±0.11	0.42±0.09	0.4±0.01	0.35±0.12	0.33±0.15

TT, total testosterone; FT, free testosterone; COR, cortisol; A.U., arbitrary units. * Significant difference from pre training values $P<0.05$

training performed on a cycle ergometer when performed in combination with strength training [20,21], as well as when it is performed alone [39]. The same effects are not observed when aerobic training consists of running or jogging [25,32]. Thus, this would seem to suggest that the recruitment of high threshold motor units, responsible for higher force production, in the endurance training, especially at intensities near VT_2, resulted in increased muscle strength in the EG, with local fatigue in these motor units, which led to decreased strength performance in the CG.

Although it has been suggested that the neural component of force production may be related to the occurrence of an interference effect [33], few studies have compared the adaptations of the EMG signal arising from strength and concurrent training [15,31] and no study has reported differences in the adaptations in maximal RMS values after training (strength vs. concurrent). In the present study, significant increases in the amplitude of the EMG signal from the vastus lateralis and rectus femoris were observed in the SG after 12 weeks of training, while no modifications were observed in the CG and EG.

Our results are in accordance with the studies from Häkkinen et al. [13,14], which found a significant increase in the amplitude of the EMG signal after strength training, which suggests greater motor unit recruitment and a higher firing rate among the motor units. Furthermore, in the present study, the subjects in the SG experienced a significant decrease in muscle activation for the same absolute load (percent of MVC before training) on the vastus lateralis (40, 60 and 80%) and rectus femoris (60 and 80%), suggesting that for the same load, subjects needed fewer motor units after training [34], which is more economical at the neuromuscular level. The absence of similar adaptations in the CG suggests that the interference effect observed in the present study may be related to neural adaptations to strength training, with the endurance training session performed immediately before strength exercises negatively influencing such adaptations. In fact, a study by Lepers et al. [28], demonstrated that 30 min at 80% of maximal aerobic power resulted in decreases in isometric and concentric force, as well as decreases in the maximal EMG:M wave ratio, which suggests a central fatigue mechanism, indicating a reduction in the number of motor units recruited and/or lower firing rate during maximal effort. Thus, the fatigue imposed by endurance training may have prevented the neuromuscular system from developing the maximal capacity of voluntary recruitment of motor units and increases in the firing rate in the CG, resulting in lower strength development when compared to the SG. However, caution should be applied when dealing with the EMG data because it cannot detect activity at the level of single motor units and it underestimates the activation signal sent from the spinal cord to muscle [11]. Thus, it is possible that lower alterations to the maximal muscular activation in the CG might have occurred but remained undetected by the EMG, since it is unlikely that the strength improvements seen in the CG were exclusively the result of an increase in the muscle cross sectional area.

Besides mobilizing the energetic substrate after exercise, the endocrine system plays a regulatory role in muscular tissue repair and growth [26]. It has been suggested that modifications to the balance between anabolic (i.e., testosterone) and catabolic hormones (i.e., cortisol) may play a role in the interference effect seen in concurrent training, when such an effect is accompanied by increases in basal cortisol [4,5,25]. However, there were no significant modifications to basal hormones in the CG, indicating these subjects experienced no chronic catabolic state, and, consequently, the absence of any relationship between hormonal status and the strength gains found in the present study.

There was a significant reduction in FT, as well as a decreases in TT (3.7 ± 1.5 vs. 3.4 ± 1.6 ng/mL, p = 0.06) and cortisol (27.8 ± 3.0 vs. 24.5 ± 2.0 mg/dL, p = 0.052) approaching significance in the EG. These results, besides a reduction in FT approaching significance in the CG, suggest that the modifications observed might be related to endurance training, since no modification was observed in SG. Some studies have demonstrated that endurance athletes have a lower testosterone concentration than sedentary age-matched subjects [20, 30, 38]. Although there is no clear explanation for the reduction in the free testosterone observed in the EG in the present study, it is possible that the periodization performed, which included constant increases in volume and intensity, required more time for the endocrine system to adapt and reach an homeostatic state. In addition, modifications to resting testosterone levels may be transient and reflect the variation in volume and intensity of training and be explained by modifications to plasma volume [26, 30].

Several studies have demonstrated that testosterone levels and parameters related with this hormone (i. e., TT:COR ratio) are strongly related with muscle strength enhancement [1, 6, 12]. Surprisingly, in the present investigation, a significant correlation was found in the EG between the improvement in lower-body muscle strength and the TT concentration (r = 0.94) and TT:COR ratio values (r = 0.93). This may be explained by the fact that in the CG and SG the volume and intensity of the strength training was high, with 18 sets of knee extensors being performed until exhaustion (maximum repetitions) per week. Thus, the improvement in strength in the CG and SG is likely to be related with total load, as well the type of training performed (i. e., strength or concurrent) [7, 25], while in the EG, in which the stimulus was lower and non-specific (cycle ergometer training), the subjects with higher serum levels of TT and TT:COR values obtained greater gains in muscle strength.

To conclude, the differences in strength enhancement, resulting from strength and concurrent training suggests that endurance training performed before strength training can negatively interfere in the strength gains in elderly men, when the same muscle group is activated in both types of training. According to the mechanisms investigated, interference to neural adaptations seems to explain, at least in part, the interference effect seen in the concurrent strength and endurance training program. On other hand, the hormonal concentrations measured failed to suggest any increased catabolic state, reinforcing the hypothesis of a local neuromuscular and not a systemic interference effect, at least with the volume used in the present study. However, caution is necessary in the interpretation of the present results, since the small sample size and the absence of any morphological measure (i. e., magnetic resonance imaging) represent limitations. An important issue that must be highlighted is that, even though the increase in lower-body strength was at a lower magnitude than in the SG, the CG experienced a significant increase in this capacity (41 %). From the perspective of promoting health, improvements in both strength and cardiorespiratory fitness are important and concurrent training seems to be the best strategy to enhance cardiorespiratory fitness, as widely shown in the literature, and achieve strength gains.

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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 paired *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 VO_{2peak} (28.7±3.8 vs. 27.6±3.6 ml kg 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].

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).

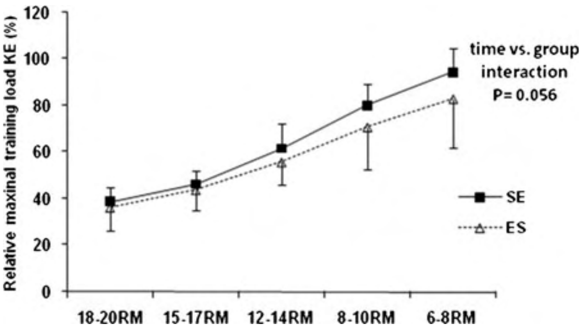

Fig. 1 Mean±SD of maximal training load (percentage) relative to pretraining one maximum repetition maximum (1RM) values during different mesocycles. Tendency toward significant time vs. group interaction ($P=0.056$)

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

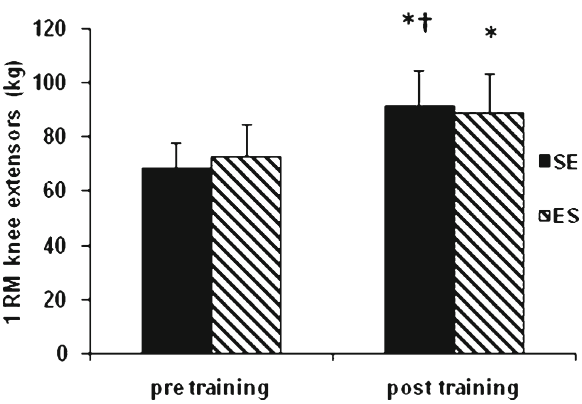

Fig. 2 Mean±SD of lower-body one maximum repetition (1RM) values (kilogram), pre- and post-12 weeks of concurrent training. *SE* strength prior to endurance training, *ES* endurance prior to strength training. *$P<0.001$, significant difference from pretraining values. †$P<0.001$, significant time vs.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

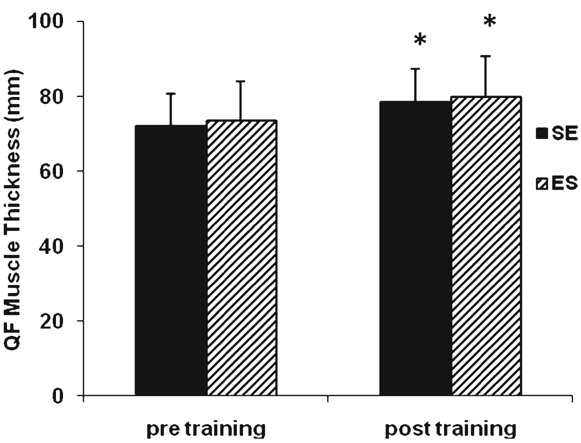

Fig. 3 Mean±SD of the quadriceps femoris muscle thickness (millimeter) pre- and post-12 weeks of concurrent training. *SE* strength prior to endurance training, *ES* endurance prior to strength training. *P<0.001, significant difference from pretraining values

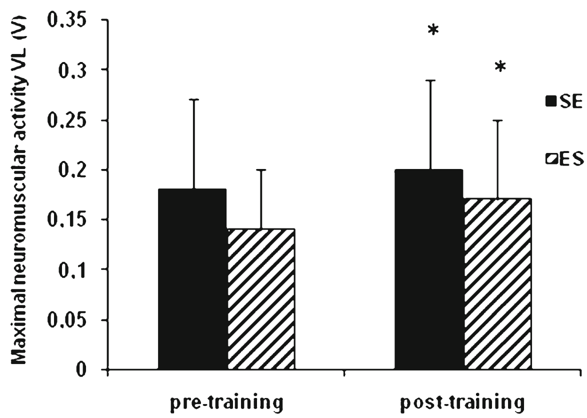

Fig. 4 Mean±SD of maximal neuromuscular activity (maximal electromiographic amplitude) of vastus lateralis (RMS values) pre- and post-12 weeks of concurrent training. *SE* strength prior to endurance training, *ES* endurance prior to strength training. *P<0.05, significant difference from pretraining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

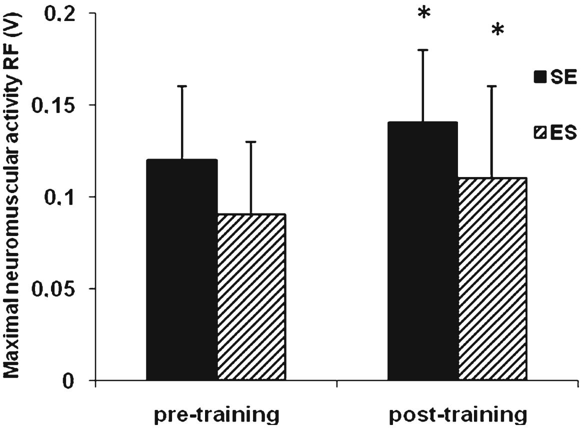

Fig. 5 Mean±SD of maximal neuromuscular activity (maximal EMG amplitude) of rectus femoris (RMS values) pre- and post-12 weeks of concurrent training. *SE* strength prior to endurance training, *ES* endurance prior to strength training. *$P<0.05$, significant difference from pretraining values

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

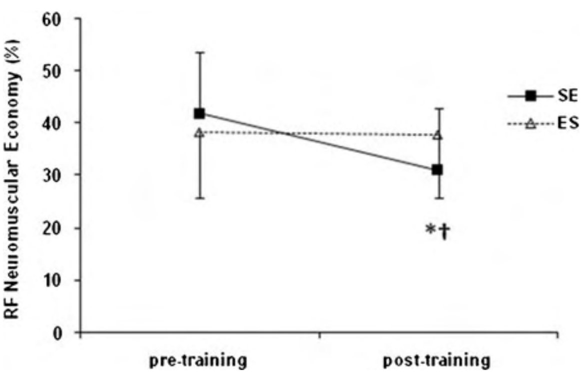

Fig. 6 Mean±SD of neuromuscular economy (normalized EMG at 50 % of pretraining MVC) of rectus femoris before and after training in strength group (SG). *$P<0.01$, significant difference from pretraining values; †$P<0.01$, significant time vs. group interaction

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.

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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How to simultaneously optimize muscle strength, power, functional capacity and cardiovascular gains in the elderly: An update

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Abstract

The purpose of the present study was to review the scientific literature that investigated the concurrent training adaptations in elderly populations, with the aim of identifying the optimal combination of both training program variables (i.e. strength and endurance) in order to avoid or minimize the interference effect in elderly. Scielo, Science Citation Index, MEDLINE, Scopus, Sport Discus and ScienceDirect databases were searched. Concurrent training is the most effective strategy to improve neuromuscular and cardiorespiratory functions, as well as functional capacity in elderly. The volume and frequency of training seems to play a critical role in the concurrent training-induced adaptations in the elderly subjects. Moreover, new evidence indicates that the intra-session exercise order may influence the magnitude of physiological adaptations. It seems that performing strength prior to endurance exercise may optimize both neuromuscular and cardiovascular gains. In despite of interference effect on strength and power gains caused by concurrent training, its advantageous aspect is that even when the interference phenomenon is observed, the combination of strength and endurance training produces neuromuscular adaptations in a great extent and cardiovascular gains at the same level of the endurance training alone. Thus, concurrent training is the most recommended intervention to promoting health in elderly.

Key-words: aging, physical training, neural adaptations, muscle mass.

1. Why combine strength and endurance training in the elderly?

Aging is associated with declines in muscle mass, strength performance and cardiorespiratory fitness, resulting in an impaired capacity to perform daily activities and maintain independent functioning (Izquierdo et al. 2001a; 2003; Snijders et al. 2009; Aagard et al. 2010). Recently, age-related declines in muscle power-output have emerged as an important predictor of functional limitations in older adults (Izquierdo et al. 1999a, 1999b; Sayers et al. 2003; Henwood et al. 2008; Miszko et al. 2003; Bottaro et al. 2007, Reid and Fielding 2012). To counteract this effect, a combination of strength and endurance training (i.e., concurrent training) in elderly populations seems to be the most effective strategy to improve both neuromuscular and cardiorespiratory functions and consequently to maintain functional capacity during aging (Wood et al. 2001; Izquierdo et al. 2004; Cadore et al. 2011a).

Strength and endurance training, however, have specific cardiovascular and neuromuscular adaptations that are different in nature. The primary adaptations to strength training (ST) include enhanced strength and power performance (Izquierdo et al. 2001b; Peterson et al. 2010; García-Pallarés and Izquierdo 2011), muscle cell hypertrophy (Kraemer et al. 1995), an increase in the neuromuscular activity (Häkkinen et al. 2003a; Cadore et al. 2010) and no changes in VO_{2max}. In contrast, endurance training (ET) induces central and peripheral adaptations that enhance VO_{2max} and the ability of skeletal muscles to generate energy via oxidative metabolism with no increase in muscle strength or hypertrophy (Izquierdo et al. 2004).

Studies investigating the effects of endurance training performed simultaneously with strength training have shown controversial results regarding strength and power gains. Some studies have shown that the combination of strength and endurance training results in fewer strength and power gains when compared with strength training alone, and this effect has been called “the interference effect” (Kraemer et al. 1995; Bell et al. 1997, 2000; Häkkinen et al. 2003a; Cadore et al. 2010). However, several studies have observed similar strength gains when comparing strength and concurrent training (CT) Dolezal and Potteiger 1998; Gravelle and Blessing 2000; Wood et al. 2001; McCarthy et al. 2002; Izquierdo et al. 2004, 2005).

Although several studies have focused on young populations (Chtara et al. 2005, 2008; García-Pallarés et al. 2010, 2011; Izquierdo-Gabarrén et al. 2010; Cadore et al. 2012c), a limited number have explored the effects of concurrent training on strength and endurance performance in older age (Izquierdo et al. 2004, Cadore et al. 2010; 2012a, 2012b; Holviala et al. 2010; Sillampaä et al. 2008; Karavirta et al. 2011). Some studies have recently examined the influence of volume and intensity manipulation and the effects of intra-session exercise sequence on concurrent training adaptations (Izquierdo et al. 2004, 2005; Cadore et al. 2010, 2011a, 2012a, 2012b). New evidence and exercise strategies have indicated that the intra-session exercise order may influence the magnitude of neuromuscular and cardiovascular adaptations in the elderly (Cadore et al. 2012a, 2012b). Some recent evidence has also suggested that the combination of strength and endurance training may produce neuromuscular and cardiovascular adaptations that are similar to those produced by endurance or resistance training alone (Izquierdo et al. 2004; 2005; Karavirta et al. 2009; Cadore et al. 2011a).

In addition to the relevant benefits in the neuromuscular and cardiovascular functions, CT results in enhanced functional capacity (Wood et al. 2001). This effect should be especially prominent in frail elderly individuals (de Vries et al. 2012). Furthermore, several studies have shown the positive effects of concurrent training on the treatment of health diseases, such as diabetes (Umpierre et al. 2011), fibromyalgia (Valkeinen et al. 2009), systemic sclerosis (Pinto et al. 2011), multiple sclerosis (Motl et al. 2012), rheumatoid arthritis (Häkkinen et al. 2003b), and heart failure (Duncan et al. 2011).

To optimize the concurrent training prescription, it seems reasonable to identify the most effective combination of intensity, volume, weekly frequency and intra-session exercise sequence (i.e., strength-endurance or endurance-strength) to promote both neuromuscular and cardiovascular adaptations in the elderly. In addition, because muscle power is an important predictor of functional performance, strategies to develop skeletal muscle power during the concurrent training prescription must be discussed. Therefore, the purpose of the present review was to recommend training strategies that prevent or minimize the interference effect of concurrent strength and cardiovascular training in the elderly based on scientific literature.

2. Literature Search

2.1. Search strategy

The Scielo, Science Citation Index, MEDLINE, Scopus, Sport Discus and ScienceDirect databases were searched from February to May of 2012 for articles published from original scientific investigations. Search terms included various combinations of the keywords 'concurrent strength and endurance training', 'exercise training in elderly', 'muscle power in elderly', 'muscle strength in elderly', 'combined resistance and aerobic training' and 'muscle quality'. The names of authors cited in some studies were also utilized in the search.

2.2. *Criteria for study consideration*

The search criteria were as follows: (i) studies must be from English peer-reviewed scholarly journals; (ii) dissertations, theses and conference proceedings were excluded; (iii) studies must refer to the effects of concurrent strength and endurance training and the manipulation of training programmed variables in the elderly; and (iv) only randomized studies using high validity and reliability technical procedures were included.

2.3. *Inclusion of studies*

Twelve original research articles that compared the effects of strength training or endurance training with the effects of concurrent training in the elderly were included and had their results described. Furthermore, an additional 16 original research studies that investigated the effects of concurrent training on health diseases were included. Finally, 7 original research investigations on the effects of power training on the functional capacity of the elderly were included to complement the concepts of the exercise prescription for the elderly.

3. Effects of concurrent training on muscle strength and power

The volume and frequency of training played a critical role in the concurrent training-induced adaptations in the elderly subjects (Izquierdo et al. 2004; Cadore et al. 2010; Karavirta et al. 2011). Most of the studies reported that CT induced similar strength adaptations using two sessions per week of each modality (i.e., strength and endurance) when compared with ST alone (Holviala et al. 2010; Sillampaä et al. 2008; Karavirta et al. 2011). However, three times a week of concurrent training can result in an interference effect in this population (Cadore et al. 2010, 2012a). Similarly, the time-course of strength development during a concurrent training periodization may be influenced by the weekly frequency of training (Cadore et al. 2010). Furthermore, recent evidence by our research group has shown that intra-session exercise sequence may also influence the magnitude of strength adaptations in the elderly, and performing strength training prior to endurance exercise may optimize the neuromuscular adaptations in this population (Cadore et al. 2012a, 2012b). Table 1 summarizes the methods applied and the results observed in the studies that investigated the CT adaptations in the elderly.

3.1. Volume and frequency of training

Volume and frequency manipulation may be adjusted to minimize the interference effect in the elderly. In the study by Wood et al. (2001), elderly subjects performed strength and concurrent training for 12 weeks, with the ST groups performing two sets and the CT group performing only one set in addition to the endurance training. These authors observed similar strength gains among the groups (38-44%). Izquierdo et al. (2004) investigated the effects of 16 weeks of strength, endurance and concurrent training among elderly men. In this study, the ST and ET groups performed specific training twice a week, and the CT group performed strength exercises on one day and cycle ergometer on the other day. These authors demonstrated that after 16 weeks of training, similar lower-body strength gains were observed in the ST and CT groups, which suggests that a minimum weekly frequency of concurrent training (1 session per week of strength and 1 session per week of cycle endurance training) may be an optimal stimulus to promote strength gains in previously untrained elderly subjects (Izquierdo et al. 2004) (Figure 1). Notably, similar results were observed in middle-aged subjects (Izquierdo et al. 2005), which reinforces that this strategy improves strength performance in early phases of concurrent training.

Using similar training volumes for ST and CT groups, Karavirta et al. (2009, 2011) observed similar isometric (14-20%) and dynamic strength gains (~22%) and similar improvements in maximal concentric power (~16%) in the groups after 21 weeks of training twice a week in 40-67-year-old men. In other studies using similar training periodization, including intensity, volume and weekly frequency, similar strength and power gains were observed in the ST and CT groups in older men (Holviala et al. 2010, 2012; Sillampaä et al. 2008, 2009a), and older women (Sillampaä et al. 2009b).

Increasing the weekly training frequency from two to three sessions per week may induce the interference effect in elderly men who perform concurrent training. Examining elderly men, Cadore et al. (2010) reported that 12 weeks of training performed three times a week led to greater dynamic and isometric strength in the leg extensor muscles in the group that performed only strength training (67%) when compared with a combined strength and cardiovascular group (41%), whereas similar upper-body strength gains were evidenced in the ST and CT groups (30-33%). Moreover, increases in the maximal isometric force were observed only in the ST group (14%). These results suggested that the interference effect of endurance training on strength adaptations occurs only in the specific muscle groups that perform both strength and endurance exercises (i.e., lower-limbs).

Notably, in the study by Cadore et al. (2010), although an interference effect was observed in the CT group, this group exhibited a similar magnitude of strength gains in relation to the results of the abovementioned studies (Karavirta et al. 2009, 2011; Holviala et al. 2010, 2012, Silampaä et al. 2008, 2009a), and the same strength adaptations occurred in a shorter period of time (12 vs. 21 weeks). These different time courses in strength development could be explained by the different weekly frequencies of training performed. Cadore et al.'s (2010) subjects performed three training sessions per week, in contrast with subjects in other previous studies, who performed two training sessions per week (i.e., ~30% lower volume) (Karavirta et al. 2009, 2011; Holviala et al. 2010, 2012, Silampaä et al. 2008, 2009a). It is possible that this greater weekly training frequency results in faster strength development in ST and CT, even with the occurrence of the interference effect in the CT group.

3.2. Intra-session exercise sequence

Another factor related to the CT session that may influence the magnitude of strength adaptations in the elderly is the intra-session exercise sequence. Greater maximal dynamic strength gains (35 vs. 21%) and greater force per unit of muscle mass (27 vs. 15%) were observed in a CT group that performed strength training prior to endurance exercise, when compared with the inverse order (Cadore et al. 2012a, 2012b), after 12 weeks of concurrent training using a similar training periodization, which had resulted in an interference effect (Cadore et al. 2010). It may be suggested that fewer strength gains obtained after the endurance-strength exercise (ES) sequence could be related to the ES group's lower workloads in the training periodization (Figure 2). These differences were more evident 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 summary, based on the results observed regarding strength and power gains induced by concurrent training in the elderly, the following may be suggested: (i) performing a minimum weekly frequency of concurrent training (1 session per week of strength and 1 session per week of cycle endurance training) may be an optimal stimulus to promote strength gains in previously untrained elderly subjects (Izquierdo et al. 2004); (ii) moderate weekly frequency (3 times a week), with both strength and endurance training performed in the same day, may induce the interference effect in the strength adaptations (Cadore et al. 2010); and iii) during training protocols in which both strength and endurance training are performed on the same day, the strength gains may be optimized with strength training prior to endurance intra-session exercise sequence (Cadore et al. 2012a, 2012b). Table 2 provides guidelines for prescribing strength and endurance training simultaneously to optimize neuromuscular and cardiovascular function in elderly populations.

4. Effects of concurrent training on muscle hypertrophy and muscle quality

4.1. Muscle hypertrophy

Studies investigating morphological adaptations to concurrent training in the elderly are scarce. In the abovementioned study by Izquierdo et al. (2004), no differences were observed between the ST group (twice a week) and CT group (1 session per week of strength and 1 session per week of cycle endurance training) in the magnitude of hypertrophy after 12 weeks of training (~11%). A unique finding of this study was that only one day of ST combined with another day of ET performed using cycle ergometer resulted in enhanced muscle mass in the elderly after 16 weeks (Figure 3).

In study of Karavirta et al. (2011), an increase in the cross-sectional area (AST) of type II muscle fibers of the vastus lateralis was observed only in the ST group (~16%), whereas no changes were observed in the CT group. Nevertheless, as previously mentioned, this difference did not result in a difference in strength gains. In other studies utilizing a training weekly frequency ranging from two to three times, intensities from 40 to 80% of 1RM (progressive load during training periodization) and multiple sets produced marked increases in muscle mass (9-16%), with no differences between the ST and CT regimes (Holviala et al. 2010, 2012; Sillampaä et al. 2008, 2009a). Moreover, although the intra-session exercise sequence influenced strength adaptations, it is important to note that the sequence of strength and endurance exercise had no influence on muscle mass gains (Cadore et al. 2012b).

4.2. Does overtraining explain the interference effect in the elderly?

The results regarding the effects of concurrent training on muscle mass enhancements in the elderly are in agreement with the studies conducted in young populations, as no difference was observed between the ST and CT groups when image technics were used to evaluate these effects (McCarthy et al. 2002; Häkkinen et al. 2003a). However, studies that used muscle biopsies demonstrated the interference phenomenon in the cross-sectional area of type I fibers in young men who performed CT with a high intensity and volume of both strength and endurance training (Kraemer et al. 1995; Bell et al. 1997, 2000). The interference occurred in parallel with increases in cortisol levels, suggesting that these subjects may have been in an overtraining state (Kraemer et al. 1995; Bell et al. 1997, 2000). In the elderly, no indication of an overtraining state has been observed. In the study by Karavirta et al. (2011), a moderate volume of training resulted in an increase in the type II fiber area only in the ST group, whereas no changes were observed in the CT group. Notwithstanding, no changes in the basal anabolic or catabolic hormone levels were evidenced in this study (Karavirta et al. 2011). In addition, in the study by Cadore et al. (2010), the interference effect on neuromuscular adaptations occurred with no changes in the levels of free and total testosterone or cortisol, suggesting that the interference phenomenon occurred with no indication of an overtraining state in the elderly.

4.3. Muscle Quality

Muscle quality can be assessed using the non-invasive, easily accessible and safe method of ultrasound imaging, whereby enhanced echo intensity (i.e., greater gray-scale values) represents changes caused by increased intramuscular connective and adipose tissue (Pillen et al. 2009; Fukumoto et al. 2012). In addition, it has been shown that elderly populations present greater gray-scale values compared to young populations. In a study that utilized ultrasonography, through gray-scale analysis, Fukumoto et al. (2011) observed negative correlations between gray-scale values and isometric strength in elderly men. These results suggested that the subjects with greater adipose and connective tissue, i.e., those with greater echo intensity values, displayed lower strength performance. Recently, our research group observed a negative association between echo intensity values with several parameters of muscle power and strength ($r = -0.48$ to $r = -0.64$; $P<0.05$) as well as endurance performance ($r = -0.46$ to $r = -0.50$; $P<0.01$) in the elderly (Cadore et al. 2012d). Hence, these results have an important clinical application, as the echo intensity evaluated by gray-scale analysis may be suggested as a useful tool for investigating the effects of strength and endurance training on the muscle quality in the elderly.

5. Effects of concurrent training on maximal and submaximal neuromuscular activity

Early adaptations to strength training in the elderly include increases in the maximal neuromuscular activity (i.e., EMG signal amplitude) (Häkkinen et al. 1996, 1998a, 1998b; 2000, 2001; Cannon et al. 2007; Brentano et al. 2008). These changes may suggest the occurrence of neural adaptations such as increases in the maximal motor unit recruitment (Knight and Kamen 2001), maximal motor unit firing rate (Kamen and Knight 2004), spinal motorneuronal excitability and efferent motor drive (Aagaard et al. 2002a; 2002b).

Although neural adaptation impairments are suggested as a mechanism to explain the interference effect, few studies have investigated the neural adaptations to concurrent training. In young subjects, no difference has been observed in the maximal EMG amplitude adaptations among ST and CT groups (McCarthy et al. 2002), whereas impaired rapid muscle activation (rate of EMG increases in 100 ms) has been observed in parallel with an interference effect in the rate of force development at 100 ms (Häkkinen et al. 2003a). Notwithstanding, in elderly subjects, damage to the neural adaptations seems to contribute to the interference effect, as this effect may occur in parallel with lower maximal neuromuscular activity adaptations in the CT group (Cadore et al. 2010).

Investigating the mechanisms underlying the strength adaptations to ST and CT in the elderly, Cadore et al. (2010) observed a significant increase in the maximal EMG amplitude of the *rectus femoris* and *vastus lateralis* only in the ST group (~30%), and these modifications were significantly greater than those observed in the CT group (~1.5%, non-significant). In addition, greater isometric neuromuscular economy (reduced submaximal EMG to the same absolute load after training) was observed in the *rectus femoris* and *vastus lateralis* only in the

ST group. It is important to highlight that the greater neuromuscular activity changes observed in ST than CT occurred in parallel with greater strength gains in ST (Cadore et al. 2010), which suggested that the interference effect occurred at least in part due to impairments in neural changes.

Recently, Cadore et al. (2012a) found significantly greater changes in the force per unit of active muscle mass (i.e., muscle quality or specific tension) in elderly individuals who performed strength training prior to an endurance exercise sequence when compared with the inverse order (27 vs. 15%, P<0.01). The force per unit of active muscle mass provides an estimation of the contribution of neuromuscular factors associated with changes in strength development, as enhanced strength with the same muscle mass suggests neural adaptations to training (Tracy et al. 1999; Frontera et al. 2000; Reeves et al., 2004; Narici et al., 2005). In another study, Cadore et al. (2012b) showed greater changes in the neuromuscular economy of the *rectus femoris* in elderly individuals who performed strength training prior to an endurance exercise sequence when compared with the inverse order (Figure 4). Taken together, these results suggest that the interference effect in the elderly might be explained at least in part by impairments in the neural adaptations to strength training.

6. Effects of concurrent training on cardiovascular performance

6.1. Concurrent training does not impair the cardiovascular adaptations

The decline in cardiorespiratory capacity in the elderly is primarily associated with a decrease in the maximal heart output caused by the reduction in the maximum stroke volume and heart rate and the change in the oxygen artero-venous difference (Astrand et al. 1973). Several authors have demonstrated that strength and power development are also important for endurance performance in elderly populations (Izquierdo et al. 2001b, 2003; Cadore et al. 2011b). In a study by Izquierdo et al. (2001), the maximal and submaximal aerobic capacities of elderly subjects were positively related to maximal strength and power values of the lower limbs (r=0.44 to 0.56, P<0.05 to 0.01). In another study, Izquierdo et al. (2003) showed that strength training that combined slow and explosive contractions significantly improved the submaximal and maximal endurance capacity of elderly subjects. However, as expected, several studies have shown that the combination of strength and endurance training is a better strategy to improve the cardiovascular performance of the elderly when compared with strength training alone. In addition, the performance of strength training simultaneously with endurance training does not impair the cardiovascular adaptations produced by endurance training alone (Wood et al. 2001; Izquierdo et al. 2004; Karavirta et al. 2009, 2011; Holviala et al. 2010, 2012, Silampaä et al. 2008, 2009a; Cadore et al. 2011b).

Studies that have investigated cardiovascular adaptations to CT have demonstrated increases ranging from 10 to 18% in the maximum oxygen uptake and maximal workload at cycle ergometer in elderly people who underwent training periods ranging from 12 to 21 weeks and a weekly frequency ranging from two to three training sessions (Wood et al. 2001; Izquierdo et al. 2004; Sillampaä et al. 2009; Holviala et al. 2010; Cadore et al. 2010; Karavirta et al. 2011). Similar to the results observed in the strength performance and hypertrophy mentioned, Izquierdo et al. (2004) observed similar aerobic power gains in elderly men who underwent 1 session per week of strength training and 1 session per week of cycle endurance training in the CT group (28%) and those who underwent ET twice per week (23%) after 16 weeks of training. Similar results were observed in middle-aged subjects (12 vs. 14% in CT and ET, respectively), which suggests that a minimum weekly frequency of concurrent training may be an optimal stimulus to promote cardiovascular gains in early phases of training in previously untrained middle-aged and elderly subjects.

6.2. Effects of intra-session exercise sequence

Another interesting finding observed in the literature is the influence of the intra-session exercise order on cardiovascular adaptations. In the study by Cadore et al. (2012a), similar enhancements were observed in the peak oxygen uptake, maximal workload at cycle ergometer, and the workload at the second ventilatory threshold among groups that performed strength training prior to an endurance exercise sequence and the opposite exercise order. However, greater improvement was found in the workload at the first ventilatory threshold in the group that strength trained prior to endurance exercise in each session. It is possible that this difference was observed as a consequence of the greater increases in the muscle strength achieved by performing strength training prior to endurance training, as strength gains have been associated with maximal and submaximal endurance gains (Izquierdo et al. 2003) and dynamic neuromuscular economy in the elderly (Cadore et al. 2011a). If this is the case, from a practical standpoint, performing strength training prior to endurance exercise may be more beneficial for improving functional activities because several functional activities are performed at lower aerobic intensities (Hartman et al. 2007).

7. Effects of concurrent training on functional capacity and Frailty syndrome

Few studies have compared the effects of strength, endurance and concurrent training on the functional capacity of the elderly. In Wood et al.'s (2001) investigation, no differences were observed between ST, ET and CT groups in the functional performance gains assessed by the sit and reach test, agility/dynamic balance assessed by repeatedly standing from a chair, walking around cones and returning to the chair and coordination tests. Holviala et al. (2010) showed increases in the treadmill load carrying walking test performance (10.1 kg in each hand) only in the CT group (4.5%), whereas no changes were observed in the ST and ET groups. These results suggested that only the combination of strength and endurance capacities improved the performance on this test. In addition to the positive effects of concurrent training on the functional capacity of healthy elderly individuals, another issue that must be further investigated is the potential benefits of combined strength and endurance training on the functional capacity of frail individuals.

7.1. *Long-term concurrent training programs*

Despite the limited number of studies comparing the effects of ST, ET and CT interventions on functional test performance, it is important to highlight the positive effect of concurrent training on the functional capacity of elderly populations (Binder et al. 2004; Pahor et al. 2006; Rejeski et al. 2009). In study by Rejeski et al. (2009), two years of combined endurance and strength training resulted in an improved 400- meter walking speed and physical performance battery that included balance, 4 meters of self-paced walking speed and chair stands. In another study, Binder et al. (2004) demonstrated enhanced scores in an assessment of muscle strength, gait, balance, body composition and quality of life after five years of a physical therapy program composed of strength and endurance training in elderly men and women who had experienced surgical repair of a proximal femur fracture.

7.2. The role of muscle power to improve functional capacity

In view of improving the concurrent strength and endurance training prescription, results concerning the effects of combining slow and explosive mode contractions into the strength training program should be considered to optimize the functional capacity enhancements. The inclusion of explosive contractions in strength training results in overall neuromuscular adaptations in the elderly, such as increases in the maximal concentric power, rate of force development and rapid muscle activation, and maximal dynamic strength (Häkkinen et al. 2001; Izquierdo et al. 2001a). Moreover, some studies have shown that strength training using high velocity during concentric contractions results in greater improvements in functional capacity when compared with strength training using only slow velocity of contractions (Earles et al. 2001; Sayers et al. 2003; Henwood et al. 2008; Miszko et al. 2003; Orr et al. 2006; Bottaro et al. 2007; Pereira et al. 2012; Reid and Fielding 2012). In the study by Pereira et al. (2012), 12 weeks of high speed power training improved walking speed and performance on functional tests such as "*sit to stand*" and "*get up and go*" in elderly women. Similarly Bottaro et al. (2007) showed greater increases in functional performance in a ST performed with explosive muscle contractions when compared with a traditional ST group (i.e., only slow contractions). Thus, muscle power seems to be a more important predictor of functional performance in elderly adults than muscle strength. Strength training programs that combine high with slow velocity of contractions should be included in the concurrent training prescription to improve physical fitness to a greater extent.

7.3. *Frailty syndrome*

The oldest old is a growing age group in the world, and frailty is one of the main health problems in this population (de Vries et al. 2012). Falls, immobility, dependency and disability are some of the problems associated with advanced age (Fiataroni et al. 1990; Christenses et al. 2009). In addition, intellectual disability and dementia are diseases associated with restraint and, consequently, with declines in neuromuscular function and functional capacity (Calders et al. 2011; Hauer et al. 2012). It has been shown that strength training improves the functional capacity in the oldest old (Serra-Rexach et al. 2011), and patients with dementia (Hauer et al. 2012). A home-based program consisting of functional activities, strength and walking capacity has been shown to improve the functional capacity of the frail elderly (Matsuda et al. 2010; de Vries et al. 2012; Oosting et al. 2012). However, the effects of systematic concurrent strength and endurance training in frail subjects, as a more complete exercise intervention, must be further investigated. Thus, future studies addressing the effects of concurrent training in frail elderly individuals are necessary to elucidate the extent of the capacity to develop both strength and endurance performance in this population.

8. Role of concurrent training on health disease treatment

8.1. Concurrent training in patients with cardiovascular, endocrine and immune diseases

Several studies have shown the beneficial effects of the simultaneous performance of strength and endurance training in elderly individuals with health diseases. After only 26 ± 4 days, concurrent training improved strength and cardiovascular risk factors in elderly patients during cardiac rehabilitation, with no differences between strength training volumes [(2 sets x 12 repetitions + 6 days of cycling (~17 minutes) + 5 days of walking (45 minutes) vs. 3 set x 15 repetitions + 6 days of cycling (~17 minutes) + 5 days of walking (45 minutes)] (Berent et al. 2011a), and the discontinuation of the CT program increased these patients' cardiovascular risk (Berent et al. 2011b). In postmenopausal women, combined strength and endurance training performed 3 days per week improved arterial stiffness and blood pressure (Figueroa et al. 2011). These results are quite relevant because in addition to declines in muscle strength, menopause is associated with increased arterial stiffness. In another study, CT improved the physical capacity of patients with peripheral arterial disease (Mosti et al. 2011).

In type II diabetic patients, significantly improved glycemic control and declines in the hemoglobin A_{1c} have been observed after concurrent training programs (Balducci et al. 2004; Church et al. 2010). Moreover, a recent meta-analysis showed that strength, endurance or concurrent training performed for at least 12 weeks, with weekly exercise of more than 150 minutes, was associated with improved glycemic control and declines in the hemoglobin A_{1c}

(Umpierre et al. 2011). It should be highlighted that several type II diabetic patients in this meta-analysis were ~60 years old (Umpierre et al. 2011).

Other studies have demonstrated beneficial effects of CT on physical fitness and functional capacity in patients with several diseases, such as fibromyalgia (Valkeinen et al. 2009), systemic sclerosis (Pinto et al. 2011), multiple sclerosis (Moti et al. 2012), rheumatoid arthritis (Häkkinen et al. 2003b), and heart failure (Duncan et al. 2011; Gary et al. 2011). All of these studies indicated the safeness and efficacy of the concurrent training in improving the functional capacity of patients with these diseases.

9. CONCLUSIONS

The combination of strength and endurance training in the elderly is the best strategy to improve both neuromuscular and cardiorespiratory functions and, consequently, to maintain functional capacity during aging. In addition, patients with several diseases may improve their functional capacity by combining strength and endurance training programs; thus, concurrent training should be included in their treatment and daily routine.

The interference phenomenon may be observed in elderly subjects when a moderate weekly volume of concurrent training (i.e., 3 times per week) is performed. This interference phenomenon seems to be associated with impairments in the neural adjustments to training. However, based on recent evidence, strategies have been provided to optimize the muscle strength and power gains to develop the cardiovascular function, as follows:

- The performance of a minimum weekly frequency of concurrent training (1 session per week of strength training and 1 session per week of cycle endurance training) may be an excellent stimulus to promote muscle hypertrophy, strength and power gains in previously untrained elderly subjects;

•For concurrent training protocols in which both strength and endurance training are performed on the same day, the strength gains may be optimized with strength training prior to endurance intra-session exercise sequence;

•Endurance parameters may be also optimized when strength exercises are performed prior to endurance exercises in each session. This exercise sequence may promote greater increases in the workload at the first ventilatory threshold, and these changes may be associated with enhanced neuromuscular economy as a consequence of greater strength gains;

•Regarding improving the functional capacity of the elderly, the concurrent strength and endurance training prescription should include explosive mode contractions into the strength training program, as skeletal muscle power has been strongly associated with the functional capacity of this population.

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TABLES:

Table 1: Neuromuscular adaptations to concurrent training vs. strength training in elderly.

Authors	Period and weekly frequency	Volume and intensity	Findings
Wood et al. 2001	12 wk; ST: 3x/wk; ET: 2x/wk; CT: ST +ET	ST: 2 sets, 12-15 rep (75% 5RM) to 8-12RM. ET: 60-70% of $FC_{máx}$ estimated, 20-45 min cycling. CT: 1 set of 8-12RM + 30 min cycling	↑1RM (15-29%)* in ST and CT. ↑ functional performance in both groups*. No difference among CT and ST.
Izquierdo et al. 2004	16 wk; ST: 2x/wk; ET: 2x/wk; CT: 1x/wk ST + 1x/wk ET.	3-5 sets, 6-15 rep (50-80% 1RM) slow + fast contractions (20% of total volume, 30-50% of 1RM). ET: 30-40 min cycling, at loads (W) of 2, 3 and $4mmol{\cdot}L^{-1}$ of lactate.	↑1RM in ST and CT (22-41%)**; ↑ muscle power at 45% of 1RM in ST and CT (45%)*. ↑CSA QF in ST and CT (11%)*. No difference among CT and ST.
Sillanpaä et al. 2008	21 wk; ST: 2x/wk; ET: 2x/wk; CT: ST +ET separated days.	ST: multiple sets (40-90% 1RM). ET: 30 -60 min cycling below LVT_1, between VT_1 and VT_2, and above VT_2.	↑1RM in ST and CT (22%)***; ↑ VL +VM MT in ST and CT (9%)***. No difference among CT and ST.
Sillanpaä et al. 2009a	21 wk; ST: 2x/wk; ET: 2x/wk; CT: ST +ET separated days.	ST: multiple sets (40-90% 1RM). ET: 30 -60 min cycling below LVT_1, between VT_1 and VT_2, and above VT_2.	↑PT in ST and CT (15-17%)***. No difference among CT and ST.
Karavirta et al. 2009	21 wk; ST: 2x/wk; ET: 2x/wk; CT: ST +ET separated days.	ST: multiple sets (40-90% 1RM). ET: 30 -60 min cycling below LVT_1, between VT_1 and VT_2, and above VT_2.	↑1RM em TF e TC (22%)***. No difference among CT and ST.
Cadore et al. 2010	12 wk; ST: 3x/wk; ET: 3x/wk: CT: ST +ET, ET prior to ST at same session.	ST: 18-20RM progressing to 6-8RM. ET: 20-30 min cycling, 80 - 100% of FC at VT_2.	greater ↑1RM in ST (67%)*** than CT (41%)***; greater ↑ PT in ST (14%)* than CT (1%, NS). greater ↑EMG VL and RF in ST (30%)* than CT (16%, NS); greater ↑NEURO ECO* in ST than CT.
Holviala et al. 2010	21 wk; ST: 2x/wk; ET: 2x/wk; CT: ST +ET separated days.	ST: multiple sets (40-90% 1RM). ET: 30 -60 min cycling below LVT_1, between VT_1 and VT_2, and above VT_2.	↑1RM in ST and CT (22%)***. No difference among CT and ST. ↑EMG VL (18%)* and RF (14%)* in CT and ↑EMG VM (32%) in ST*. ↑PT in ST and CT (8-12%)*. No difference among CT and ST.
Holviala et al. 2012	21 wk; ST: 2x/wk; ET: 2x/wk; CT: ST +ET separated days.	ST: multiple sets (40-90% 1RM). ET: 30 -60 min cycling below LVT_1, between VT_1 and VT_2, and above VT_2.	↑ power at 50% 1RM (10%)**; ↑EMG VL and VM in ST (~25%)** and CT (23-33%)**; ↑ functional performance in ST and CT. No difference among CT and ST.
Karavirta et al. 2011	21 wk; ST: 2x/wk; ET: 2x/wk; CT: ST +ET separated days.	ST: multiple sets (40-90% 1RM). ET: 30 -60 min cycling below LVT_1, between VT_1 and VT_2, and above VT_2.	↑1RM in ST and CT (22%)***. ↑PT in ST and CT (14 e 20%)*; ↑EMG VM (41%)* and CT (28%)*. Greater ↑EMG VL in ST than CT in week 10, no differences between groups in week 21. ↑CSA of type II muscle fibers only in ST (16%)*.

Authors	Period and weekly frequency	Volume and intensity	Findings
Cadore et al. 2011a	12 wk; ST: 3x/wk; ET: 3x/wk: CT: ST +ET, ET prior to ST at same session.	ST: 18-20RM progressing to 6-8RM. ET: 20-30 min cycling, 80 - 100% of FC at VT_2.	↑ dynamic NEURO ECO* of RF in CT and ET at 50, 75 and 100W; and, in ST, CT and ET in the dynamic NEURO ECO* of VL at 100W.
Cadore et al. 2012a	12 wk; ST: 3x/wk; ET: 3x/wk: CT: ST +ET.	ST: 18-20RM progressing to 6-8RM. ET: 20-30 min cycling, 80 - 100% of FC at VT_2. CT performed with ET performed prior to (ES group) vs. after ST (SE group).	greater ↑force per unit of muscle mass in SE than ES (27 vs. 15%) ***. ↑MT QF similar in both groups (9%)***.
Cadore et al. 2012b	12 wk; ST: 3x/wk; ET: 3x/wk: CT: ST +ET.	ST: 18-20RM progressing to 6-8RM. ET: 20-30 min cycling, 80 - 100% of FC at VT_2. CT performed with ET performed prior to (ES group) vs. after ST (SE group).	greater ↑1RM in SE than ES***; (9%)***. ↑ MT of VL, VM, RF and VI in both groups (4-16%)***; ↑ EMG of VL and RF in both groups (16-22%) **; greater ↑NEURO ECO** of RF in SE than ES.

↑, increases; min, minutes; NEURO ECO, neuromuscular economy; 1RM, one maximum repetition; PT, isometric peak torque; CSA, cross-sectional area; MT, muscle thickness; QF, quadriceps femoris; VL, *vastus lateralis*; VM, *vastus medialis*; RF, *rectus femoris*; VI, *vastus intermedius*; wk, weeks; x/wk, training sessions per week; ST, strength training; ET, endurance training; CT, concurrent training; EMG, electromyographic signal; VT_1 and VT_2, first and second ventilatory threshold, respectively. Significant difference: *P<0.05; **P<0.01; ***P<0.001; NS, non significant.

Table 2: Key-points to prescribe strength and endurance training simultaneously.

- Strength training intensity should start with 40 - 50% of 1 RM (18 - 20RM) and progressing to 70 - 80% of 1 RM. This progression should occur during 12 or 21 weeks, depending of the weekly frequency.
- Endurance training intensity should start with 80% of the VT_2 (50-60% of VO_{2peak}), progressing to 100% of VT_2 (80% of VO_{2peak}).
- Strength training volume should start with 2 sets, progressing to 3 sets for each exercise.
- Endurance training volume can start with 20 to 30 min, progressing to 40 - 60 minutes.
- Weekly frequency could start with strength exercises on one day, and endurance exercise performed in cycle ergometer on the other, since cycling may warrant stimulus to induce neuromuscular adaptations in untrained elderly.
- Strength prior to endurance intra-session exercise sequence should be performed

1RM, one maximum repetition; VT_2, second ventilatory threshold; VO_{2peak}, Peak oxigen uptake.

FIGURE CAPTIONS:

Fig. 1: Maximal bilateral concentric 1RM half-squat at pretraining, after 8 and 16 wk of training for each subject. *Significantly different ($P < 0.05$) from the corresponding pretraining value; #significantly different ($P < 0.05$) from week 8 (Izquierdo et al. 2004).

Fig. 2: Strength prior to endurance exercise sequence results in greater maximal training load values during the training periodization (A); and, greater lower-body strength gains (kg), after 12 weeks of concurrent training (B). SE, strength prior to endurance training; ES, endurance prior to strength training. *Significant difference from pre training values ($P<0.001$). †Significant time vs. group interaction ($P<0.001$). Adapted from Cadore et al. 2012b.

Fig. 3: Muscle cross-sectional area of the quadriceps femoris muscle group for the strength, endurance and combined strength and endurance groups at pretraining and the subsequent 16 wk of training for each subject. *Significantly different ($P < 0.05$) from the corresponding pretraining value (Izquierdo et al. 2004).

Fig. 4: Neuromuscular economy (normalized EMG at 50% of pre-training MVC) of *rectus femoris.* SE, strength prior to endurance training; ES, endurance prior to strength training. *Significant difference from pre training values ($P <0.01$). †Significant time vs. group interaction ($P<0.01$) (Cadore et al. 2012b).

FIGURE 1:

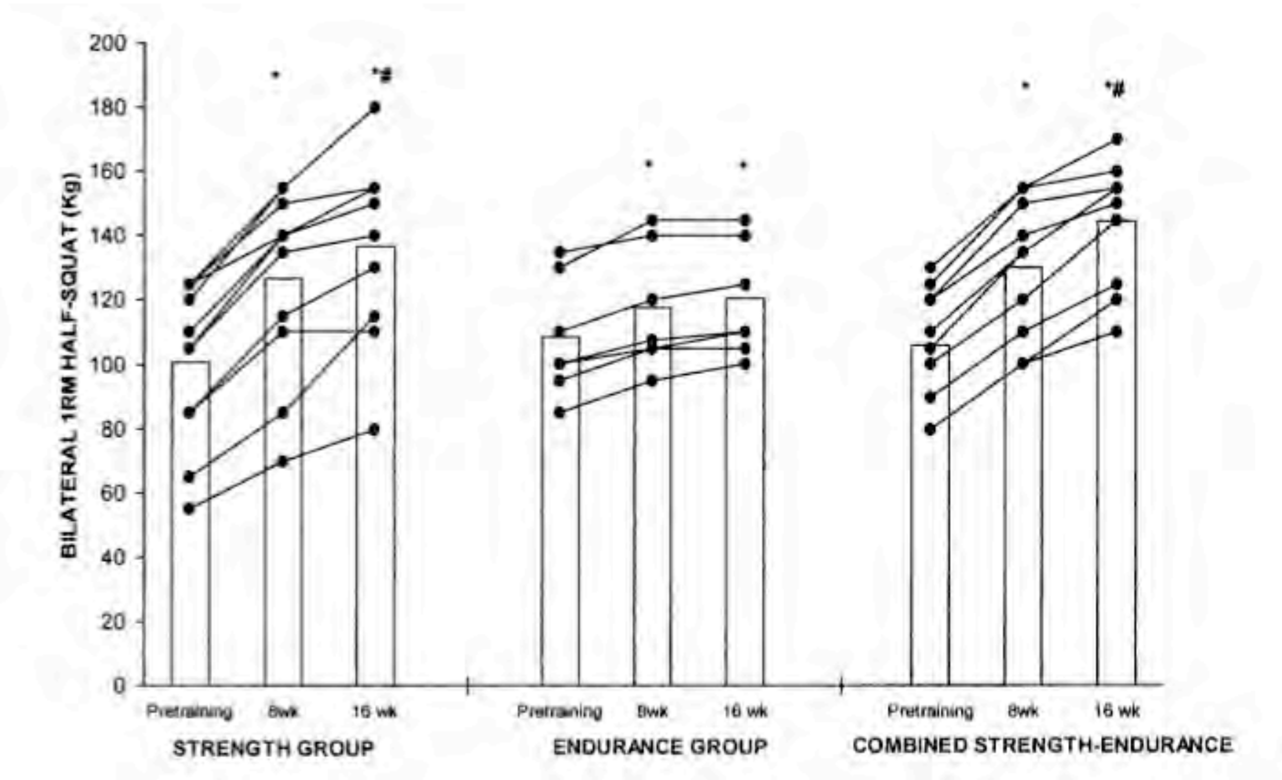
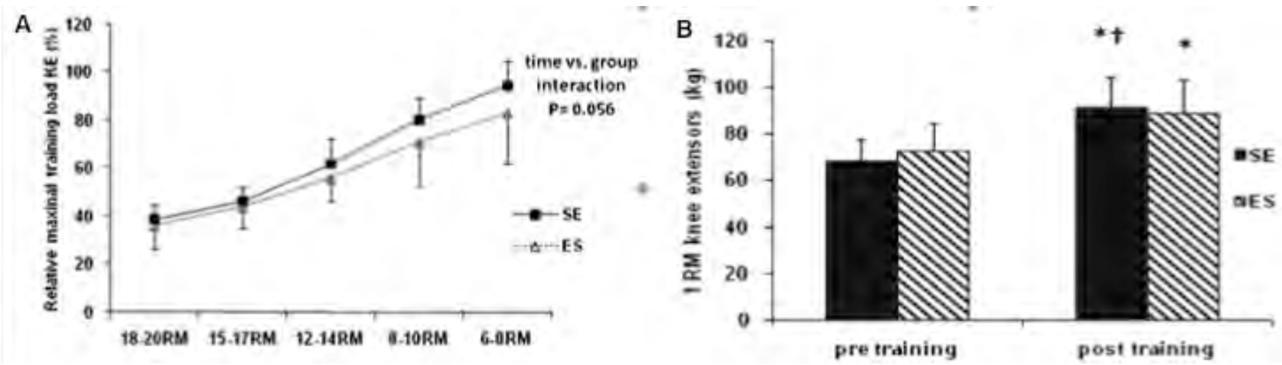


FIGURE 2:



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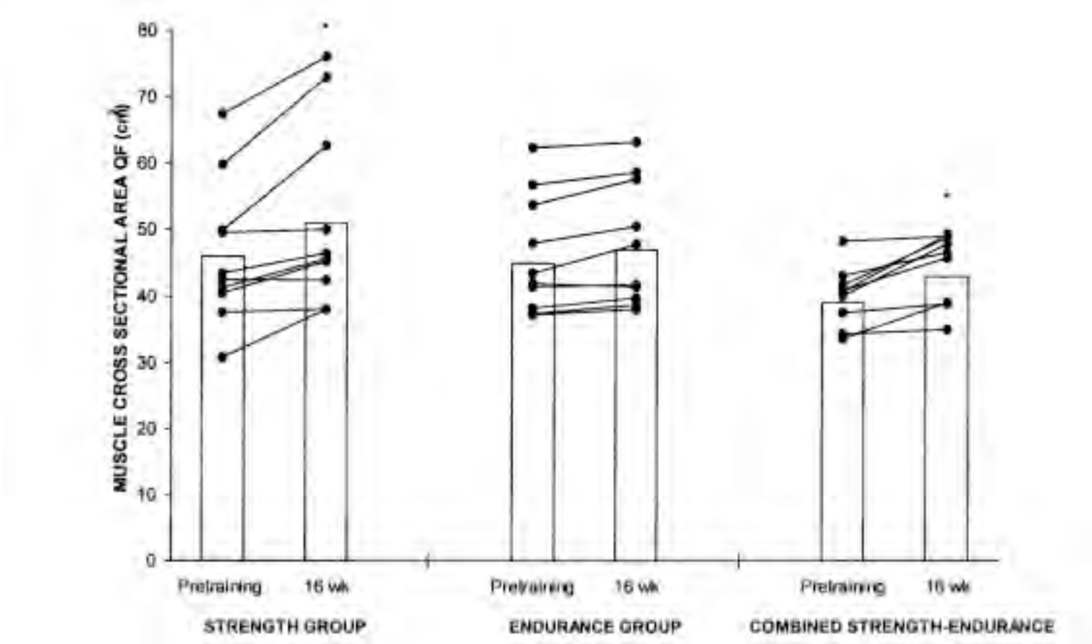
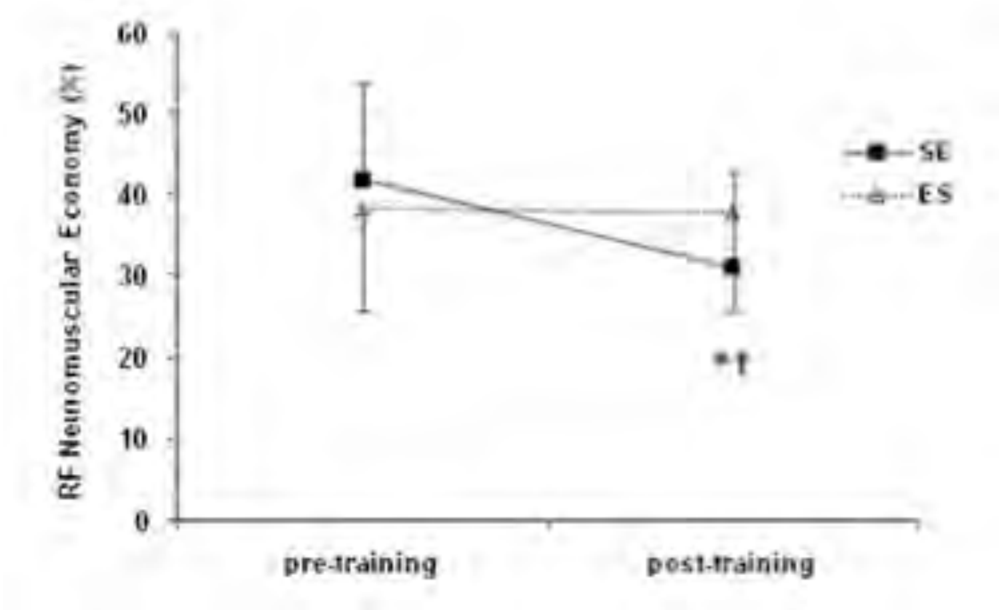


FIGURE 4:



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