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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 concurrent training adaptations in elderly populations, with the aim of identifying the optimal combination of both training program variables (i.e., strength and endurance) to avoid or minimize the interference effect in the elderly. Scielo, Science Citation Index, MEDLINE, Scopus, SPORTDiscus, and ScienceDirect databases were searched. Concurrent training is the most effective strategy by which to improve neuromuscular and cardiorespiratory functions as well as functional capacity in the elderly. The volume and frequency of training appears to play a critical role in concurrent training-induced adaptations in elderly subjects. Furthermore, new evidence indicates that the intra-session exercise order may influence the magnitude of physiological adaptations. Despite the interference effect on strength gains that is caused by concurrent training, this type of training is advantageous in that the combination of strength and endurance training produces both neuromuscular and cardiovascular adaptations in the elderly. The interference phenomenon may be observed in elderly subjects when a moderate weekly volume of concurrent training (i.e., three times per week) is performed. However, even with the occurrence of this phenomenon, the performance of three concurrent training sessions per week appears to optimize the strength gains in relative brief periods of training (12 weeks). Moreover, performing strength prior to endurance exercise may optimize both neuromuscular and cardiovascular gains.

Keywords Aging · Combined training · Physical training · Neural adaptations · Muscle mass

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 to maintain independent functioning (Fleg and Lakatta 1988; Izquierdo et al. 2001a, 2003; Christensen et al. 2009; Snijders et al. 2009; Aagaard et al. 2010). Recently, age-related declines in muscle power output have also emerged as an important predictor of functional limitations in older adults (Izquierdo et al. 1999a, b; 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

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training (i.e., concurrent training) in elderly populations appears to be the most effective strategy by which 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).

However, strength and endurance training are characterized by specific and different cardiovascular and neuromuscular adaptations. The primary adaptations to strength training include muscle cell hypertrophy (Kraemer et al. 1995), increased maximal motor unit recruitment (Knight and Kamen 2001), enhanced maximal motor unit firing rate (Kamen and Knight 2004), elevated spinal motoneuronal excitability, and increased efferent motor drive (Aagaard et al. 2002a, b). These neuromuscular adaptations result in enhanced strength and power performance (Izquierdo et al. 2001b; Peterson et al. 2010; García-Pallares and Izquierdo 2011; Correa et al. 2012). Moreover, strength training appears to promote cardiovascular adaptations at a lower magnitude than endurance training; however, small improvements may be observed in the VO_{2max} of elderly individuals who perform this type of training (Frontera et al. 1990). In contrast, endurance training induces central and peripheral adaptations that enhance VO_{2max} and the ability of skeletal muscles to generate energy via oxidative metabolism. These adaptations include enhanced mitochondrial biogenesis, myoglobin content, capillary density, substrate stores, and oxidative enzyme activities (Seals et al. 1984; Meredith et al. 1989), as well as enhanced maximal cardiac output (Beere et al. 1999). Moreover, endurance training results in small or no increases in muscle strength or hypertrophy (Izquierdo et al. 2004).

Certain studies have reported that the combination of strength and endurance training results in lower strength and power gains when compared with strength training alone—an effect that has been referred to as “the interference effect” (Kraemer et al. 1995; Bell et al. 1997, 2000; Häkkinen et al. 2003a; Cadore et al. 2010). This phenomenon may occur due to the negative influence of endurance training performance on strength training-induced neuromuscular adaptations (Dolezal and Potteiger 1998; Kraemer et al. 1995). Although several studies have focused on concurrent training in young populations (García-Pallarés et al. 2010; García-Pallares and Izquierdo 2011; Izquierdo-Gabarren et al. 2010; Cadore et al. 2012c; Silva et al. 2012), a limited number of studies have explored the effects of concurrent training on strength and endurance performance in older individuals (Izquierdo et al. 2004; Cadore et al. 2010, 2012a, b; Holviala et al. 2010; Sillampää et al. 2008; Karavirta et al. 2011). Certain studies have recently examined the influence of volume and intensity manipulation and the effects of the intra-session exercise sequence on concurrent training adaptations (Izquierdo et al. 2004, 2005; Cadore et al. 2010, 2011a, 2012a, b). New evidence and exercise strategies have indicated that intra-session exercise order may influence the magnitude of neuromuscular and cardiovascular adaptations in the elderly (Cadore et al. 2012a, b).

In addition to the relevant benefits in the neuromuscular and cardiovascular functions in healthy elderly, several studies have reported the positive effects of concurrent training on the treatment of diseases, such as diabetes (Umpierre et al. 2011), fibromyalgia (Valkeinen et al. 2008), 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 appears 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, given that muscle power is an important predictor of functional performance, strategies by which 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. Furthermore, the second purpose of this review was to describe the positive effects of concurrent training on physical fitness in elderly patients with cardiovascular, endocrine, and immune diseases.

Literature search

Search strategy

The Scielo, Science Citation Index, MEDLINE, Scopus, SPORTDiscus, and ScienceDirect databases were searched for studies that were published between 1980 and 2012 and that were based on original scientific investigations. The 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 the authors that are cited in certain studies were also utilized in the search.

Criteria for study consideration: types of studies, outcome measures, and participants

The search criteria were as follows: (1) the studies must be from English peer-reviewed scholarly journals; (2) dissertations, theses, and conference proceedings were excluded; (3) the studies must refer to the effects of concurrent training, strength training and endurance training, or the effects of different combination of concurrent training variables in the elderly (i.e., volume, intensity, and intra-session exercise order); (4) only randomized studies using technical procedures for which the validity and reliability have been reported in the literature were included (i.e., low intra-measure coefficients of variation and high intra-class correlation coefficients); and (5) the studies were included if the type of participants was older men and women, with a mean age of ≥55 years.

Inclusion of studies

From the preliminary search, the titles of 939 manuscripts were read, and 107 were selected for a second analysis, which included the reading of the abstracts. Twelve original research studies that investigated the effects of concurrent training in the elderly were included, and their results were described. From these studies, 10 compared the effects of concurrent training with strength training and endurance training that were performed alone (Wood et al. 2001; Izquierdo et al. 2004; Sillampää et al. 2008, 2009a, b; Cadore et al. 2010, 2011a; Holviala et al. 2010, 2011; Karavirta et al. 2009, 2011), and two studies compared different types of concurrent training (Cadore et al. 2012a, b).

Analytical methods

To analyze the effects of concurrent training on neuromuscular variables (i.e., maximal strength and power, hypertrophy, as well maximal and submaximal neuromuscular activity), the magnitude of such adaptations was described and compared with the magnitude of the adaptations that were induced by strength training alone or by different methods of concurrent training prescription (i.e., different intra-session exercise sequence). In addition, to analyze the effects of concurrent training on cardiorespiratory variables (i.e., VO_{2max} and maximal and submaximal aerobic powers), the magnitude of such adaptations was described and compared with the magnitude of the adaptations that were induced by endurance training alone or by two methods of concurrent training prescription. Furthermore, the magnitude of neuromuscular and cardiovascular adaptations was compared between different studies to describe possible differences that were related to concurrent training variables, such as volume, intensity, weekly frequency, and intra-session exercise order.

The 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 elderly subjects (Izquierdo et al. 2004; Cadore et al. 2010; Karavirta et al. 2011). The majority of the studies reported that concurrent training induced similar strength adaptations using two sessions per week of each modality on separate days (i.e., strength and endurance) when compared with strength training alone (Holviala et al. 2010; Sillampää et al. 2008; Karavirta et al. 2011). However, concurrent training sessions three times per week can result in an interference effect in the elderly, because greater strength gains are observed in the strength training group when compared with the concurrent training group when this weekly frequency is performed (Cadore et al. 2010). 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 demonstrated 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, b). Table 1

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

Authors	Period (weeks)	Weekly frequency	Volume and intensity	Findings
Wood et al. (2001)	12	ST: 3x/wk	ST: 2 sets, 12–15 rep (75 % 5RM) of 8–12RM	ST: ↑ 5RM (44 %)*
		ET: 2x/wk	ET: 60–70 % of FC$_{max}$ estimated, 20–45 min cycling	CT: ↑ 5RM (38 %)*
		CT: ST+ET	CT: 1 set of 8–12RM+30 min cycling	No difference between CT and ST
Izquierdo et al. (2004)	16	ST: 2x/wk	ST: 3–5 sets, 6–15 rep (50–80 % 1RM) slow+fast contractions (20 % of total volume, 30–50 % of 1RM)	ST: ↑ 1RM (41 %)**; ↑ muscle power (37 %)*. ↑ CSA QF (11 %)*
		ET: 2x/wk	ET: 30–40 min cycling, at loads (W) of 2, 3, and 4 mmolL^{-1} of lactate	CT: ↑ 1RM (38 %)**; ↑ muscle power (38 %)*. ↑ CSA QF (11 %)*
		CT: 1x/wk ST+ 1x/wk ET		No differences between CT and ST
(Sillampää et al. 2008)	21	ST: 2x/wk	ST: multiple sets (40–90 % 1RM)	ST: ↑ 1RM (22 %)***; ↑ QF MT (9 %)***
		ET: 2x/wk CT: ST+ET at separated days	ET: 30–60 min cycling below LVT$_1$, between VT$_1$ and VT$_2$, and above VT$_2$	CT: ↑ 1RM (23 %)***; ↑ QF MT (9 %)***
		No difference between CT and ST		
(Sillampää et al. 2009a)	21	ST: 2x/wk	ST: multiple sets (40–90 % 1RM)	ST: ↑ PT (15 %)***
		ET: 2x/wk	ET: 30–60 min cycling below LVT$_1$, between VT$_1$ and VT$_2$, and above VT$_2$	CT: ↑ PT (17 %)***
		CT: ST+ET on separate days		No difference between CT and ST
Karavirta et al. (2009)	21	ST: 2x/wk	ST: multiple sets (40–90 % 1RM)	ST: ↑ 1RM (21 %)***
		ET: 2x/wk	ET: 30–60 min cycling below LVT$_1$, between VT$_1$ and VT$_2$, and above VT$_2$	CT: ↑ 1RM (22 %)***
		CT: ST+ET on separate days		No difference between CT and ST
Cadore et al. (2010)	12	ST: 3x/wk	ST: 18–20RM progressing to 6–8RM	ST: ↑ 1RM (67 %)***; ↑ PT (14 %)*; ↑ EMG QF (30 %)*
		ET: 3x/wk	ET: 20–30 min cycling, 80–100 % of FC at VT$_2$	CT: ↑ 1RM (41 %)***
		CT: ST+ET, ET prior to ST at the same session		ST had greater increases in the 1RM, PT, and EMG than CT
Holviala et al. (2010)	21	ST: 2x/wk	ST: multiple sets (40–90 % 1RM)	ST: ↑ 1RM (20 %)***; ↑ PT (10 %)*; ↑ EMG QF (31 %)*
		ET: 2x/wk	ET: 30–60 min cycling below LVT$_1$, between VT$_1$ and VT$_2$, and above VT$_2$	CT: ↑ 1RM (21 %)***; ↑ PT (13 %)*; ↑ EMG QF (15–17 %)*
		CT: ST+ET on separate days		No difference among CT and ST
Holviala et al. (2011)	21	ST: 2x/wk	ST: multiple sets (40–90 % 1RM)	ST: ↑ power (6 %)**; ↑ EMG QF (~25 %)**
		ET: 2x/wk	ET: 30–60 min cycling below LVT$_1$, between VT$_1$ and VT$_2$, and above VT$_2$	CT: ↑ power (10 %)**; ↑ EMG QF (23–33 %)**
		CT: ST+ET on separate days		No difference among CT and ST
Karavirta et al. (2011)	21	ST: 2x/wk	ST: multiple sets (40–90 % 1RM)	ST: ↑ 1RM (21 %)***; ↑ PT (14 %)*; ↑ EMG QF (35–41 %)*; ↑ CSA of type II muscle fibers (16 %)*
		ET: 2x/wk	ET: 30–60 min cycling below LVT$_1$, between VT$_1$ and VT$_2$, and above VT$_2$	CT: ↑ 1RM (22 %)***; ↑ PT (20 %)*; ↑ EMG QF (11–18 %)*; no changes on CSA

Table 1 (continued)

Authors	Period (weeks)	Weekly frequency	Volume and intensity	Findings
		CT: ST+ET on separate days		Greater ↑ EMG VL in ST than CT in week 10, but no differences between the groups in week 21
Cadore et al. (2011a)	12	ST: 3x/wk	ST: 18–20RM progressing to 6–8RM	ST: ↑ dynamic NEURO ECO at 100 W of VL (14 %)*
		ET: 3x/wk CT: ST+ET, ET prior to ST at the same session	ET: 20–30 min cycling, 80–100 % of FC at VT_2	CT: ↑ dynamic NEURO ECO at 100 W of VL (10 %)* and 50, 75, and 100 W of RF (14–35 %)**
Cadore et al. (2012a)	12	ST: 3x/wk	ST: 18–20RM progressing to 6–8RM	SE: ↑ force per unit of muscle mass (27 %)***; ↑ MT QF (9 %)***
		ET: 3x/wk	ET: 20–30 min cycling, 80–100 % of FC at VT_2	ES: ↑ force per unit of muscle mass (15 %)***; ↑ MT QF (9 %)***
		CT: ST+ET	CT performed with ET performed prior to (ES group) vs. following ST (SE group)	Greater changes in the SE than in the force per unit of muscle mass (27 vs. 15 %)**
Cadore et al. (2012b)	12	ST: 3x/wk	ST: 18–20RM progressing to 6–8RM	SE: ↑ 1RM (35 %)***; ↑ PT (8 %)*; ↑ MT of VL, VM, RF, and VI (4–16 %)***; ↑ QF EMG (~20 %)**; ↑ NEURO ECO** of RF in SE (22 %)
		ET: 3x/wk	ET: 20–30 min cycling, 80–100 % of FC at VT_2	ES: ↑ 1RM (21 %)***; ↑ PT (5.7 %)*; ↑ MT of VL, VM, RF, and VI (4–16 %)***; ↑ QF EMG (~20 %)**
		CT: ST+ET	CT performed with ET performed prior to (ES group) vs. following ST (SE group)	Greater changes in the SE than in the 1RM (35 vs. 21 %)**

↑ 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, x/wk training sessions per week, ST strength training, ET endurance training, CT concurrent training, EMG electromyographic signal, VT_1 first ventilatory threshold, VT_2 second ventilatory threshold, NS nonsignificant

*$P<0.05$; **$P<0.01$; ***$P<0.001$

summarizes the methods that were applied and the results that were observed in the studies that investigated concurrent training adaptations in the elderly.

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 strength training groups performing two sets and the concurrent training group performing only one set in addition to the endurance training. These authors observed similar strength gains for 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 strength training and endurance training groups performed specific training twice per week, and the concurrent training group performed strength exercises on one day and cycle ergometer exercises on the other day. These authors demonstrated that, after 16 weeks of training, similar lower body strength gains were observed in both the strength and concurrent training groups, suggesting that a minimum weekly frequency of concurrent training (one session per week of strength and one session per week of cycle endurance training) may be an optimal stimulus by which to promote strength gains in previously untrained elderly subjects (Izquierdo et al. 2004). Figure 1 shows the magnitude of strength gains after 16 weeks of strength, endurance, and concurrent training, with no difference in the

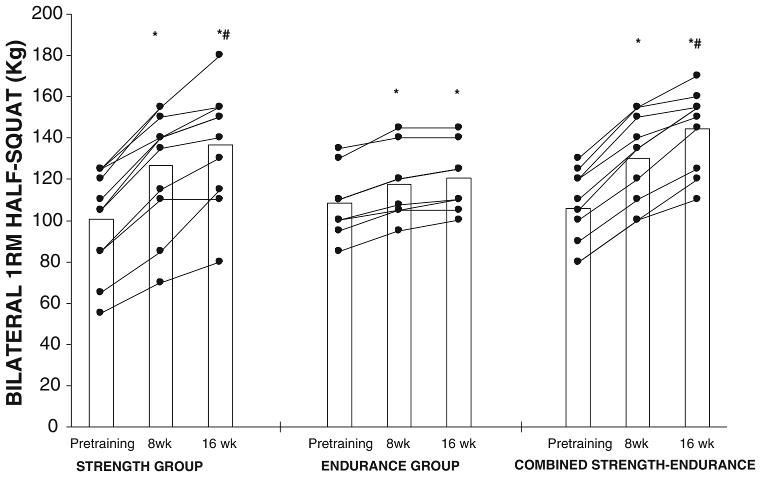

Fig. 1 Maximal bilateral concentric 1 RM half-squat at pretraining, after 8 and 16 weeks of training for each subject. *$P<0.05$, significantly different from the corresponding pretraining value; #$P<0.05$, significantly different from week 8 (Izquierdo et al. 2004)

strength gains being observed between the strength and concurrent training groups (Izquierdo et al. 2004). Notably, similar results were observed in middle-aged subjects (Izquierdo et al. 2005), reinforcing the idea that this strategy improves strength performance in early phases of concurrent training.

Using similar training volumes for strength training and concurrent training groups, Karavirta et al. (2009, 2011) observed similar isometric (14–20 %) and dynamic strength gains (approximately 22 %) and similar improvements in maximal concentric power (approximately 16 %) in the study groups after 21 weeks of training twice per 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 strength training and concurrent training groups in older men (Holviala et al. 2010, 2011; Sillampää et al. 2008, 2009a) and older women (Sillampää et al. 2009b). It should be noted that in these abovementioned studies (Sillampää et al. 2008; Holviala et al. 2010; Karavirta et al. 2011), the strength and endurance training were performed on separate days, which may have prevented the influence of the residual fatigue of one type of exercise on the subsequent performance of the other. Thus, the performance of both types of exercise on alternate days may be an effective strategy by which to avoid the interference effect of endurance training on strength training-induced strength gains.

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 %). In contrast, similar upper body strength gains were observed in the strength and concurrent training groups (30–33 %). Moreover, increases in the maximal isometric force were observed only in the strength training 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., the lower limbs).

Notably, in the study by Cadore et al. (2010), although an interference effect was observed in the concurrent training 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, Sillampää 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 were explained by the different weekly frequencies of the training performed. The subjects of Cadore et al. (2010) performed three training sessions per week, in contrast to subjects in other previous studies, in which two training sessions per week were performed (i.e., ~30 % lower volume) (Karavirta et al. 2009, 2011; Holviala et al. 2010, 2012; Sillampää et al. 2008, 2009a). It is possible that this greater weekly training frequency results in more rapid strength development in strength training and concurrent training, even with the occurrence of the interference effect in the concurrent training group. Thus, as these strength gains are similar than those that were observed when a lower weekly frequency (twice per week) is used over longer periods of training (21 weeks), the performance of three concurrent training sessions per week appears to optimize the strength gains during a shorter period of training (12 weeks).

Intra-session exercise sequence

Another factor that is related to the concurrent training session and which 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 concurrent training group that performed strength training prior to endurance exercise when compared with the group that performed the training in the reverse order (Cadore et al. 2012a, b). These results were observed after 12 weeks of concurrent training using a training periodization which had previously been demonstrated to induce an interference effect (Cadore et al. 2010). It may be suggested that lower strength gains that were obtained following the endurance–strength exercise (ES) sequence may be related to the ES group's lower workloads during the training periodization. These differences were more evident when the volume per exercise during the strength training was between 10 and 6 maximum repetition (RM) and the endurance intensity was near to the second ventilatory threshold. Figure 2 shows the time course of strength training load development (i.e., maximal training load at different mesocycles) during the periodization of the training groups that performed strength prior to endurance exercise sequence or the reverse order (Fig. 2a). Also shown are the different magnitudes of maximal strength gains (i.e., one maximal repetition values) that were induced by these different intra-session exercise sequences (Fig. 2b) (Cadore et al. 2012b).

In summary, based on the results observed regarding strength and power gains induced by concurrent training in the elderly, the following may be suggested: (1) performing a minimum weekly frequency of concurrent training (one session per week of strength and one session per week of cycle endurance training) may be an optimal stimulus by which to promote strength gains in previously untrained elderly subjects (Izquierdo et al. 2004); (2) moderate weekly frequency (three times per 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 (3) 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 the endurance intra-session exercise sequence (Cadore et al. 2012a, b). Table 2 provides guidelines for prescribing strength and endurance training simultaneously to optimize neuromuscular and cardiovascular function in elderly populations.

The effects of concurrent training on muscle hypertrophy

Muscle hypertrophy

Studies that have investigated 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 strength training (twice per week) and the concurrent training groups (one session per week of strength and one session per week of cycle endurance training) with respect to the magnitude of hypertrophy after 12 weeks of training (approximately 11 %). A unique finding of this previous study was that only 1 day of strength training in combination with another day of endurance training performed using cycle ergometer resulted in enhanced muscle mass in the elderly after 16 weeks (Fig. 3).

In a study by 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 strength training group (~16 %), whereas no changes were observed in the concurrent training group. Nevertheless, as previously mentioned, this difference did not result in a difference in strength gains. In other studies using training weekly frequency that ranged from two to three sessions, 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 strength training and concurrent training regimes (Holviala et al. 2010, 2012; Sillampää et al. 2008, 2009a). Moreover, although the intra-session exercise sequence influenced strength adaptations, it is important to note that the sequence of

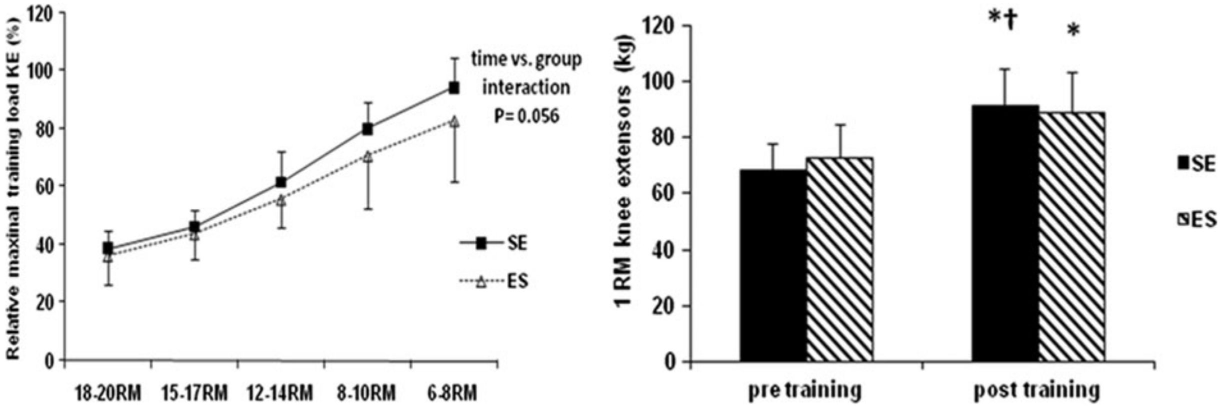

Fig. 2 Strength prior to endurance exercise sequence results in greater maximal training load values during training periodization (**a**) and greater lower body strength gains (kilogram) after 12 weeks of concurrent training (**b**). *SE* strength prior to endurance training, ES endurance prior to strength training. *$P<0.001$, significant difference from pretraining values. †$P<0.001$, significant time vs. group interaction. Adapted from Cadore et al. (2012b)

strength and endurance exercise did not influence muscle mass gains (Cadore et al. 2012b). Thus, independent of the intra-session exercise sequence, the performance of endurance training does not impair strength training-induced hypertrophy when both types of training are performed simultaneously.

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 studies that have been conducted in young populations, as no difference was observed between the strength training and concurrent training groups when imaging techniques 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 concurrent training 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

Table 2 Key points to prescribe strength and endurance training simultaneously

Training type	Weekly frequency	Volume	Intensity	Exercise sequence
Strength training	Should begin with 1 session, progressing to 2–3 sessions following 8 weeks	Should begin with 2–3 sets of 15–20 repetitions for each exercise	Should begin with 40–50 % of 1RM, progressing to 70–80 % of 1RM. If the maximum repetition (RM) method is elicited, training should begin with 18–20RM, progressing to 6–8RM	Should be performed prior to endurance training
Endurance training	Should begin with 1 session, progressing to 2–3 sessions after 8 weeks	Should begin with 20 to 30 min, progressing to 40–60 min	Should begin with 80 % of the VT_2 (50–60 % of VO_{2peak}), progressing to 100 % of VT_2 (80 % of VO_{2peak})	Should be performed following strength training

1RM one maximum repetition, VT_2 second ventilatory threshold, VO_{2peak} peak oxygen uptake

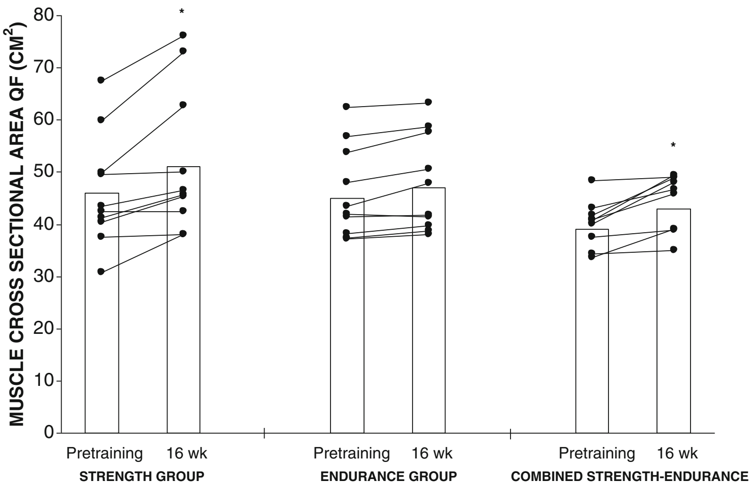

Fig. 3 Muscle cross-sectional area of the quadriceps femoris muscle group for the strength, endurance, and combined strength and endurance groups at pretraining and following 16 weeks of training for each subject. *$P<0.05$, significantly different from the corresponding pretraining value (Izquierdo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

strength training group, whereas no changes were observed in the concurrent training group. Notwithstanding these results, no changes in the basal anabolic or catabolic hormone levels were evidenced in this previous study (Karavirta et al. 2011). Moreover, 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. Hence, it may be concluded that a weekly training volume that is composed of as many as three sessions of concurrent training does not result in overtraining in the elderly.

The 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, b, 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 motoneuronal excitability, and efferent motor drive (Aagaard et al. 2002a, b).

Although neural adaptation impairments are suggested to be a mechanism by which to explain the interference effect, only a small number of studies have investigated the neural adaptations that occur in response to concurrent training. In young subjects, no difference has been observed in the maximal EMG amplitude adaptations among strength training and concurrent training 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, the interference effect in elderly subjects may be related to impaired neural adaptations to strength training. This conclusion could be reached given that lower concurrent training-induced strength gains when compared with strength training alone may occur in parallel with lower maximal neuromuscular activity adaptations that are induced by concurrent training (Cadore et al. 2010).

Investigating the mechanisms that underlie the strength adaptations to strength and concurrent training 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 strength training group (approximately 30 %), and these modifications were significantly greater than those that were observed in the concurrent training group (1.5 %, nonsignificant). In addition, greater isometric neuromuscular economy (i.e., reduced submaximal EMG to the same absolute load following training) was observed in the rectus femoris and vastus lateralis only in the strength training group. It is important to highlight that the greater neuromuscular activity changes that were observed in the strength training than in the concurrent training group occurred in parallel with greater strength gains in strength training (Cadore et al. 2010), suggesting that the interference effect occurred at least in part due to impairments in neural modifications.

Recently, Cadore et al. (2012a) reported 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 reverse order (27 vs. 15 %, $P<0.01$). As enhanced strength with the same muscle mass suggests neural adaptations to training, the force per unit of active muscle mass provides an estimation of the contribution of neuromuscular factors that are associated with changes in strength development (Tracy et al. 1999; Frontera et al. 2000; Reeves et al. 2004; Narici et al. 2005). In another study, Cadore et al. (2012b) reported 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 reverse order. Figure 4 shows an example of the influence of the intra-session exercise order on the neural adaptations to concurrent training (Cadore et al. 2012b). Altogether, these results suggest that the interference effect in the elderly may be explained at least in part by impairments in the neural adaptations to strength training. From a practical perspective, although the concurrent training performance may impair neuromuscular adaptations, the performance of strength prior to endurance intra-session exercise sequence appears to minimize this negative effect and should be considered to optimize the benefits of concurrent training in terms of neuromuscular function in the elderly.

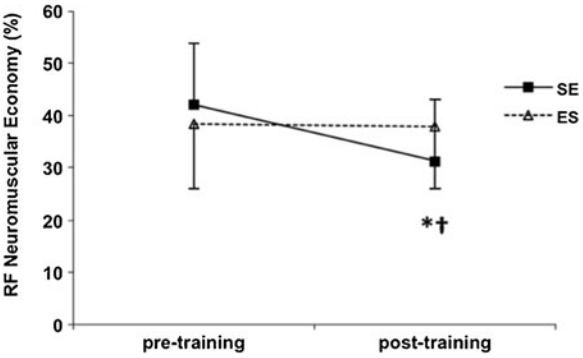

Fig. 4 Neuromuscular economy (normalized EMG at 50 % of pretraining MVC) of rectus femoris. SE strength prior to endurance training, ES endurance prior to strength training. *$P<0.01$, significant difference from pretraining values. †$P<0.01$, significant time vs. group interaction (Cadore et al. 2012b)

The effects of concurrent training on cardiovascular performance

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, which is caused by the (1) a reduction in the maximum stroke volume, (2) decreased heart rate, and (3) changes in the arteriovenous oxygen difference (Astrand et al. 1973; Fleg and Lakatta 1988). 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, 2012d). In a study by Izquierdo et al. (2001a), 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) reported 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 reported that the combination of strength and endurance training is a better strategy by which to improve the cardiovascular performance of the elderly when compared with strength training alone. Moreover, the performance of strength training simultaneously with endurance training does not impair the cardiovascular adaptations that are produced by endurance training alone (Wood et al. 2001; Izquierdo et al. 2004; Karavirta et al. 2009, 2011; Holviala et al. 2010, 2012; Sillampää et al. 2008, 2009a; Cadore et al. 2011b).

Studies that have investigated cardiovascular adaptations to concurrent training have demonstrated increases ranging from 10 to 18 % in the maximum oxygen uptake and maximal cycle ergometer workload in elderly participants who underwent training periods that ranged from 12 to 21 weeks with a weekly frequency ranging from two to three training sessions (Wood et al. 2001; Izquierdo et al. 2004; Sillampää et al. 2009; Holviala et al. 2010; Cadore et al. 2010;

Karavirta et al. 2011). In the study by Sillampää et al. (2008), elderly participants who performed concurrent training twice per week achieved similar VO_{2max} increases when compared with endurance training alone after 21 weeks of training (11 vs. 11 %, respectively). Similarly, Karavirta et al. (2009) observed no difference between cardiovascular adaptations induced by concurrent training and endurance training alone in elderly men after 21 weeks of training (10 vs. 12 %, respectively). In another study that used three training sessions per week, Cadore et al. (2010) observed that both concurrent training and endurance training alone resulted in the same magnitude of VO_{2max} and maximal cycle ergometer workload after 12 weeks of training in the elderly (20.4 vs. 22 %, respectively). In these previous studies, only slight VO_{2max} changes were observed when the elderly performed strength training alone, reinforcing the idea that the combination of strength and endurance training in the elderly is necessary to improve both neuromuscular and cardiorespiratory functions.

Similar to the previously mentioned results that were observed for strength performance and hypertrophy, Izquierdo et al. (2004) observed similar aerobic power gains in elderly men who underwent one session per week of strength training and one session per week of cycle endurance training in the concurrent training group (28 %) and those who underwent endurance training twice per week (23 %) after 16 weeks of training. Similar results were observed in middle-aged subjects (12 vs. 14 % in concurrent and endurance training, respectively), suggesting that a minimum weekly frequency of concurrent training may be an optimal stimulus by which to promote cardiovascular gains in early phases of training in previously untrained middle-aged and elderly subjects.

The effects of intra-session exercise sequence

Another interesting finding is the influence of intra-session exercise order on cardiovascular adaptations. In the study by Cadore et al. (2012a), similar enhancements were observed in peak oxygen uptake, maximal workload at cycle ergometer, and the workload at second ventilatory threshold for groups that performed strength training prior to an endurance exercise sequence and the reverse exercise order. However, greater improvement was observed in the workload at the first ventilatory threshold in the group that strength-trained prior to endurance exercise in each session. 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), it is possible that this difference occurred due to the greater increases in muscle strength that were achieved by performing strength training prior to endurance training. If so, from a practical standpoint, given that several functional activities are performed at lower aerobic intensities, performing strength training prior to endurance exercise may be more beneficial for improving functional activities (Hartman et al. 2007).

The effects of concurrent training on functional capacity

Few studies have compared the effects of strength, endurance, and concurrent training on the functional capacity of the elderly. In the investigation of Wood et al. (2001), no differences were observed between strength, endurance, and concurrent training groups in terms of functional performance gains as assessed using the sit and reach test. Neither were differences observed in agility/dynamic balance, as assessed by coordination tests and by having the participants repeatedly stand up from a chair, walk around cones, and return to the chair. Holviala et al. (2010) reported increases in the treadmill load carrying walking test performance (10.1 kg in each hand) only in the concurrent training group (4.5 %), whereas no changes were observed in the strength training and endurance training groups. These results suggested that only the combination of strength and endurance capacities improved the performance on this test.

Long-term concurrent training programs

Despite the limited number of studies comparing the effects of strength training, endurance training, and concurrent training 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; Izquierdo et al. 2012). In the study by Rejeski et al. (2009), 2 years of combined endurance and strength training resulted in an improved 400-m walking speed and physical performance battery that included balance, 4 m 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 5 years of a physical therapy program that was composed of strength and endurance training in elderly men and women who had experienced surgical repair of a proximal femur fracture.

The role of muscle power in improving functional capacity

In view of improving the concurrent strength and endurance training prescription, results concerning the effects of combining slow and explosive mode contractions in the strength training program should be considered to optimize 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, the rates of force development and rapid muscle activation, and maximal dynamic strength (Häkkinen et al. 2001; Izquierdo et al. 2001a). Moreover, certain studies have reported 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; Correa et al. 2012; 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) reported greater increases in functional performance with a strength training protocol that was performed with explosive muscle contractions when compared with a traditional strength training group (i.e., only slow contractions). Thus, muscle power appears to be a more important predictor of functional performance than muscle strength in the elderly. An example of concurrent training prescription using typical explosive strength training was presented in study of Karavirta et al. (2011). These authors divided 21 weeks of training periodization into three blocks of 7 weeks. For this protocol, 20 % of the knee extensors training volume was used in the last block (i.e., leg press and knee extension exercises) to perform sets of five to eight repetitions with 40–50 % of 1RM at the maximal possible speed. Both strength training and concurrent training programs improved the maximal concentric power to the same extent, suggesting that the simultaneous performance of endurance and strength training did not compromise the power gains. Hence, the performance of strength training that combine high with slow velocity of contractions may be included in the concurrent training prescription, with no impairment on power gains magnitude. This result may have an important practical application given that power development is associated with enhanced functional performance.

The role of concurrent training in disease treatment

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

Several studies have demonstrated the beneficial effects of the simultaneous performance of strength and endurance training in elderly individuals with 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×12 repetitions+6 days of cycling (~17 min)+5 days of walking (45 min) vs. 3 sets×15 repetitions+6 days of cycling (~17 min)+5 days of walking (45 min)] (Berent et al. 2012). Moreover, the discontinuation of the concurrent training program increased these patients' cardiovascular risk (Berent et al. 2011). 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 given that, in addition to declines in muscle strength, menopause is associated with increased arterial stiffness. In another study, concurrent training improved the physical capacity of patients with peripheral arterial disease (Mosti et al. 2011).

In patients with type II diabetes, significantly improved glycemic control and declines in the hemoglobin A_{1c} have been observed following concurrent training programs (Balducci et al. 2004; Church et al. 2010). Moreover, a recent meta-analysis reported that strength, endurance, or concurrent training performed for a minimum of 12 weeks, with weekly exercise of more than 150 min, was associated with improved glycemic control and declines in the hemoglobin A_{1c} (Umpierre et al. 2011). It should be highlighted that several patients with type II diabetes in this meta-analysis were approximately 60 years of age (Umpierre et al. 2011).

Other studies have demonstrated the beneficial effects of concurrent training on physical fitness and functional capacity in patients with several diseases, such as fibromyalgia (Valkeinen et al. 2008), 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; Gary et al. 2012). All of these studies indicated the safety and efficacy of concurrent training in improving the functional capacity of patients with these diseases.

Conclusions

The combination of strength and endurance training in the elderly is the optimum strategy by which to improve both neuromuscular and cardiorespiratory functions and, consequently, to maintain functional capacity during aging. In addition, patients with any of 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 can be observed in elderly subjects when a moderate weekly volume of concurrent training (i.e., three times per week) is performed. This interference phenomenon appears 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 cardiovascular function, as follows:

- The performance of a minimum weekly frequency of concurrent training (one session per week of strength training and one session per week of cycle endurance training) may be an excellent stimulus by which 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 also be 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;
- With respect to improving the functional capacity of the elderly, skeletal muscle power has been strongly associated with the functional capacity of this population; therefore, the concurrent strength and endurance training prescription should include explosive mode contractions as part of the strength training program.

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