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ORIGINAL ARTICLE

Adaptations in mechanical muscle function, muscle morphology, and aerobic power to high-intensity endurance training combined with either traditional or power strength training in older adults: a randomized clinical trial

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Abstract

Purpose There is a lack of information on the effects of power training (PT) as an alternative to traditional strength training (TST) during concurrent training (CT) in older individuals. This study aimed to verify the neuromuscular adaptations that occurred following 16-week interventions with two CT models in older men: high-intensity interval training (HIIT) combined with either TST or PT.

Methods Thirty-five older men (65.8 ± 3.9 years) were randomly assigned into one of two training groups CTS: TST + HIIT (n = 18) or CTP: PT + HIIT (n = 17). CTS performed resistance training at intensities ranging from 65 to 80% of 1 RM at slow controlled speed, whereas CTP trained at intensities ranging from 40 to 60% of 1 RM at maximal intentional speed. Lower body one-repetition maximum (1 RM), isometric rate of force development (RFD), countermovement jump (CMJ) muscle power output, quadriceps femoris muscles thickness (QF MT), and peak oxygen uptake (VO_{2peak}) were assessed before training and after 8 and 16 weeks of CT.

Results Groups improved similarly in all primary outcomes ($P < 0.05$), with mean increases ranging: 1 RM (from 39.4 to 75.8%); RFD (from 9.9 to 64.8%); and CMJ muscle power (from 1.8 to 5.2%). Significant increases ($P < 0.05$) were observed in all secondary outcomes (QF MT, specific tension and VO_{2peak}) with no differences between groups.

Conclusion CT models were effective for improving maximal and explosive force (1 RM, RFD, and CMJ power), QF MT, and VO_{2peak}. Moreover, despite that using lower loading intensities, PT induced similar adaptations to those of TST.

Keywords Concurrent training · Explosive force · HIIT · Aging · Functional capacity

Abbreviations

ANOVA	Analysis of variance
CMJ	Countermovement jump
CT	Concurrent training
CTP	Concurrent training composed by power-type strength training
CTS	Concurrent training composed by traditional strength training
ES	Effect size
HIIT	High-intensity interval training
HR_{max}	Maximal heart rate
KE	Knee extension exercise
LP	Leg press exercise
MIVC	Maximal isometric voluntary contraction
MT	Muscle thickness
PT	Power training
QF	Quadriceps femoris
1 RM	One maximum repetition
RF	Rectus femoris
RFD	Rate of force development
SD	Standard deviation

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TST	Traditional strength training
VL	Vastus lateralis
VM	Vastus medialis
RF	Rectus femoris
VO_{2peak}	Peak oxygen uptake

Introduction

The aging process is characterized by gradual declines in maximal strength, muscle power, and cardiorespiratory capacity (Izquierdo et al. 1999; Fleg and Lakatta 1988), resulting in impairments in intrinsic capacity and increased mortality risk for this population (Artero et al. 2012). Muscle power output and explosive force (i.e., the rate of force development) seem to be strongly associated with the performance of activities of daily living, but these capacities decline faster than maximal strength in older individuals (Izquierdo et al. 1999; Reid and Fielding 2012; Cadore et al. 2018a). Because of this, it has been suggested that strength training performed at maximal intentional speed in the concentric phase (i.e., power training—PT) is an effective and safe strategy for minimizing aging decline and promoting increases in the muscle power output, rate of force development, and maximal strength (Izquierdo et al. 1999; Caserotti et al. 2008; Reid and Fielding 2012; Cadore et al. 2018a).

Previous studies comparing the effects of PT and traditional strength training (TST) on functional performance in older individuals have shown superior improvements in functional tests following PT (Miszko et al. 2003; Bottaro et al. 2007; Tschopp et al. 2011; Ramirez-Campillo et al. 2014). However, there is a lack of studies in the literature comparing the effects of these two strength training models when combined with endurance training (i.e., concurrent training—CT). Since it has been demonstrated that CT may compromise explosive force (RFD) gains (i.e., exerting a negative interference effect) even when strength gains are comparable to strength training performed alone (Häkkinen et al. 2003), it is relevant to determine whether PT and TST combined with endurance training would induce different magnitudes of neuromuscular adaptations in older individuals. Indeed, because CT is an effective method to improve both cardiovascular and mechanical muscle function concomitantly in older individuals (Cadore and Izquierdo 2013), it becomes relevant to investigate different models of CT to improve exercise prescription in older populations.

Previous studies in older adults have predominantly used continuous endurance training as the aerobic component of CT (Wood et al. 2001; Izquierdo et al. 2004; Sillanpää et al. 2008; Cadore et al. 2010, 2013). With such exercise protocols, CT composed of continuous endurance training appears to consistently improve cardiorespiratory fitness and reduce cardiovascular risk factors (Wood et al. 2001; Izquierdo et al. 2004; Sillanpää et al. 2008; Cadore et al. 2011, 2018b). On the other hand, single-mode high-intensity interval training (HIIT) may elicit similar cardiorespiratory adaptations compared to continuous endurance training despite using markedly shorter training sessions (Gibala et al. 2012). Thus, HIIT seems to be a time-efficient mode of endurance training, and its inclusion in CT interventions could be effective in promoting physical fitness in older individuals. Notwithstanding, only few studies have investigated the adaptations induced by HIIT in older populations (Knowles et al. 2014; Hwang et al. 2016), and to our best knowledge, no previous study has investigated the adaptations to HIIT combined with TST or PT (i.e., CT) in older individuals, which demands for further study. To advance the body of knowledge on different exercise training protocols to improve physical performance of older people, it would be interesting to compare distinct modes of strength training, such as PT and TST when combined with HIIT. Therefore, this study aimed to compare the adaptations in mechanical explosive-type muscle function, muscle hypertrophy, and cardiorespiratory fitness induced by two different CT models in older men: TST + HIIT and PT + HIIT. Our hypothesis was that both modes of CT would promote similar improvements in the maximal strength, muscle hypertrophy, and aerobic power, but PT + HIIT would promote superior gains in muscle power output and rate of force development.

Methods

Participants

Forty community-dwelling healthy elderly men volunteered for this study. Across the intervention, five participants dropped out (three for health problems not related to the intervention, and two due to professional issues). Participants were recruited using widely read local newspapers and local university announcements as well as social media. The participants were carefully informed about the design of the study, and special information was provided regarding the possible risks and discomfort related to the procedures. An informed consent form was read and signed prior to onset of the study by all participants. Subsequently, participants were randomly assigned into two separate intervention groups through electronic randomization (https://www.randomizer.org): CT composed of PT combined with HIIT (CTP, $n = 20$; 64.2 ± 3.1 years; 80.0 ± 14.3 kg; 176.5 ± 7.6 cm); and CT composed of TST combined with HIIT (CTS $n = 20$; 65.2 ± 4.0 years; 84.7 ± 9.7 kg; 174.6 ± 22.5 cm). The sample size was calculated using G POWER software (version 3.0.1), which determined that a sample of $n = 20$ participants per group would be necessary to detect an effect size of 0.5 and to provide a statistical power of over 0.85 for all primary outcomes. After calculating the sample size for maximal dynamic strength, muscle power output, and rate of force development outcomes, we chose the greatest value observed among these outcomes, which in our case was in the RFD variables (i.e., 20 participants per group). Concealment was guaranteed by a researcher who was blinded with respect to the participants. The inclusion criteria were an age older than 60 years old and that participants were not engaged in any regular and systematic exercise program for 6 months prior to study onset. Medical evaluations were performed using clinical anamnesis and an effort electrocardiograph test to ensure each subject's suitability for the testing procedure. The exclusion criteria were any history of neuromuscular, cognitive, metabolic, hormonal, or cardiovascular diseases (except controlled stage 1 hypertension); and smoking or having stopped smoking less than 1 year prior to the study. The participants were not taking any medications that could influence hormonal or neuromuscular metabolism, and they were advised to maintain their normal dietary intake throughout the study. Moreover, to be included in the pre- to post-comparisons, individuals had to attend at least 85% of the scheduled number of training sessions. However, participants had the opportunity to make up the training sessions missed during the same week. The complete screening, recruitment, and allocation of individuals are presented in Fig. 1. The physical characteristics of the participants are shown in Table 1.

Experimental design

To compare different models of concurrent training in older adults, participants performed CT interventions composed of power training (CTP) or traditional strength training (CTS) combined with high-intensity interval training (HIIT) for 16 weeks. The primary outcomes of the study were maximal dynamic lower limb muscle strength (leg press 1 RM, knee extensor 1 RM), maximal lower limb muscle power output during countermovement jumping (CMJ), and isometric rate of force development variables of the knee extensors. The secondary outcomes were muscle thickness, specific tension, and peak oxygen uptake (VO_{2peak}). To assess the stability and reliability of these outcome variables, fourteen participants (65.0 ± 3.8 years, 85.3 ± 12.8 kg, 172.4 ± 7.4 cm) were assessed twice before the start of the intervention to

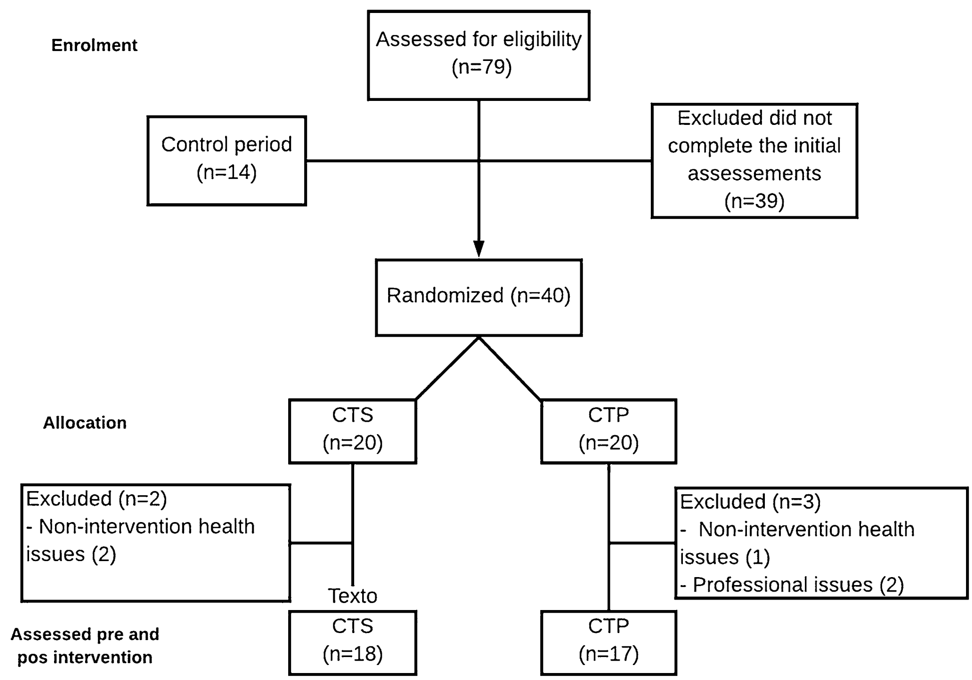

Fig. 1 Flowchart for enrollment, allocation and assessment of individuals. *CTS* concurrent traditional strength and endurance training, *CTP* concurrent power and endurance training

Table 1 Physical characteristics pre- and post-intervention

	CTP (*n* = 17)			CTS (*n* = 18)		
	Pre	Post 8	Post 16	Pre	Post 8	Post 16
Age (years)	64.3 ± 3.3	64.3 ± 3.3	65.1 ± 3.3	65.7 ± 4.2	65.7 ± 4.2	66.4 ± 4.3
Height (cm)	176 ± 7.2	176 ± 7.2	176 ± 7.2	174.2 ± 2.2	174.2 ± 2.2	174.2 ± 2.2
Body mass (kg)	84.7 ± 14.8	84.9 ± 14.4	85.2 ± 14.4	89.9 ± 9.1	90.1 ± 9.6	89.4 ± 9.1

CTS concurrent traditional strength and endurance training, *CTP* concurrent power and endurance training provide control period data (weeks − 4 and 0). After the control period, these participants were equally randomized in the groups. Tests were performed by the same investigators (who were blinded regarding group allocation) before the intervention and 8 and 16 weeks post-intervention. An exception of blinding was noted for the 1 RM testing, in which all assessors were not completely blinded, although during post-training, they were blinded regarding the pre training values. One week before the data collections, participants were familiarized with all tests procedures. Data collections were taken in three different days, separated by 48 h. In the first day, participants performed the muscle thickness assessments, followed by the 1 RM tests. In the second day, rate of force development test was performed. Finally, in the third day, participants performed CMJ during the morning, followed by the VO_{2peak} test in the afternoon. Ambient conditions were kept constant throughout all tests (temperature: 22–24 °C) and interventions. This randomized clinical trial was conducted according to the Declaration of Helsinki and was approved by the local Institutional Ethics Committee (register number 79277917.3.0000.5347). In addition, this randomized clinical trial was designed according to CONSORT guidelines (https://www.consort-statement.org/).

Maximal dynamic strength

Maximal strength was assessed using the one-repetition maximum test (1 RM) with the bilateral leg press (LP 1 RM) and bilateral knee extension (KE 1 RM) exercises (KonnenGym, Beijing, China). Before the test, participants performed ten repetitions at approximately 50% of the estimated 1 RM. Thereafter, the resistance was increased until no additional weight could be lifted using proper technique and the complete range of motion. The 1 RM range of motion reached by each participant during the familiarization period was recorded by a customized device and used to establish the range of motion during all test assessments. The 1 RM was defined as the maximum weight that the participant could move through a full range of motion once (90° to 180°; 180° = knee fully extended). The same knee range of motion was adopted during LP and KE 1 RM tests. Participants' 1 RM was determined in no more than four attempts, separated by 180 s of rest between successive attempts. The intra class coefficient values were 0.99 and 0.95 for repeated assessments of LP 1 RM and KE 1 RM, respectively.

Rate of force development

The rate of force development (RFD) of the right knee extensors was calculated using torque–time curves obtained during a maximal isometric voluntary contraction (MIVC) performed on a portable customized isometric dynamometer chair (Cefise, São Paulo, Brasil) and calibrated according to the manufacturer's specifications before each test. Prior to the tests, all participants performed a 5-min warm-up on a cycle ergometer. The participants were positioned in the dynamometer with their hips and thighs firmly strapped to the seat and the hip angle at ~ 90°. The tests were performed at 60° of knee flexion (0° represents full extension), and two 5-s knee extension MIVCs were repeated with 1 min of rest between each attempt (Da Silva et al. 2018; Radaelli et al. 2018). The participants were instructed to perform knee extension MIVCs as hard and fast as possible (Maffiuletti et al. 2016; Sahaly et al. 2001), while strong verbal encouragement was given during all tests. The torque–time curve was digitally recorded using Miotool software (Miotec, Brazil), with an acquisition rate of 2000 Hz. The MIVC was defined as the highest torque value determined with the Miotool software. The RFD was calculated as the average slope of the torque–time curve (N s^{-1}) over time intervals from 0 to 200 ms relative to the onset of the contraction (Aagaard et al. 2002), which was considered the point at which the torque exceeded the baseline by 2.5% of MIVC, which was determined using a customized MATLAB software routine. The isometric torque–time interval analysis, which included the RFD from 0 to 50, 0 to 100, and 100 to 200 ms (Aagaard et al. 2002), was obtained using a customized Excel spreadsheet. The intra class coefficient values were ≥ 0.88 for all RFD variables.

Muscle power output

To determine the maximal power output, participants performed a jump test using an electronic contact mat system (Cefise, Jump System Pro, São Paulo, Brazil). Jump height was determined using an acknowledged flight-time calculation (Bosco and Rusko 1983) and the software Jump System Pro 1.0. Each participant was instructed to use maximum effort to perform the double-leg countermovement jump (CMJ) test. They were given three attempts to obtain their maximum jump height in each test, with 30 s of rest between attempts, and the highest value was utilized for subsequent analysis. During the CMJ test, participants started in the orthostatic position. They were instructed to jump for maximal height. Participants were carefully instructed to leave the electronic contact mat system with their knees and ankles fully extended and to land in a similarly extended position to ensure the validity of the test. Four techniques were stressed: (a) using correct posture (i.e., spine erect, shoulders back) and body alignment (e.g., chest over knees) throughout the jump; (b) jumping straight up with no excessive side-to-side or forward–backward movement; (c) landing softly, with toe-to-toe heel rocking and bent knees; and (d) having instant recoil preparation for the next jump (Cadore et al. 2018b). When performing the jumps, all the participants held their hands on their hips to standardize the position and avoid upper limb help in the development of lower limb power output. Before the tests, we also instructed them regarding the knee angle they should achieve in the end of the countermovement (i.e., approximately 90°). Absolute power was determined based on the following calculation: absolute power (W) = [60.7 × (jump height) + 45.3 × body mass – 2055] (Sayers et al. 1999). Muscle power output subsequently was normalized to relative to body mass. The intra class coefficient value for repeated testing was 0.95 for CMJ muscle power.

Muscle thickness

The muscle thickness (MT) was measured using B-mode ultrasound (Nemio XG, Toshiba, Japan). A 9.0-MHz linear array probe (38 mm) was placed on the skin perpendicular to the tissue interface, and 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 analyzed using ImageJ software (National Institutes of Health, USA, version 1.42). 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 the MT. The MT images were determined in the muscles vastus lateralis (VL), vastus medialis (VM), and rectus femoris (RF). Probe positioning for the measurement of each muscle has been described elsewhere (Cadore et al. 2013), while also informed in the Supplementary file. The sum of the three lower body muscles' MTs was considered representative of overall quadriceps femoris (QF) MT (QF MT), which was used to calculate specific tension. The MT values were calculated as the mean of three different images taken pre- and post-training (at 8 and 16 weeks). To ensure the same probe position in subsequent tests, the right thigh of each subject was mapped for the position of the probe using moles and small angiomas indicated by markings on transparent paper (Cadore et al. 2013). Participants were evaluated in a supine position after 5 min of rest and after 72 h without any vigorous physical activity. The intra class coefficient values for repeated MT recordings in the quadriceps muscle compartments were ≥ 0.96.

Specific tension

Specific tension, a parameter to assess muscle quality, was calculated from the ratio between the KE 1 RM/2 and the sum of the squared QF muscles. Thus, specific tension (N cm^{-2}) was calculated following the formula: (1 RM KE/2) (N)/($VL^2 + VM^2 + RF^2$) (cm^2) (Åstrand and Rodahl 1970).

Peak oxygen uptake (VO_{2peak})

To determine the intensity of aerobic training and access the peak oxygen uptake (VO_{2peak}), participants performed an incremental test on a cycle-ergometer (Cybex, USA). Participants were positioned in the equipment to start the test, in first stage a period of 3 min was used as warm-up at 25 W. After the first stage, every 1 min the load increase in 25 W, 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 breath-by-breath expired gas was analyzed using a metabolic cart (Quark CPET, Cosmed, Italy). The maximum VO_2 value (ml kg^{-1} min^{-1}) 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 cadence of 70 rpm; and (3) an RER greater than 1.1 was obtained. The heart rate was measured using a heart rate monitor (Polar model 2610, Finland). The maximal heart rate values obtained during the VO_{2peak} test were 160 ± 14 for CTP, and 158 ± 9 for CTS. The intra class coefficient value for repeated testing was 0.88 for VO_{2peak}.

Training interventions

The participants exercised both strength and endurance training in the same session, twice weekly, on non-consecutive days, and all groups always performed strength prior to endurance training, to optimize the expected strength/power adaptations (Cadore et al. 2013). Importantly, the different velocity of movement between training interventions occurred only in the bilateral leg press (LP) and bilateral knee extension (KE) exercises performed in isoinertial plate loaded machines. We focused the investigation on those muscles because its importance to the functional activities in older individuals. During the intervention period, CTP performed the concentric phase of knee extensors exercises at the maximum intentional speed possible (hence termed power training), while using a controlled slower speed in the eccentric movement phase. Conversely, CTS group performed both phases at a slow, controlled speed of motion (i.e., approximately 2 s in each phase). All participants were oriented and supervised by experienced researchers to efficiently perform the targeted movement speeds. Complete information on all training variables during the period of intervention is shown in Table 2. CTP group performed three sets of eight repetitions at 40% of 1 RM (weeks 1–4), progressing to four sets of six repetitions at 60% of 1 RM (weeks 13–16). The intensities of CTP intervention were prescribed accordingly to recent recommendations to power training

Table 2 Training periodization

ST- CTS				ST—CTP			HIIT	
Week	Sets	Repetitions	Intensity (% 1 RM)	Sets	Repetitions	Intensity (% 1 RM)	Time (min)	Intensity (% VO_{2peak})
1–4	2	12–15	65	3	8	40	3×4/2	75–80
5–8	3	10–12	70	3	8	50	3×4/2	80–85
9–12	3	8–10	75	4	6	55	4×4/2	80–85
13–16	4	6–8	80	4	6	60	4×4/2	85–90

ST strength training, *CTS* concurrent traditional strength and endurance training, *CTP* concurrent power and endurance training, *HIIT* high-intensity interval training

prescription in older individuals (Fragala et al. 2019), since optimal power values are produced approximately in this range of intensities during knee extensors exercises (i.e., from 40 to 60% of 1 RM) in older adults (Izquierdo et al. 1999; Strand et al. 2019). CTS group performed 2 sets of 12–15 repetitions at 65% of 1 RM (weeks 1–4), progressing to 4 sets of 6–8 repetitions at 80% of 1 RM (weeks 13–16). The rest interval between successive sets was 180 s. Along with LP and KE exercises, individuals also performed knee flexion, chest press, lat pull down, elbow flexion, and elbow extension. In these exercises, participants performed similar training volume compared to the knee extensor exercises (in each respective group), using approximately 60% of the 1 RM load in a controlled (i.e. non-explosive) form. The endurance training program was performed using a cycle ergometer. Initially all participants performed 5 min of warm-up to 60–65% of maximal heart rate (HR_{max}). Participants started performing three sets of 4 min at 75–80% of the heart rate at VO_{2peak}, (weeks 1–4), progressing until 85–90% of the heart rate at VO_{2peak} (weeks 13–16). While exercising at target intensity, participants were advised to maintain a cadence of 70–75 rpm. The time interval between successive HIIT bouts was 2 min, while biking at a self-selected confortable speed. Both training groups performed the same endurance training program. All training sessions were carefully supervised by experienced strength and conditioning coaches (minimum three concurrently present).

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. The training-related effects were assessed using a two-way analysis of variance (ANOVA) (group × time). If a time vs. group interaction was observed, follow-up analysis was proceed using independent *t* tests for group factor, as well as repeated measures ANOVA for time factor. Significance was accepted when $P < 0.05$. The effect size (ES) between pre- and post-training for each group was calculated using Cohen's *d*, represented by the following formula: $ES = (Mean_{post} - Mean_{pre})/SD_{pre}$, which $Mean_{post}$ is the mean post 16 weeks of training, $Mean_{pre}$ is the mean pre-training, and SDpre is the standard deviation of the pre-training measurements (Nakagawa and Cuthill 2007). The classification used was ES > 0.20 (small), ES > 0.50 (moderate), ES > 0.8 (large), and ES > 1.2 (very large).

Results

Participants

A total of 79 individuals initially volunteered to participate in the study, and 35 older men completed the preintervention and 16-week post-intervention measurements and had their data included in the statistical analysis (CTP: $n = 17$, and CTS: $n = 18$). Due to technical problems, the sample size for the muscle thickness data was CTP: $n = 16$, and CTS: $n = 17$; and the sample size for specific tension was CTP: $n = 15$, and CTS: $n = 16$.

Control period, physical characteristics, and adverse effects

Data on the control period are presented in the Supplementary file. During the control period (i.e., between week − 4 and week 0), no significant changes were observed in any assessed outcome variables. Before and after training, there were no differences between the groups in body mass (kg), height (cm), or age (years). All individuals included in the pre- and post-analysis attended 100% of the training sessions. Across the intervention period, we constantly asked to the participants to mention any discomfort, pain, or any health problems that could be related to the interventions, and participants reported no adverse effects related to the training programs.

Overall findings

At baseline, there were no group differences for any of the outcome variables assessed (i.e., 1 RM, RFD, absolute and relative power, muscle thickness and VO_{2peak}). After 16 weeks of training, no significant time vs. group interaction or significant group effects were observed for any of the outcome variables ($P > 0.05$).

Dynamic lower limb muscle strength

A time effect ($P < 0.001$) was observed for LP 1 RM with both CTP and CTS demonstrating gains after 8 weeks (46.0 ± 37.0, and 31.4 ± 14.8%, respectively, $P < 0.001$) and after 16 weeks (CTP: 75.8 ± 44.2%, ES = 1.92; and CTS: 52.1 ± 23.0%, ES = 2.19, $P < 0.001$). LP 1 RM obtained at 16 weeks was greater than that observed after 8 weeks training ($P < 0.001$) (Fig. 2).

A time effect also was noted for KE 1 RM ($P < 0.001$), with both CTP and CTS showing increases after 8 weeks (25.3 ± 15.2% and 26.5 ± 19.8%, respectively, $P < 0.001$) and 16 weeks of training (CTP: 41.5 ± 18.0%, ES = 1.14; and CTS: 39.4 ± 21.6%, ES = 1.12, $P < 0.001$). KE 1 RM strength was greater at 16 weeks compared to 8 weeks ($P < 0.001$) (Fig. 2).

Rate of force development (RFD)

Positive time effects ($P < 0.05$) were noted for RFD in both CTP and CTS at 16 weeks: $RFD_{0\text{-}50}$: CTP: 64.8 ± 93.1%, ES = 0.61, and CTS: 35.6 ± 52.4%, ES = 0.46 ($P < 0.01$); $RFD_{0\text{-}100}$: CTP: 59.8 ± 91.2%, ES = 0.59, and CTS: 30.7 ± 56.5%, ES = 0.33 (P < 0.05); and $RFD_{100\text{–}200}$: CTP: 46.8 ± 65.8%, ES = 0.87, and CTS: 9.9 ± 43.5%, ES = 0.26 ($P < 0.05$). There were no differences between groups for the RFD outcomes or between the pre-and 8-week post-intervention values (Fig. 2).

Muscle power (CMJ)

In terms of absolute CMJ muscle power output, a time effect ($P < 0.05$) was observed in both CTP and CTS that was further manifested by pre-to-post-training gains at 16 weeks (CTP: 4.4 ± 8.9%, ES = 0.18; and CTS: 1.8 ± 6.0%, ES = 0.11; $P < 0.05$) with no differences between groups. No differences were observed pre- and 8-weeks

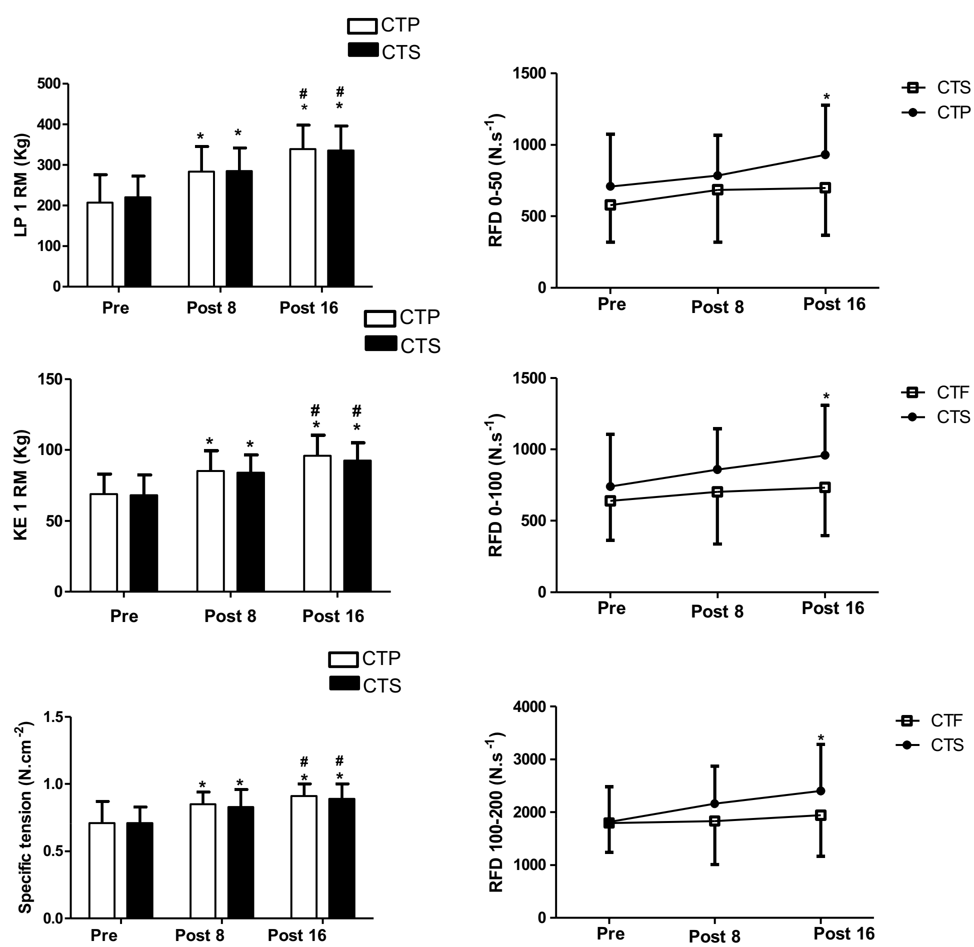

Fig. 2 Mean ± SD values of leg press one maximum repetition (LP 1 RM, kg) (upper left); knee extension (KE) 1 RM (kg) (middle left; specific tension (N cm^{-2}) (lower left); rate of force development (RFD, N s^{-1}) at 0–50 ms (upper right); RFD at 0–100 ms (middle right); and at 100–200 ms (lower right). *CTS* concurrent strength and endurance training, *CTP* concurrent power and endurance training. *Significantly greater than the pre training ($P < 0.001$); #significantly greater than the post 8 ($P < 0.001$)

post-intervention. In addition, both training groups improved ($P<0.01$) relative CMJ muscle power output at 16 weeks (CTP: 5.2 ± 7.2%, ES = 0.49; CTS: 2.0 ± 4.8%, ES = 0.22; $P<0.01$), with no differences between groups. Also, there was a trend towards increased normalized CMJ power from the pre- to 8-week post-intervention (CTP: 3.2 ± 7.2%; CTS: 0.9 ± 5.3%; $P=0.06$) (Table 3).

Muscle thickness (MT)

A time effect was noted for RF MT ($P<0.05$), with both CTP and CTS displaying increases in this parameter after 16 weeks of training (CTP: 4.6 ± 10.4%, ES = 0.34; CTS: 5.2 ± 7.6%, ES = 0.16; $P<0.05$), whereas no difference was observed between pre- and 8-week post-intervention. After 8 weeks training, both training groups showed improved VL MT (CTP: 5.1 ± 10.3%; CTS: 8.5 ± 15.3%; $P<0.01$), and even greater increases were observed at 16 weeks (CTP: 7.9 ± 6.3%, ES = 0.63; CTS: 10.2 ± 8.6%, ES = 0.71; $P<0.001$), with no differences between groups. Moreover, both CTP and CTS demonstrated improvements in VM MT after 16 weeks of training (CTP: 5.9 ± 12.4%, ES = 0.35; CTS: 5.9 ± 7.9%, ES = 0.42; $P<0.01$), with no differences between groups. No differences were observed between 8- and 16-week post-intervention MT values (Table 3).

Specific tension

Specific tension showed a time effect ($P<0.001$), with both increases in both CTP and CTS at 8 weeks (CTP: 27.3 ± 25.4%; CTS: 12.0 ± 16.8%; $P<0.001$) and 16 weeks (CTP: 33.5 ± 26.8%, ES = 1.55; CTS: 22.1 ± 20.4%, ES = 0.65; $P<0.001$), with no differences between groups (Fig. 2). Specific tension was greater at 16 weeks compared to 8 weeks ($P<0.01$) (Fig. 2).

Peak oxygen uptake (VO_{2peak})

A time effect also noted for relative VO_{2peak} (ml kg^{-1} min^{-1}) ($P<0.05$), with both groups demonstrating increases at 8 weeks (11.1 ± 15.6% and 3.9 ± 7.8% for CTP and CTS, respectively, $P<0.05$) and 16 weeks (CTP: 19.0 ± 37.9%, ES = 0.54; CTS: 8.6 ± 10.1%, ES = 0.53, $P<0.01$), with no differences between groups (Table 3). In addition, there was a significant time effect for absolute VO_{2peak} (l mim^{-1}) ($P<0.05$), with both groups demonstrating increases at 8 weeks (11.6 ± 23.4% and 4.2 ± 8.1% for CTP and CTS, respectively, $P<0.05$) and 16 weeks (CTP: 19.9 ± 38.1%, ES = 0.59; CTS: 8.1 ± 10.1%, ES = 0.51, $P<0.01$), with no differences between groups (Table 3).

Discussion

The main findings of the present study were that both training modalities (i.e., both CTS and CTP) achieved similar improvements in mechanical muscle function including explosive-type muscle output (RFD, power) and VO_{2peak} after 16 weeks of CT consisting of aerobic high-intensity interval training (HIIT) combined with either strength or power training. These results clearly demonstrate that strength training with low to moderate loading intensity (i.e., 40–60% of 1 RM) performed at maximal intentional speed in combination with aerobic HIIT can promote similar

Table 3 Changes in the values (mean ± standard deviation) of muscle power, muscle thickness, and peak oxygen uptake across 8 and 16 weeks of training

Outcomes	Group	Pre	Post 8	Post 16
Absolute power (W)	CTP	2.937 ± 570	3.010 ± 583	3.044 ± 506*
	CTS	3.152 ± 454	3.178 ± 494	3.205 ± 454*
Relative power (W/Kg)	CTP	34.5 ± 3.3	35.5 ± 2.9	36.2 ± 2.4**
	CTS	35.3 ± 2.9	35.6 ± 3.3	36 ± 3.2**
Relative VO_{2peak} (mL kg^{-1} min^{-1})	CTP	24.5 ± 6.1	26.2 ± 4.3*	27.8 ± 5.2***
	CTS	24.8 ± 3.8	25.7 ± 4.4*	26.8 ± 4.5***
Absolute VO_{2peak} (L min^{-1})	CTP	2.04 ± 0.49	2.20 ± 0.36*	2.33 ± 0.40**
	CTS	2.22 ± 0.35	2.32 ± 0.46*	2.39 ± 0.43**
RF MT (mm)	CTP	24.4 ± 3.8	24.8 ± 3.6	25.7 ± 3.6*
	CTS	24.8 ± 6.0	25.1 ± 6.9	25.8 ± 6.4*
VL MT (mm)	CTP	21.3 ± 2.7	22.3 ± 3.1**	23.0 ± 2.9***
	CTS	21.6 ± 2.8	23.1 ± 2.6**	23.6 ± 2.9***
VM MT (mm)	CTP	32.7 ± 5.1	33.1 ± 6.1	34.5 ± 5.8**
	CTS	33.0 ± 4.2	34.7 ± 3.4	34.8 ± 3.7**

Significant differences: *$P<0.05$, **$P<0.01$, and ***$P<0.001$

CTS concurrent traditional strength and endurance training, *CTP* concurrent power and endurance training, *VO_{2peak}* peak oxygen consumption, *RF* rectus femoris, *VL* vastus lateralis, *VM* vastus medialis enhancements in mechanical lower limb muscle function compared to those achieved when HIIT is combined with traditional heavy-resistance strength training using moderate-to-high loading intensities (i.e., 65–80% of 1 RM).

Marked increases in maximal dynamic lower limb strength were noted after 8 weeks of CT (KE 1 RM ≅ 25% and LP 1 RM ≅ 31–46%), which were of even greater magnitude after 16 weeks of CT (KE 1 RM ≅ 39–42% and LP 1 RM ≅ 52–76%). These results are in close agreement with previous reports in older adults performing TST and PT, demonstrating comparable gains in lower body maximal strength (assessed as 1 RM in selected training exercises) following these two strength training models (i.e., 30–50% in strength gains) (Ramirez-Campillo et al. 2014; Bottaro et al. 2007). The similar increases with heavy-load TST and low-load PT may be explained by the high intentional movement speeds developed during PT, which involves the recruitment of high-threshold motor units (i.e., faster motor units) responsible for producing higher force and power levels compared to those of slower motor units (Duchateau and Enoka 2011). Therefore, both the high loads during CTS as well as the high contraction speeds during CTP contributed to the training-induced gains in RFD, power and maximal muscle strength observed in the present cohort of older adults. In terms of adaptive mechanisms, these improvements in mechanical muscle function potentially were caused by enhanced neural activity, which may include increases in motor unit recruitment, enhanced maximal motor unit firing rates, elevated spinal motor neuronal excitability, increased efferent motor drive, and changes in agonist coactivation (Aagaard et al. 2010), along with a contribution from muscle hypertrophy (discussed below). As yet another contributing factor that could contribute at least in part to the similar gains in RFD/power/strength observed between CTS and CTP is the intense cycle ergometer HIIT training performed in both groups. Indeed, it has previously been shown that this type of cardiovascular training induces a greater magnitude of strength/power adaptations compared to traditional continuous endurance training (Martinez-Valdes et al. 2018). In support of this notion, cycle ergometer exercise training appears to induce maximal lower body strength increases in older individuals, although these changes are substantially lower compared to the gains observed following isolated strength training (Izquierdo et al. 2004; Cadore et al. 2010). Consequently, the influence of HIIT training on the strength increases observed in the present study cannot be discarded and need to be further investigated. On the other hand, to minimize the possibility of interference by the fatigue induced by each HIIT session on subsequent strength performance in the present study, we chose the strength-endurance exercise order, which may have maximized the strength gains observed (Cadore et al. 2013). In fact, the relative increases observed suggest that these CT models (TST + HIIT and PT + HIIT) were effective in inducing maximal strength enhancements when considering the magnitude of the strength increases often observed in studies that investigated TST performed alone (Izquierdo et al. 2004; Cadore et al. 2010; Raymond et al. 2013).

Muscle power output and RFD are strong predictors of functional capacity in older adults (Reid and Fielding 2012; Bean et al. 2002; Casas-Herrero et al. 2013; Izquierdo et al. 1999) and are indispensable factors for maintaining independence with age. It has been shown that both TST and PT increase muscle power output and RFD, despite an advantage in favor of PT (Straight et al. 2015; Ramírez-Campillo et al. 2014). Regarding maximal muscle power output, the absence of a statistically significant difference between the present gains with CTP and CTS might be explained by the test used to assess power output that is by CMJ testing instead of by assessment of the maximal power output in the exercises used during training. In addition, because power output is the product of the force and velocity of the contraction and although CTP performed the exercises at higher velocities, CTS may have improved maximal power production due to the observed gains in maximal lower limb strength. It is important to note that both types of CT intervention led to RFD/power adaptations in the knee extensors that were transferable to an enhanced CMJ performance, which requires complex neuromuscular recruitment and is associated with the ability to perform vital activities of daily living (Izquierdo et al. 1999).

Regarding RFD, both training groups demonstrated marked enhancements at all time intervals assessed (50, 100, and 100–200 ms) after 16 weeks (31–65%) of CT, corroborating previous studies investigating ST adaptations (Aagaard et al. 2002; Wallerstein et al. 2012; Pinto et al. 2014; Da Silva et al. 2018). Although there were no statistically significant differences between groups, the relative increases and the calculated effect sizes suggested greater improvements in CTP compared to CTS (i.e., 46–64% vs. 17–35%, respectively). These findings indicate a greater potential for enhancing rapid force capacity (RFD) with CTP compared to CTS. Muscle recruitment velocity is determinant for rapid force development since it is highly dependent of neural properties (Duchateau and Enoka 2011; Maffiuletti et al. 2016), which may explain why this CTP model tends to be superior for RFD. Although care should be taken due to the absence of a time vs. group interaction for RFD outcomes, it has been shown that the RFD in the initial periods (i.e., < 75 ms) is more related to neural factors (Andersen and Aagaard 2006), whereas the late RFD (i.e., > 75 ms) is more dependent on intrinsic muscle contraction properties and maximal voluntary contraction (Maffiuletti et al. 2016). Thus, both models of CT seem to be effective for improving both early and late phase RFD, and our findings tend to indicate an advantage when performing the concentric phase as quickly as possible during strength training, which agrees with previous literature (Tillin and Folland 2014).

In a classic experiment by Häkkinen et al. (2003), it was demonstrated that CT may induce a negative interference effect on the explosive force production (i.e., RFD at 0–500 ms), with no attenuation in the maximal strength gains. In the present study, even though we did not have a group performing TST alone, our results indicated that the present strength training models combined with HIIT, were fully effective of improving maximal power output and rapid force production (i.e., RFD), corroborating previous observations when investigating CT adaptations in older adults (Cadore el al. 2013; Wilhelm et al. 2014; Ferrari et al. 2016).

Strength loss with aging is due to impairments in neuronal function and declines in muscle mass (Aagaard et al. 2010; Manini et al. 2013), altogether contributing to muscular function declines (Miljkovic et al. 2015) and consequently causing functional impairments (Power et al. 2013). It has been shown that both TST and PT induce muscle hypertrophy in older adults (Wallerstein et al. 2012; Nogueira et al. 2009; Cadore et al. 2014; Radaelli et al. 2018). Nevertheless, a meta-analysis by Tschopp et al. (2011) suggested that TST may induce superior increases in muscle mass compared to those induced by PT. Our findings are in agreement with previous findings demonstrating similar muscle thickness increments between PT and TST, since both CTP and CTS improved RF, VL, and VM muscle thickness (Nogueira et al. 2009). Similar to the present gains in maximal strength, it is possible that the comparable magnitude of muscle thickness gains between CTS and CTP might be explained by the characteristic recruitment of MU during explosive-type muscle actions such as those employed in CTP, and that the muscle force at which MUs are recruited (i.e. recruitment threshold) is markedly decreased in explosive-type (high RFD) muscle actions (Duchateau and Enoka 2011). It makes possible that type II MUs in such conditions may be recruited even using low to moderate loading intensities (i.e., 40–60% of 1 RM). Despite the fact that the greater workload in CTS results in greater total training volume (i.e., sets × repetitions × load), the higher accelerations during the concentric phase of CTP may have generated comparable high levels of applied force and mechanical work, thereby inducing similar adaptations in muscle thickness with CTP and CTS (Raymond et al. 2013). Our findings indicate that high nominal loading intensities and volumes of strength training may not always be necessary to induce muscle hypertrophy, and that lifting low to moderately heavy loads at maximal intentional speed in the concentric phase also seems efficient of inducing muscle hypertrophy in older adults. Indeed, it has previously been shown that PT performed at low to moderate intensities and low to moderate volume (i.e., 1–3 sets per exercise) can evoke substantial improvements in the muscle mass in older populations (Cadore et al. 2014; Radaelli et al. 2018). Our results in CTP agree with those of Wilhelm et al. (2014), who observed marked muscle thickness increases in the quadriceps femoris after 12 weeks of CT using fast concentric muscle actions, although in that study, the strength training intensity achieved across the periodization was greater than that in the present study, using 8 RM training loads and maximal repetitions (Wilhelm et al. 2014).

The present enhancements in specific tension suggest that neural adaptations took place with training, potentially accompanied by improvements in intrinsic muscle quality (i.e., reducing muscle fat infiltration) (Pinto et al. 2014; Cadore et al. 2012; Wilhelm et al. 2014). Our findings show that both training groups improved specific tension to the same extent after the intervention period, although greater effect size was observed in CTP. These improvements are in agreement with previous studies investigating the effects of CT (Cadore et al. 2012) and TST (Tracy et al. 1999; Frontera et al. 2008; Pinto et al. 2014). Notwithstanding, to our best knowledge, no previous study has compared the adaptation in specific tension induced by TST and PT, especially not in the context of CT. Our findings are clinically relevant because it has been shown that improvements in specific tension may be associated with gains in functional capacity in older adults (Pinto et al. 2014). The effect sizes calculated for this parameter suggested that there may be an advantage to CTP compared to CTS, but due to the absence of statistical differences between groups, this comparison need to be further investigated.

It has been shown that high-intensity interval training (HIIT) is an effective intervention modality to improve cardiorespiratory capacity in older individuals (Knowles et al. 2014; Hwang et al. 2016). Likewise, in the present study, VO_{2peak} increased after 8 (4–11%) and 16 weeks (9–19%) of CT, independently of the CT mode. These magnitudes of VO_{2peak} gains corroborate previous findings from CT studies in older adults using continuous endurance training programs (Ferrari et al. 2013; Wilhelm et al. 2014) and continuous progressing to interval training programs with cycle ergometers (Cadore et al. 2010, 2012) (i.e., ≅ 11–20%). The present study employed HIIT training protocol that was highly time efficient, since participants performed three bouts of 4-min active cycling which progressed to four 4-min bouts, summing 16 min of HIIT exercise in each training session. The resulting gains in VO_{2peak} reinforce the use of HIIT as a time-efficient strategy for endurance exercise prescriptions intended to induce cardiorespiratory adaptations in healthy older adult populations (Osuka et al. 2017; Hwang et al. 2016; Knowles et al. 2014).

Strengths and limitations

A number of limitations may be noted with the present study. It can be argued that the absence of experimental groups performing strength training alone (i.e., no combination with HIIT) limits the interpretation of the adaptations in mechanical muscle function (strength, RFD, power) observed with CTS and CTP. In addition, the absence of experimental groups performing TST and PT combined with continuous moderate intensity endurance training does not allow us to state that the HIIT adaptations were superior to those of continuous training during CT. In terms of strengths, the present study demonstrated the effectiveness of two different models of CT for (1) improving important aspects of mechanical muscle function including maximal muscle power and rapid force capacity, (2) evoking gains in lower limb muscle size and (3) increasing maximal aerobic capacity in older adults. In addition, the present study demonstrated the feasibility of CT intervention combining HIIT aerobic training with either low-load explosive-type power training or heavy-load strength training in healthy older men. Notably, no adverse effects emerged in the present study despite the highly intensive training efforts.

Conclusion

The present findings demonstrated similar gains in mechanical muscle function (strength, RFD, power), muscle morphology, and VO_{2peak} induced by CT programs composed of traditional and power-type strength training in healthy older men. The present study appears to be the first to compare these different strength training models combined with HIIT in older adults. Notably, CTP induced similar adaptations to CTS, despite using lower workloads and lower total strength training load during the intervention period. Moreover, based on effect size analysis CTP tended to induce greater clinical effects on RFD outcomes, although caution is needed in the interpretation of this effect due to the absence of statistically significant differences between the intervention groups. Finally, HIIT appears to be a safe and time-efficient strategy to improve VO_{2peak} in older men.

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Author contributions DCM, ELC, MI, RSP, RR and PA, and DB conceived and designed research as well as contributed in the manuscript writing. DCM, FPB, RG, JLT, HB, and RN conducted experiments. ELC and DCM analyzed data. All authors read and approved the manuscript.

Compliance with ethical standards

Conflict of interest Authors disclose there are no conflict of interests that could have direct or potential influence or impart bias on the work.

References

Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P (2002) Increased rate of force development and neural drive of human skeletal muscle following resistance training. J Appl Physiol 93:1318–1326

Aagaard P, Suetta C, Caserotti P, Magnusson SP, Kjaer M (2010) Role of the nervous system in sarcopenia and muscle atrophy with aging: strength training as a countermeasure. Scand J Med Sci Sports 20:49–64

Andersen LL, Aagaard P (2006) Influence of maximal muscle strength and intrinsic muscle contractile properties on contractile rate of force development. Eur J Appl Physiol 96:46–52

Artero EG, Lee D, Lavie CJ et al (2012) Effects of muscular strength on cardiovascular risk factors and prognosis. J Cardiopulm Rehabil 32:351–358

Åstrand P-O, Rodahl K (1970) Textbook of work physiology. McGraw-Hill, New York

Bean JF, Kiely DK, Herman S et al (2002) The relationship between leg power and physical performance in mobility-limited older people. J Am Geriatr Soc 50:461–467

Bosco C, Rusko (1983) The effect of prolonged skeletal muscle stretch-shortening cycle on recoil of elastic energy and on energy expenditure. Acta Physiol Scand 119:219–224

Bottaro M, Machado SN, Nogueira W, Scales VJ (2007) Effect of high versus low-velocity resistance training on muscular fitness and functional performance in older men. Eur J Appl Physiol 99:257–264

Cadore EL, Casas-Herrero A, Zambom-Ferraresi F et al (2014) Multicomponent exercises including muscle power training enhance muscle mass, power output, and functional outcomes in institutionalized frail nonagenarians. Age (Dordr) 36:773–785

Cadore EL, Izquierdo M (2013) How to simultaneously optimize muscle strength, power, functional capacity, and cardiovascular gains in elderly: an update. Age (Dordr) 35:2329–2344

Cadore EL, Izquierdo M, Pinto SS et al (2013) Neuromuscular adaptations to concurrent training in the elderly: effects of intra session exercise sequence. Age (Dordr) 35:891–903

Cadore EL, Menger E, Teodoro JL et al (2018a) Functional and physiological adaptations following concurrent training using sets with and without concentric failure in elderly men: a randomized clinical trials. Exp Gerontol 110:182–190

Cadore EL, Pinto RS, Lhullier FLR et al (2011) Effects of strength, endurance and concurrent training on aerobic power and dynamic neuromuscular economy in elderly men. J Strength Cond Res 25:758–766

Cadore EL, Pinto RS, Reischak-Oliveira A, Izquierdo M (2018b) Explosive type of contractions should not be avoided during resistance training in elderly. Exp Gerontol 102:81–83

Cadore EL, Pinto RS, Lhullier FLR et al (2010) Physiological effects of concurrent training in elderly men. Int J Sports Med 31:689–697

Cadore EL, Izquierdo M, Alberton CL et al (2012) Strength prior to endurance intra-session exercise sequence optimizes neuromuscular and cardiovascular gains in elderly men. Exp Gerontol 47:164–169

Casas-Herrero A, Cadore E, Zambom-Ferraresi F et al (2013) Functional capacity, muscle fat infiltration, power output and

cognitive impairment in institutionalized frail oldest-old. Rejuven Res 16:396–403
Caserotti P, Aagaard P, Larsen JB, Puggaard P (2008) Explosive heavy-resistance training in old and very old adults: changes in rapid muscle force, strength and power. Scand J Med Sci Sports 18:773–782
Da Silva LXN, Teodoro JL, Menger E et al (2018) Repetitions to failure versus not to failure during concurrent training in healthy elderly men: a randomized clinical Trial. Exp Gerontol 108:18–27
Duchateau J, Enoka RM (2011) Human motor unit recordings: origins and insight into the integrated motor system. Brain Res 1409:42–61
Ferrari R, Fuchs SF, Kruel LFM et al (2016) Effects of different concurrent resistance and aerobic training frequencies on muscle power and muscle quality in trained elderly men: a randomized clinical trial. Aging Dis 7:697–704
Ferrari R, Kruel LF, Cadore EL et al (2013) Efficiency of twice weekly concurrent training in trained elderly men. Exp Gerontol 48:1236–1242
Fleg JL, Lakatta EG (1988) Role of muscle loss in the age-associated reduction in VO_{2max}. J Appl Physiol 65:1147–1151
Fragala MS, Cadore EL, Dorgo S et al (2019) Resistance training for older adults: position statement from the National Strength and Conditioning Association. J Strength Cond Res 33:2019–2052
Frontera WR, Reid KF, Phillips EM et al (2008) Muscle fiber size and function in elderly humans: a longitudinal study. J Appl Physiol 105:637–642
Gibala MJ, Little JP, Macdonald MJ et al (2012) Physiological adaptations to low-volume, high-intensity interval training in health and disease. J Physiol 590:1077–1084
Häkkinen K, Alen M, Kraemer WJ et al (2003) Neuromuscular adaptations during concurrent strength and endurance training versus strength training. Eur J Appl Physiol 89:42–52
Hwang CL, Yoo JK, Kim HK et al (2016) Novel all-extremity high-intensity interval training improves aerobic fitness, cardiac function and insulin resistance in healthy older adults. Exp Gerontol 82:112–119
Izquierdo M, Ibañez J, Gorostiaga E et al (1999) Maximal strength and power characteristics in isometric and dynamic actions of the upper and lower extremities in middle-aged and older men. Acta Physiol Scand 167:57–68
Izquierdo M, Ibañez J, Häkkinen K et al (2004) Once weekly combined resistance and cardiovascular training in health yolder men. Med Sci Sports Exerc 36:435–443
Knowles A, Herbert P, Easton C et al (2014) Impact of low-volume, high-intensity interval training on maximal aerobic capacity, health-related quality of life and motivation to exercise in ageing men. Age(Dordr) 37:25. https://doi.org/10.1007/s11357-015-9763-3
Maffiuletti NA, Aagaard P, Blazevich AJ et al (2016) Rate of force development: physiological and methodological considerations. Eur J Appl Physiol 116:1091–1116
Manini TM, Lee Hong S, Clark BC (2013) Aging and muscle: a neuron's perspective. Curr Opin Clin Nutr Metab Care 16:21–26
Martinez-Valdes E, Farina D, Negro F et al (2018) Motor unit conduction velocity changes to HIIT versus continuous training. Med Sci Sports Exerc 50:2339–2350
Miljkovic N, Lim J, Miljkovic I et al (2015) Aging of skeletal muscle fibers. Ann Rehabil Med 39:155–162
Miszko TA, Cress ME, Slade JM (2003) Effect of strength and power training on physical function in community-dwelling older adults. J Gerontol A Biol Sci Med Sci 58:171–175
Nakagawa S, Cuthill IC (2007) Effect size, confidence interval and statistical significance: a practical guide for biologists. Biol Rev Camb Philos Soc 82:591–605
Nogueira W, Gentil P, Mello SN, Oliveira RJ, Bezerra AJ, Bottaro M (2009) Effects of power training on muscle thickness of older men. Int J Sports Med 30:200–204
Osuka Y, Matsubara M, Hamasaki A et al (2017) Development of low-volume, high-intensity, aerobic-type interval training for elderly Japanese men: a feasibility study. Eur Rev Aging Phys Act. https://doi.org/10.1186/s11556-017-0184-4
Pinto RS, Correa CS, Radaelli R et al (2014) Short term strength training improves muscle quality and functional capacity of elderly women. Age (Dordr) 36:365–372
Power GA, Dalton BH, Rice CL (2013) Human neuromuscular structure and function in old age: a brief review. J Sport Health Sci 2:215–226
Radaelli R, Brusco CM, Lopez P et al (2018) Higher muscle power training volume is not determinant for the magnitude of neuromuscular improvements in elderly women. Exp Gerontol 110:15–22
Ramírez-Campillo R, Castillo A, Fuente CIF et al (2014) High-speed resistance training is more effective than low-speed resistance training to increase functional capacity and muscle performance in older women. Exp Gerontol 58:51–57
Raymond MJ, Bramley-Tzerefos RE, JeffsKJ WA, Holland AE (2013) Systematic review of high-intensity progressive resistance strength training of the lower limb compared with other intensities of strength training in older adults. Arch Phys Med Rehabil 94:1458–1472
Reid KF, Fielding RA (2012) Skeletal muscle power and functioning in older adults. Exerc Sport Sci Rev 40:1–12
Sahaly R, Vandewalle H, Driss T, Monod H (2001) Maximal voluntary force and rate of force development in humans—importance of instruction. Eur J Appl Physiol 85:345–350
Sayers SP, Harackiewicz DV, Harman EA, Frykman PN, Rosenstein MT (1999) Cross-validation of three power equations. Med Sci Sports Exerc 31:572–577
Sillanpää E, Häkkinen A, Nyman K et al (2008) Body composition and fitness during strength and/or endurance training in older men. Med Sci Sports Exerc 40:950–958
Straight CR, Lindheimer JB, Brady AO et al (2015) Effects of resistance training on lower-extremity muscle power in middle-aged and older adults: a systematic review and meta-analysis of randomized controlled trials. Sports Med. https://doi.org/10.1007/s40279-015-0418-4
Strand KL, Lucchi L, Copo TG, Cherup NP, Signorile JF (2019) Optimal loads for power in older men and women using plate-loaded machines. Exp Gerontol 124:110638. https://doi.org/10.1016/j.exger.2019.110638
Tillin NA, Folland JP (2014) Maximal and explosive strength training elicit distinct neuromuscular adaptations, specific to the training stimulus. Eur J Appl Physiol 114:365–374
Tracy BL, Ivey FM, Hurlbut D et al (1999) Muscle quality. II. Effects of strength training in 65- to 75-year-old men and women. J Appl Physiol 86:195–201
Tschopp M, Sattelmayer MK, Hilfiker R (2011) Is power training or conventional resistance training better for function in elderly persons? A meta-analysis. Age Ageing 40:549–556
Wallerstein LF, Tricoli V, Barroso R et al (2012) Effects of strength and power training on neuromuscular variables in older adults. J Aging Phys Act 20:171–185
Wilhelm EN, Rech A, Minozzo F et al (2014) Concurrent strength and endurance training exercise sequence does not affect neuromuscular adaptations in older men. Exp Gerontol 60:207–214
Wood RH, Reyes R, Welsch MA et al (2001) Concurrent cardiovascular and resistance training in healthy older adults. Med Sci Sports Exerc 33:1751–1758

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