



Effects of high-resistance circuit training in an elderly population [☆]

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ABSTRACT

The aim of this study was to determine the efficacy of a program of high-resistance circuit (HRC) training, and to compare the effects of HRC to traditional heavy strength (TS) training on strength, muscle size, body composition and measures of cardiovascular fitness in a healthy elderly population. Thirty-seven healthy men and women (61.6 ± 5.3 years) were randomly assigned to HRC (n = 16), TS (n = 14), or a control group (CG, n = 7). Training consisted of weight lifting twice a week for 12 weeks. Before and after the training, isokinetic peak torque in the upper and lower body, and body composition (dual X-ray absorptiometry) were determined. In addition, cardiovascular parameters were evaluated during an incremental treadmill test. Both HRC and TS groups showed significant increases in isokinetic strength ($p < 0.001$), and the increase was significantly greater in the experimental groups than in CG ($p < 0.03$). There were significant increases in lean mass (HRC, $p < 0.001$; TS, $p = 0.025$) and bone mineral density (HRC, $p = 0.025$; TS, $p = 0.018$) in the experimental groups. Only HRC showed a significant decrease in fat mass ($p = 0.011$); this decrease was significantly greater in HRC than in CG ($p = 0.039$). There were significant improvements in walking economy in the HRC group ($p < 0.049$), although there were no statistical differences between groups. There were no changes in any variables in CG. Hence, HRC training was as effective as TS for improving isokinetic strength, bone mineral density and lean mass. Only HRC training elicited adaptations in the cardiovascular system and a decrease in fat mass.

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1. Introduction

The biological aging process is associated with a structural and functional deterioration in most physiological systems, including the neuromuscular and cardiovascular systems. These age-related changes affect a broad range of tissues, organ systems and functions which, cumulatively, can negatively impact activities of daily living in older adults (Chodzko-Zajko et al., 2009). Changing body composition is a hallmark of the physiological aging process, which has

profound effects on health. Specific examples include the gradual accumulation of body fat and its redistribution to central and visceral depots during middle age (Hunter et al., 2002), the loss of muscle mass and muscle function (sarcopenia) (Cruz-Jentoft et al., 2010) during middle and old age with the attendant metabolic (Janssen and Ross, 2005) and cardiovascular disease risks (Chodzko-Zajko et al., 2009), and a marked osteopenia (Marshall et al., 1996). Declines in maximal aerobic power and skeletal muscle force production with advancing age are examples of functional declines with aging, which can severely limit physical performance and independence and are negatively correlated with all cause mortality (Blair et al., 1995; Gulati et al., 2005; Laukkanen et al., 1995; Metter et al., 2002; Rantanen et al., 2000; Ruiz et al., 2008; Sui et al., 2007).

Exercise can elicit a broad range of physiological changes. Nonetheless, adaptations are specific to the exercise mode and intensity, so several concurrently implemented regimes need to be performed. For example, it is well known that both endurance exercise and resistance training can substantially improve physical fitness and health-related factors in older individuals (Cadore et al., 2012, in press; Paoli et al., 2010). However, while endurance training is purported to be more effective for decreasing fat mass (Kay and Fiatarone Singh, 2006), resting

Abbreviations: BMD, bone mineral density; CG, control group; DEXA, dual X-ray absorptiometry; ECG, electrocardiogram; EE, energy expenditure; GPAQ, global physical activity questionnaire; HRC, high-resistance circuit; LM, lean mass; RM, repetition maximum; TS, traditional heavy strength; VCO₂, carbon dioxide production; VE, ventilation; VO₂, oxygen uptake; VT, second ventilatory threshold.

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heart rate (Huang et al., 2005) and blood pressure (Seals et al., 1984), resistance training has been shown to be more effective for increasing basal metabolism (Hunter et al., 2000; Paoli et al., 2012), bone mineral density (BMD) (Rhodes et al., 2000; Vincent and Braith, 2002), muscle strength and power (Fiatarone et al., 1990; Hakkinen et al., 2001; Lexell et al., 1995), and muscle and connective tissue cross-sectional area (Hunter et al., 2004). Thus, whilst an exercise program incorporating both aerobic and resistance exercises can result in significant and wide-ranging improvements in body composition and physiological function, the time (and monetary) investment may be problematic for program adherence.

Some researchers have shown that circuit-based resistance training, where lighter loads are lifted with minimal rest, is very effective for increasing maximum oxygen consumption, maximum pulmonary ventilation, functional capacity, and strength while improving body composition (Brentano et al., 2008; Camargo et al., 2008; Gettman et al., 1979; Harber et al., 2004). Thus, circuit training is a time-efficient training modality that can elicit demonstrable improvements in health and physical fitness. A significant drawback of standard circuit training programs, however, is that the loads lifted are typically low, so the stimulus for strength and muscle (Paoli et al., 2010) and bone mass (Brentano et al., 2008) adaptations is minimal. This is a notable problem for older individuals, for whom increasing muscle and bone mass in addition to functional strength is essential for improvements or maintenance in overall functional capacity.

Recent research (Alcaraz et al., 2008, 2011) has shown that healthy young adults could produce the same muscular force output in a session of high-resistance circuit (HRC) training as in a traditional heavy strength training session, under the same loading conditions, but that the cardiorespiratory response was greater with HRC training. Thus, HRC training may be an effective alternative for older individuals. In the present study, we have examined the effects of HRC training on muscle mass and strength, body composition and measures of cardiovascular fitness in healthy older adults. Specifically, whilst we hypothesized that HRC training would lead to significant improvements in cardiovascular fitness, we were particularly interested in determining whether muscle mass, strength and body composition (including bone mineral density) changes would be comparable to those elicited by traditional heavy strength training.

2. Methods

2.1. Subjects

Healthy, untrained 55–75 year-old men and women were recruited for the investigation by poster advertising. A telephone interview was conducted by an examiner to ascertain medical history, occupational commitments and current physical activity status. Subjects with no contraindications to exercise were invited for a clinical examination. The participants were informed about the design of the study and possible risks and discomforts related to the testing and training, after which they read and signed an informed consent document. All participants were free to withdraw from the study at any time, the study was conducted according to the Helsinki Declaration (1964; revised in 2001), and the experimental protocol was approved by the Human Subjects Ethics Committee of the San Antonio Catholic University of Murcia, Spain. All participants underwent an examination of general health and a resting 12-lead electrocardiogram (ECG), the results of which were analyzed by a cardiologist. Subjects without cardiovascular or musculoskeletal disorders, or taking medications known to influence cardiovascular or neuromuscular performance, were invited to continue in the study. These subjects were considered healthy and physically active, but none had background in systematic strength or endurance training. The characteristics of the final subject cohort at baseline are presented in Table 1.

Table 1
Descriptive data by training groups. Values are given as mean (SD).

	HRC (n = 16)	TS (n = 14)	CG (n = 7)	P-value
Age (years)	62.1 (6.3)	64.8 (4.5)	58.0 (5.0)	0.714
BMI ($\text{kg} \cdot \text{m}^{-2}$)	29.7 (4.1)	30.2 (6.0)	29.9 (5.8)	0.973
VO_2 LM peak ($\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$)	37.0 (7.4)	35.2 (8.2)	41.7 (5.4)	0.494
$\text{TQ}_{\text{KE}} 90^\circ \cdot \text{s}^{-1}$ (N·m)	47.2 (23.5)	43.1 (20.8)	52.0 (12.2)	0.477
$\text{TQ}_{\text{EF}} 90^\circ \cdot \text{s}^{-1}$ (N·m)	22.8 (8.2)	21.7 (7.7)	27.7 (10.9)	0.811

BMI = body mass index; $\text{VO}_{2\text{peak}}$ = peak oxygen uptake; LM = lean mass; $\text{TQ}_{\text{KE}} 90^\circ \cdot \text{s}^{-1}$ = Peak isokinetic torque in knee extension at $90^\circ \cdot \text{s}^{-1}$; $\text{TQ}_{\text{EF}} 90^\circ \cdot \text{s}^{-1}$ = peak isokinetic torque in elbow flexion at $90^\circ \cdot \text{s}^{-1}$; HRC = high-resistance circuit group; TS = traditional strength group; CG = control group.

2.2. Experimental design

Before data collection, the participants took part in a familiarization session for each test. One week after the familiarization the dependent variables were tested, as described below. Subsequently, the participants were matched with respect to gender, age, body mass index, peak oxygen uptake and pre-training torque production (peak isokinetic torque measured at $90^\circ \cdot \text{s}^{-1}$), and then randomly allocated to either a high-resistance circuit training (HRC), traditional heavy strength training (TS) or control group (CG). To test the reliability of the performance variables, ten subjects were evaluated twice before the start of training (weeks -1 and 0). The subjects were tested by the same investigator, using the same protocol and at the same time of day at weeks 0 and 13. In session 1, isokinetic concentric strength of the knee and elbow extensor/flexor muscle groups was measured at 90 and $270^\circ \cdot \text{s}^{-1}$. In session 2, completed 3–4 days after session 1, body composition (dual X-ray absorptiometry; DEXA) and aerobic power (progressive treadmill test to exhaustion) tests were completed. For the completion of all experimental protocols, the subjects fasted for 3–4 h before the testing, did not ingest stimulants for 8 h (i.e. caffeine), were allowed to hydrate at will, and avoided practicing intense exercise during the previous 24 h. During the 12-week training period, both training groups (HRC and TS) performed training with heavy loads (6RM) using a BH Fitness equipment (BH Fitness, Vitoria, Spain), in undulating periodized programs twice a week. All subjects were asked to maintain their normal daily routines and eating habits, to not take nutritional supplements that might affect lean tissue mass or bone metabolism, and to refrain from commencing new exercise programs for the duration of the study. Diet and training logs were obtained unannounced by an instructor in weeks 1, 6 and 11 to ensure compliance (see details below).

2.3. Isokinetic strength measurements

Seated knee and elbow flexion/extension strength of the dominant limb was tested on a Biodex System Pro isokinetic dynamometer (Biodex Medical Systems, Shirley, NY) at angular velocities of 90 and $270^\circ \cdot \text{s}^{-1}$. The subjects sat upright on the adjustable chair and were tightly secured with shoulder, waist and thigh straps to minimize extraneous movement. The dynamometer was calibrated prior to testing according to procedures outlined by the manufacturer, and gravity correction was performed with the dynamometer lever arm close to the horizontal position. The respective joint centers were aligned with the axis of rotation of the dynamometer. The lever arm (shin pad) was attached immediately proximal to the ankle for knee flexion/extension tests and a handle was grasped tightly by the hand for performance of elbow flexion/extension tests. Time between tests was kept constant at 15 min, which allowed sufficient time for setting up the subsequent tests.

After a general warm-up (5 min on a cycle ergometer and active stretching) each subject performed 3–5 sub-maximal contractions

at the test velocity to become accustomed the movement, before commencing the test. The subjects performed one set of three ($90^\circ \cdot s^{-1}$) or five ($270^\circ \cdot s^{-1}$) maximal concentric knee and elbow flexion/extension movements after being instructed to generate maximum force as rapidly as possible. The peak concentric torque obtained for each test was used for analysis. The test–retest reliability coefficient (ICC) for this device was 0.99.

2.4. Body composition measurement

Total and regional bone, fat and lean (body mass – [fat mass + bone mass]) masses were assessed by dual-energy X-ray absorptiometry (DEXA). The DEXA scanner (XR-46, Norland Corp., Fort Atkinson, WI, USA) was calibrated using a lumbar spine phantom. To ensure the reliability of the DEXA measurements, all pre- and post-training scans were conducted and analyzed by the same operator. The subjects were scanned in the supine position with the least (non-metallic) clothing possible. The X-ray scanner performed a series of transverse scans moving at 1-cm intervals from top to bottom of the whole body. Lean mass (g) and fat mass (g) were calculated from total and regional analysis of the whole body scan. Areal bone mineral density (BMD; $g \cdot cm^{-2}$) was calculated using the formula $BMD = BMC \times area^{-1}$. Lean mass of the limbs was assumed to be equivalent to the muscle mass. The test–retest reliability coefficient (ICC) for this device was very high ($R^2 = 0.99$; $p = 0.001$) in both cases. DEXA measures were performed before any strength measures to minimize any effects of fluid shifts.

2.5. Cardiovascular parameters

An incremental treadmill (Naughton protocol) exercise test supervised by a physician was used to assess aerobic capacity, with simultaneous ECG monitoring. After a 1-min warm-up walking at $3 \text{ km} \cdot \text{h}^{-1}$ at 0% inclination the treadmill velocity was increased to $5 \text{ km} \cdot \text{h}^{-1}$ and kept constant throughout the test. Inclination was increased 3.2° at each 2-min stage until voluntary exhaustion; subjects were encouraged to continue to exercise as long as possible. During the exercise test, the subjects breathed through a face mask, which allowed breath-by-breath analysis of expired O_2 and CO_2 using an automated gas-analysis system (Vmax 29c, SensorMedics, Yorba Linda, USA). Ventilation (VE), oxygen uptake (VO_2) and carbon dioxide production (VCO_2) were determined from the expired air. Before each test, the O_2 and CO_2 analysis systems were calibrated using ambient air and a gas mixture of known O_2 and CO_2 concentrations (15% O_2 and 5% CO_2). The pneumotachograph was calibrated before each test with a 3-L calibration syringe (3 liter calibrated syringe-d, SensorMedics, Yorba Linda, USA) for low and high flows. Heart rate was monitored and continuously recorded (Polar S610). For data analysis, VO_2 , VE, VCO_2 , and HR values were averaged every 20 s. Peak VO_2 was defined as the mean VO_2 during the last minute of the exercise test. The second ventilatory threshold (VT) was determined by two experienced, independent physiologists using a combination of breakpoints in the relationship between VO_2 and VCO_2 (the V-slope method) and a systematic increase in the VE/VO_2 without a concomitant increase in VE/VCO_2 . Gas exchange was converted to energy expenditure (EE) with the use of the Weir formula (Weir, 1949). Physiologic and electrocardiographic exercise termination points were consistent with the Guidelines for Exercise Testing and Prescription of the American College of Sports Medicine (Thompson et al., 2009). The test–retest reliability coefficients were 0.88 for VO_2 peak and 0.85 for VT.

2.6. Traditional heavy strength (TS) training

Subjects in the TS group performed resistance training twice a week for 12 weeks with at least 1-day of rest between each training day (i.e. Monday and Thursday or Tuesday and Friday). An undulating periodized resistance training program was followed, as shown in

Fig. 1b. After a general warm-up, the subjects performed 2 sets of three exercises (leg curl, pec deck, seated calf raise) using the following sequence: 12 repetitions at 50% of 6RM (i.e. the load that induced failure after 6 repetitions), 1-min rest, 10 repetitions at 75% of 6RM, 2-min rest, and then the first main training set (i.e., 100% of 6RM). The 6RM load was adjusted for the subsequent set by approximately 2% if a subject performed ± 1 repetitions, or by approximately 5% if a subject performed ± 2 repetitions. In every session the subjects lifted weights that allowed only six repetitions to be performed (6RM, ~85–90% of 1RM). The eccentric phase of each exercise was performed over approximately 3 s, whereas the concentric phase was performed at maximum velocity. This sequence was standardized in the first training week and eccentric phase duration was regularly timed as feedback for the subjects. After completion of the first three exercises, the subjects completed the other three exercises (seated pulley row, leg extension, and preacher curl) with same warm-up sequence (~5 min; Fig. 1a). The subjects performed the exercises one after the other with a rest of 3 min between each series. These exercises were chosen to emphasize both major and minor muscle groups, using single- as well multi-joint exercises, based on recommendations of the ACSM (Garber et al., 2011). The subjects were supervised by an experienced lifter to ensure that volitional fatigue was achieved safely, and the control of the rest was strict. The total training time in the TS group ranged between 45 min (1 set) and 87 min (3 sets).

2.7. High-resistance circuit (HRC) training

Training performed by the HRC group differed from TS only in the rest interval between the exercises and the sequencing of exercises. While the TS subjects performed the exercises one after the other with a rest of 3 min between each series, HRC subjects executed the training in two short circuits with a separation of 5 min. The first circuit consisted of leg curl, pec deck and seated calf raise exercises, whilst the second circuit consisted of seated pulley row, leg extension and preacher curl exercises (Fig. 1a). Approximately 35 s separated each exercise, which allowed enough time to move safely between exercises. These two short circuits were performed for 1–3 series' (undulating periodization; Fig. 1b). The warm-up, and intensity and volume of exercises were the same as that completed by TS. Again, the subjects were supervised by an experienced lifter to ensure that volitional fatigue was achieved safely, and the control of the rest was strict. The total training time in the HRC group ranged between 35 min (1 set) and 47 min (3 sets).

2.8. Diet and activity logs

Subjects were instructed to maintain their accustomed dietary and physical activity habits throughout the course of the study. To verify compliance with these instructions, dietary and activity habits were assessed on three occasions (1, 6 and 11 weeks). An experienced instructor obtained dietary and physical activity records from the subjects without warning. On all occasions, dietary logs were recorded for three consecutive days, including one weekend day. The 3-day dietary records were analyzed for total caloric intake and for carbohydrate, fat and protein composition using commercially available computer software (DietSource 3.0; Novartis, Barcelona, Spain). The three groups demonstrated a substantial similarity: 61% carbohydrates, 20% proteins, 19% lipids. To monitor physical activity, Global Physical Activity Questionnaire (Armstrong and Bull, 2006) was also completed by the subjects.

2.9. Statistical analyses

SPSS (v18.0) statistical software was used to analyze all data. Subjects' physical characteristics are reported as means \pm standard deviation. The normal Gaussian distribution and homogeneity parameters

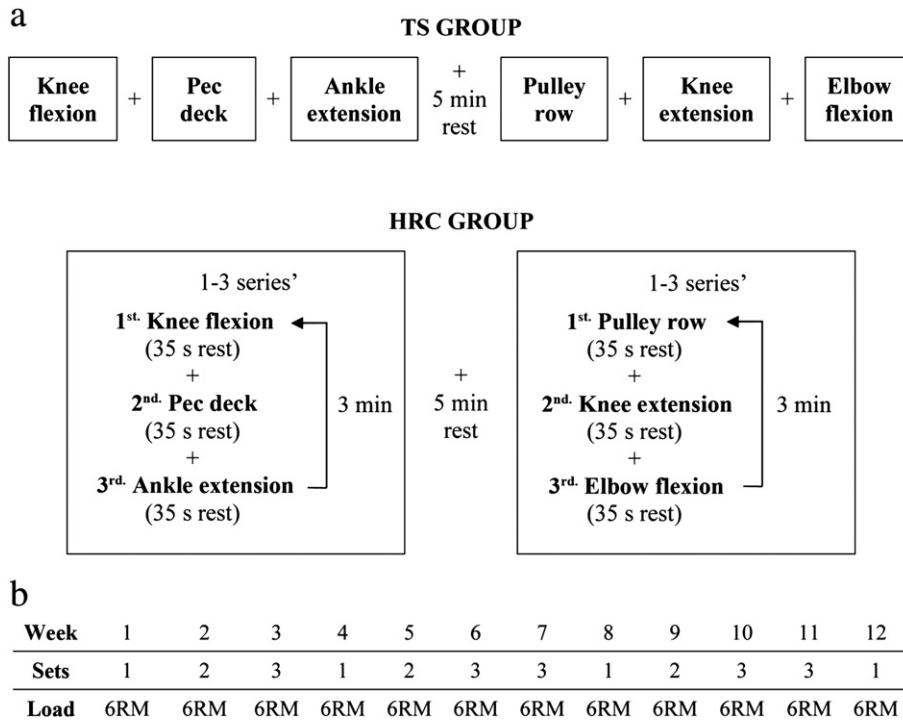


Fig. 1. Experimental design. TS performed 1–3 sets of each exercise with a 3-min rest between sets, although a 5-min rest was allowed after the third exercise. HRC performed 1–3 series' of two circuits with a 5-min rest. An undulating periodized resistance training program was followed by both experimental groups.

were checked with Shapiro–Wilk and Levene tests, respectively. The training-related effects were analyzed using two-way ANOVA with repeated measures to differentiate between pre- and post-training scores. Selected relative changes between groups were then compared using one-way ANOVAs. Significance was accepted when $p < 0.05$ and statistical power was over 80% for all analysis.

3. Results

The study was based on 37 participants selected among 45 respondents to the initial invitation. Of the 45 respondents, three were rejected after the clinical examination due to medical problems (active tuberculosis, electrocardiographic abnormalities, musculo-skeletal pathology). The 42 subjects who passed the medical examination were randomly allocated to HRC ($n = 16$), TS ($n = 16$) and CG ($n = 10$). Five subjects dropped out during the training period: two participants dropped out due to illness in TS, and another three dropped out citing professional problems in CG. At the end of the study, the number of subjects in each group was as follows: HRC, $n = 16$; TS, $n = 14$; and CG, $n = 7$. None of the drop-outs left the program as a result of injuries or adverse responses to the treatment.

Pre-training characteristics of subjects in each training group are presented in Table 1. No significant differences in any of these characteristics were found between HRC, TS and CG at the beginning of exercise training. No significant differences were observed in training compliance between HRC and TS (91.2 ± 3.7 vs. $94.6 \pm 3.1\%$, respectively).

3.1. Isokinetic strength

Concentric isokinetic strengths for knee and elbow flexion/extension tests are presented in Fig. 2. Two-way ANOVA with repeated measures revealed a significant effect of time ($p < 0.001$) for the HRC and TS groups, but not CG, for all tests. One-way ANOVA showed that the increases in TS and HRC were greater than CG for elbow flexion at $90^\circ \cdot s^{-1}$ (TS: $p = 0.001$; and HRC: $p = 0.014$), knee extension at $90^\circ \cdot s^{-1}$ (TS: $p = 0.009$; and HRC: $p = 0.007$) and knee flexion at

$270^\circ \cdot s^{-1}$ (TS: $p = 0.005$; and HRC: $p = 0.030$). There was no difference in the change in performance between HRC and TS.

3.2. Body composition

Two-way ANOVA with repeated measures revealed a significant effect of time for changes in body fat (%) ($p = 0.000$), total lean mass ($p = 0.000$), total fat mass ($p = 0.011$) and BMD_{total} ($p = 0.025$) for the HRC group, and for the change in total lean mass ($p = 0.025$) and BMD_{total} ($p = 0.018$) for the TS group. There were no changes in any variables in CG (Table 2). One-way ANOVA showed that the decrease in HRC was greater than in TS for body fat (%) ($p = 0.036$), and the decrease in HRC was greater than in CG for body fat (%) ($p = 0.016$), fat mass ($p = 0.039$) and the increase in HRC was greater than in CG for lean mass ($p = 0.033$).

3.3. Cardiovascular parameters and walking economy

Mean values (\pm SD) for VO_2 and energy expenditure (EE) obtained in the incremental treadmill test are presented in Table 3. All subjects performed valid tests. Two-way ANOVA with repeated measures revealed a significant decrease in VO_2 relative to lean mass (VO_2 LM) to 1 min ($p = 0.001$), 3 min ($p = 0.000$) and VT ($p = 0.049$) in HRC group. In addition, there was a significant decrease in EE to 1 min ($p = 0.022$), 3 min ($p = 0.000$) and 5 min ($p = 0.012$) for the HRC group. There were no changes in any variables in TS and CG (Table 3). There were no differences in the changes between any groups.

4. Discussion

The present results clearly demonstrate that the performance of high-resistance circuit (HRC) training can be as effective as traditional heavy strength (TS) training for improving muscle mass, strength and bone mineral density (BMD), but is more effective at stimulating positive cardiovascular and body composition (i.e. fat mass decrease)

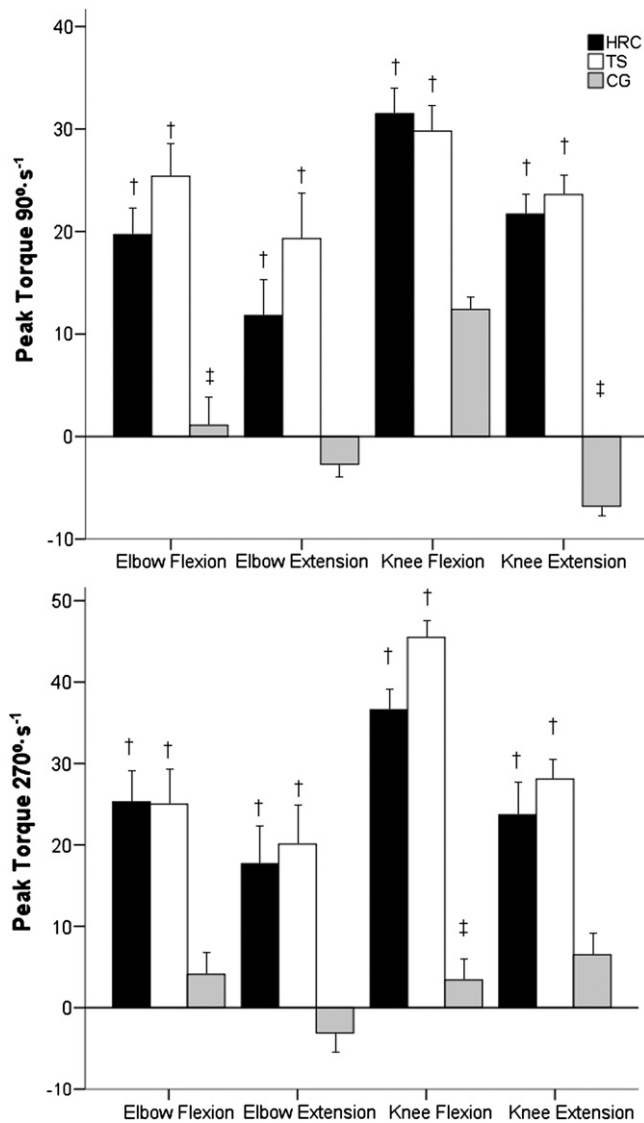


Fig. 2. Change (%) in peak torque at angular velocities of $90^{\circ}\cdot\text{s}^{-1}$ and $270^{\circ}\cdot\text{s}^{-1}$ for elbow and knee flexion/extension for each group. †significant difference from pre- to post-training ($p < 0.01$); ‡significant difference between the training groups (HRC and TS) and CG ($p < 0.05$).

adaptations in older individuals. The present findings are important because they indicate that HRC training might be a time (and hence cost) effective way of triggering multiple positive physiological adaptations in this population.

Maximum muscular strength is strongly and negatively associated with risk of all cause mortality (Laukkanen et al., 1995; Metter et al., 2002; Rantanen et al., 2000; Ruiz et al., 2008) and is thought to be a major factor influencing ambulatory or daily ability and fall risk in

the elderly (Hyatt et al., 1990; Robbins et al., 1989; Tiedemann et al., 2011). Although it is known that heavy strength training elicits substantial gains in muscular strength, even in the oldest individuals (Fiatarone et al., 1990), circuit training using lower loads has previously been shown not to promote comparable strength increases as traditional weights training (Brentano et al., 2008) in older adults. This is probably because the use of high loads in resistance training is known to be mandatory for optimum gains in muscular strength (Berger, 1962; Caiozzo et al., 1981) and is a key determinant of overall muscle fiber hypertrophy (see Fry, 2004 for review). However, we found that improvements in muscular strength in response to HRC training were similar to those obtained by TS. Muscle strength improved 22–46% for knee flexion/extension and 12–25% for elbow flexion/extension at both slower ($90^{\circ}\cdot\text{s}^{-1}$) and faster ($270^{\circ}\cdot\text{s}^{-1}$) angular velocities. Both training groups, HRC and TS, demonstrated large increases in strength in the current study, which was not surprising considering that the subjects had little or no previous training experience. In previous studies it was considered that, in view of short duration of the study, the strength gains were likely to be a result of neural adaptation rather muscular hypertrophy (Staron et al., 1994). In the present study it was found that these improvements in strength were accompanied by an increase in muscle mass (HRC = 3.4%; and TS = 2.2%), which suggests that, in addition to neural adaptations, morphological adaptations were also elicited. One possible limitation was the use of non-specific isokinetic tests for the strength measurements rather than specific, 1RM, tests. The use of isoinertial tests (using the same movement patterns as used in training) in future might more clearly demonstrate the changes in muscular strength elicited by the training.

Few previous studies have examined the effect of high-load circuit training, probably because subjects were not considered to be able to develop the same muscular force outputs due to fatigue resulting from the short recovery time. However, Alcaraz et al. (2008) found that the strength, power and total workload were similar when young adults performed HRC vs. TS training. Paoli et al. (2010) subsequently examined the effects of HRC vs. traditional (lower load) circuit training in older adults (age = 50–65 years) and found that HRC was more effective than low intensity circuit training for improving body composition (i.e. decreased fat mass) and improving muscle strength. Nonetheless, it was still not known whether significant cardiovascular and BMD adaptations, comparable to traditional heavy strength training, could be induced using a higher-load and lower-volume version of circuit training. The present results clearly show that HRC can elicit significant and broad ranging physiological adaptations.

Another important finding was that HRC training resulted in significant increases in BMD. After 12 weeks of training whole body BMD was moderately but uniformly increased (1.1–1.2%) in both experimental groups, whereas it did not change (–0.3%) in the control group. Aging is associated with a significant loss of BMD, which makes the bones more susceptible to fractures (Marshall et al., 1996). It is unsurprising that positive effects were seen in our previously untrained older participants since increases in BMD have been

Table 2
Changes in body composition parameters. Values are given as mean (SD).

	HRC			TS			CG		
	Pre	Post	%Δ	Pre	Post	%Δ	Pre	Post	%Δ
Body fat (%)	42.3 (5.4)	40.5 (5.0)	–4.4 ^a	42.2 (9.1)	41.6 (9.1)	–1.4 ^b	41.1 (11.3)	41.1 (11.0)	0.0 ^b
Fat mass (kg)	31.0 (5.7)	29.9 (6.1)	–3.7 ^a	31.8 (9.7)	31.4 (10.2)	–1.3	31.4 (11.5)	31.8 (11.6)	1.0 ^b
Lean mass (kg)	40.3 (9.1)	41.7 (9.0)	3.4 ^a	40.3 (6.8)	41.2 (6.9)	2.2 ^a	41.8 (7.8)	42.1 (7.8)	1.0 ^b
BMD _{total} ($\text{g}\cdot\text{cm}^{-2}$)	0.918 (0.098)	0.929 (0.108)	1.2 ^a	0.932 (0.137)	0.942 (0.130)	1.1 ^a	0.900 (0.078)	0.897 (0.071)	–0.3

BMD = bone mineral density; Δ = change.

^a Significant difference from pre- to post-training ($p < 0.05$).

^b Significantly different from HRC ($p < 0.05$).

Table 3

Cardiovascular parameters before and after training. Values are given as mean (SD).

	HRC			TS			CG		
	Pre	Post	%Δ	Pre	Post	%Δ	Pre	Post	%Δ
VO ₂ LM to 1 min (ml/kg·min)	27.3 (6.7)	23.9 (6.3)	−14.2 ^a	27.3 (5.7)	23.5 (4.5)	−16.2	28.2 (7.4)	26.7 (7.7)	−5.6
VO ₂ LM to 3 min (ml/kg·min)	32.4 (7.7)	27.9 (5.9)	−16.1 ^a	29.7 (5.6)	29.3 (3.7)	−1.4	32.2 (8.8)	29.7 (6.1)	−8.4
VO ₂ LM to VT (ml/kg·min)	34.1 (7.9)	31.0 (6.7)	−10.0 ^a	30.9 (4.5)	31.4 (6.8)	1.6	33.6 (5.5)	33.6 (2.4)	0.0
VO ₂ LM peak (ml/kg·min)	37.0 (7.4)	35.6 (7.9)	−3.9	35.0 (5.7)	36.2 (8.2)	3.3	41.7 (5.4)	43.2 (10.2)	3.5
EE to 1 min (kcal)	22.7 (5.5)	20.8 (5.9)	−9.1 ^a	23.0 (4.8)	20.6 (5.4)	−11.7	23.2 (4.3)	20.5 (3.8)	−13.2
EE to 3 min (kcal)	27.9 (6.7)	24.3 (6.1)	−14.8 ^a	25.6 (4.1)	24.2 (6.1)	−5.8	26.8 (4.2)	24.0 (2.6)	−11.7
EE to 5 min (kcal)	29.6 (7.2)	26.7 (7.0)	−10.9 ^a	27.6 (5.0)	28.1 (5.7)	1.8	27.1 (2.5)	25.5 (2.0)	−6.3
EE to 7 min (kcal)	32.5 (8.7)	30.9 (7.0)	−5.2	29.6 (6.0)	30.7 (6.6)	3.6	27.7 (2.1)	28.7 (3.0)	3.5

LM = lean mass; VO₂ = oxygen consumption; EE = energy expenditure; Δ = change.^a Significant difference from pre- to post-training (*p* < 0.05).

shown to be stimulated by strength training (Lohman et al., 1995; Vincent and Braith, 2002). However, that such increases could be elicited by a training mode that also resulted in significant positive improvements in body composition and movement (walking) economy is of substantial clinical importance. The low intensities normally adopted in traditional circuit weight training may limit the possibility of increasing BMD (Brentano et al., 2008; Gettman et al., 1982), and the few studies (Brentano et al., 2008; Rhodes et al., 2000) that have examined the effects of circuit resistance training on BMD in older people found no change, suggesting that the higher loading intensity was key to stimulating increases in BMD.

Although the main aims of the study were to compare changes in muscle mass, strength and BMD elicited by HRC training to those achieved with TS training, we also hypothesized that HRC training would promote substantial improvements in body composition and cardiovascular fitness. Such improvements were clearly seen, despite the use of the lower training volumes associated with the need for a high force production in HRC training. Modifications in lean-to-fat mass ratios and improved cardiovascular function have been closely linked with reductions in disease risk and all cause mortality (Blair et al., 1995; Gulati et al., 2005; Sui et al., 2007). Thus, HRC training shows enormous promise as a health modification intervention. O₂ consumption at submaximal walking intensities decreased, which is indicative of an improvement in walking economy. We speculate that the training did not change movement kinematics, although this remains to be verified, so our data most likely suggest that there was an improvement in intra-muscular energy conversion efficiency (e.g. changes in mitochondrial function, glucose transport or muscle fiber type, which occur with high-intensity fatiguing exercise; e.g. Baar, 2006), an improved neuromuscular economy (e.g. lesser motor unit recruitment at the same absolute load during the incremental aerobic test after strength training; Cadore et al., 2011a, 2011b) or an improved efficiency of force transfer from the muscles to the ground (e.g. altered tendon mechanical properties; Reeves et al., 2004). The lesser energy expenditure, and thus greater movement economy, should reduce perceptions of effort and overall fatigue during walking, and may increase the likelihood that individuals will tolerate walking exercise (McAuley, 1992) and increase exercise adherence. A more detailed examination of the mechanisms underpinning the greater movement economy is an important goal of future research.

In summary, the present study shows that 12 weeks of high-resistance circuit training is well tolerated and can lead strength, muscle mass and bone mineral density gains in healthy older population. These improvements are similar to those obtained with traditional heavy-resistance training, with the advantage that HRC training requires less time than TS training. From a practical point of view these results are of particular significance for the elderly since the decrease in muscle mass, strength and power associated with aging can have a negative influence on mobility, which, when added to the loss of balance and decreased bone mass, increases fall, and subsequently fracture,

risk. In addition, only HRC training elicited greater adaptations in cardiovascular system and body composition (i.e. decrease fat mass), which indicates that its use may help to prevent cardiovascular disease and improve movement economy in older individuals.

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