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Comparison of time-matched aerobic, resistance, or concurrent exercise training in older adults

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A supervised 12-week intervention of time-matched aerobic vs resistance versus concurrent exercise training was employed to investigate mode- and time course-specific effects of exercise training in older adults. Community-dwelling men and women (n = 84; M/F, 45/39; 69.3 ± 3.5 years; 26.4 ± 3.8 kg m^{-2}) were randomly assigned (n = 21 each) to either non-exercise control (CON), aerobic exercise only (AER), resistance exercise only (RES), or concurrent aerobic and resistance exercise (CEX). Training groups trained three times per week, each performing 72 minutes of active exercise time per week. Body composition, physical and cognitive function, and markers of metabolic health were assessed before (PRE), and after 6 (MID) and 12 (POST) weeks of exercise training. Hand-grip strength, 1RM chest press, and arm LBM were improved by both RES and CEX, but not AER. Aerobic fitness increased in AER and RES, but not CEX. Cognitive function improved in all groups, but occurred earlier (ie, at MID) in AER. CEX improved gait speed and lower limb strength and reduced trunk fat compared to either AER or RES. Leg LBM was unchanged in any group. Temporal patterns were observed as early as 6 weeks of training (gait speed, upper and lower limb strength, aerobic fitness), whereas others were unchanged until 12 weeks (hand-grip strength, timed up-and-go, sit-to-stand). Compared to either aerobic or resistance exercise training alone, concurrent exercise training is as efficacious for improving a range of health-related parameters and is more efficacious for increasing gait speed and lower limb strength, and decreasing trunk fat in older adults.

KEYWORDS
aerobic fitness, body composition, combined training, function, lean body mass, strength

1 | INTRODUCTION

A lack of adequate physical activity is associated with elevated risk of lifestyle-related chronic diseases such as type 2 diabetes, obesity, and cardiovascular disease,[1] in addition to the etiology of the loss of muscle mass and function in sarcopenia.[2] Regular exercise can delay the onset of many of these conditions or can be used for therapeutic means when a clinical condition manifests.[3] Both aerobic and resistance exercise trainings have efficacy in prevention and treatment of lifestyle-related chronic disease,[4] but much remains to be elucidated about optimal exercise prescription in older adults.[5]

There is increasing interest in the therapeutic value of combined aerobic and resistance exercise, termed concurrent exercise training.[5] In insulin-resistant, obese adults[6] and type 2 diabetics,[7] concurrent exercise training is more effective than either mode alone for improving insulin sensitivity and

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glycemic control. Importantly, in the context of older adults and the threat of declining lean body mass (LBM) to healthy aging, a resistance exercise component is essential if an increase in LBM is to be achieved.[6] Concurrent training has historically been associated with an "interference" effect, whereby improvements in muscle size and strength associated with resistance exercise training alone are attenuated when aerobic exercise is performed concurrently.[8] However, in recent years, evidence has accrued that contradicts this interference effect,[9-11] particularly, in older adults for whom concurrent exercise training is likely the most appropriate approach to simultaneously target improvements in muscle strength, aerobic fitness, and physical function in a time-efficient manner.[5]

Previous studies in older adults have investigated various parameters that influence training prescription including effects of concurrent training per se,[6,9-14] training frequency,[15,16] and exercise order.[17,18] However, in many studies to date, the concurrent exercise training groups have typically performed a larger total training volume than either mode alone, with only a handful examining outcomes when the training volume of concurrent training is matched or similar to either training mode alone.[11,19-22] Hence, whether the observed differences between single mode and concurrent training interventions are due to the volume of exercise, or the concurrent stimulus is unresolved, particularly in older adults. In addition, the time course of change is poorly described, yet this is a key practical question when considering exercise interventions for therapeutic aims. Therefore, this study employed a supervised 12-week intervention of time-matched aerobic versus resistance versus concurrent exercise training to investigate mode- and time course-specific effects of exercise training on body composition, physical and cognitive function, and markers of metabolic health in older adults.

2 | MATERIALS AND METHODS

2.1 | Study design and participants

A randomized controlled trial of 12 weeks of time-matched aerobic versus resistance versus concurrent exercise training was performed in men and women aged over 65 years. All experimental procedures were approved by the University College Dublin (UCD) Research Ethics Committee (permit: LS-15-35-Timmons-Egan) in accordance with the *Declaration of Helsinki*. Participants provided written informed consent prior to participation. Recruitment was primarily through the UCD Alumni newsletter seeking men and women aged >65 years who were medically stable,[23] and who were free-living, fully mobile and capable of completing the proposed intervention. Participants were excluded if they reported a history of myocardial infarction, cardiac illness, vascular disease, uncontrolled metabolic disease, stroke, or major systemic disease; or if already engaging in two or more structured exercise sessions per week.

A sample size requirement of n = 20 per group was calculated a priori (G*Power v3.1). This was based on a four group design and the assumption of detecting a moderate effect size (partial $\eta^2 = 0.06$) for a given parameter, a moderate correlation of $r = 0.5$ among repeated measures, an α level of 0.05, and power ($1-\beta$) of 0.8. Of the n = 173 individuals who expressed interest in the study, n = 63 did not meet the inclusion criteria, n = 22 declined to participate, and n = 4 either moved abroad or had unexpected travel commitments prior to the commencement of the assessments (Figure S1). Upon entry to the study, participants (n = 86; Figure S1) were randomly assigned to one of the following four groups: non-exercise control (CON), aerobic exercise only (AER), resistance exercise only (RES), concurrent aerobic, and resistance exercise (CEX). Two members of the RES group discontinued the intervention because of travel commitments and moving abroad leaving a final sample size of n = 84 (Table 1). A member of the research team not involved in the intervention or assessments was responsible for the assignment of groups via random number generation. The respective training groups trained at the same facility, but in small groups separate from one another. A battery of assessments including body composition, physical and cognitive function, and blood-borne markers of metabolic health was performed before (PRE), and after 6 (MID) and 12 (POST) weeks of exercise training. Investigators involved in these assessments were blinded to the group assignments, and participants were asked not to discuss the intervention during these visits.

2.2 | Assessments

The assessment procedure was identical in content and sequence at each time point and performed over two consecutive days by the same personnel. On day 1, participants arrived to the laboratory after an overnight fast and minimal morning ambulation. Body mass (to the nearest 0.2 kg) using a calibrated digital scales (SECA, Hamburg, Germany), height (to the nearest 0.01 m) using a wall-mounted stadiometer (Holtain, Crymych, Pembs., UK), and body composition by dual-energy X-ray absorptiometry (DXA; Lunar iDXA, GE Healthcare, Chicago, IL, USA) were measured. Supine resting heart rate and blood pressure were then measured in duplicate using an automated blood pressure monitor (Omron, Lake Forest, IL, USA). Next, a blood sample was collected from a superficial forearm vein by venipuncture. Whole blood was collected in two separate tubes (~4 mL each) for the separation of serum and plasma (lithium heparin-coated tubes) by centrifugation at 3000 g for 10 minutes at 4°C, followed by storage of aliquots at −80°C. Samples were

Table 1. Participant characteristics at baseline (PRE)

	CON (n = 21) Mean ± SD	AER (n = 21) Mean ± SD	RES (n = 21) Mean ± SD	CEX (n = 21) Mean±SD	ALL (n = 84) Mean±SD	*P* value ANOVA
Anthropometry						
M/F (n/n)	8/13	11/10	10/11	16/5	45/39	
Age (y)	69.0 ± 3.3	69.2 ± 3.1	69.6 ± 4.9	69.2 ± 2.7	69.3 ± 3.5	0.895
Height (m)	1.68 ± 0.11	1.68 ± 0.09	1.68 ± 0.08	1.73 ± 0.06	1.69 ± 0.09	0.164
Body mass (kg)	75.2 ± 16.2	70.2 ± 13.8	76.6 ± 13.2	82.6 ± 15.3	76.2 ± 15.1	0.061
BMI (kg m^{-2})	26.4 ± 3.8	24.9 ± 4.0	26.9 ± 3.6	27.5 ± 3.7	26.4 ± 3.8	0.158
Body fat (%)	35.5 ± 6.8	31.7 ± 7.3	35.3 ± 6.1	31.6 ± 7.1	33.5 ± 7.0	0.211
Fat mass (kg)	25.77 ± 8.38	21.61 ± 6.99	26.19 ± 7.50	25.75 ± 8.87	24.83 ± 8.05	0.103
LBM (kg)	46.40 ± 10.34	45.79 ± 9.03[d]	47.36 ± 8.04	53.48 ± 9.15[b]	48.26 ± 9.52	0.030
Arm fat mass (kg)	2.73 ± 0.74	2.21 ± 0.61	2.75 ± 0.81	2.54 ± 0.69	2.56 ± 0.74	0.061
Arm LBM (kg)	5.17 ± 1.84	5.20 ± 1.45	5.47 ± 1.42	6.40 ± 1.44	5.56 ± 1.60	0.040
Leg fat mass (kg)	8.30 ± 2.05	6.54 ± 2.22	7.58 ± 2.73	6.70 ± 2.29	7.28 ± 2.40	0.059
Leg LBM (kg)	15.39 ± 3.88	14.92 ± 3.02[d]	15.57 ± 2.81	17.90 ± 3.32[b]	15.94 ± 3.42	0.020
Trunk fat mass (kg)	13.82 ± 6.41	11.91 ± 5.14	14.94 ± 4.99	15.50 ± 6.78	14.04 ± 5.94	0.214
Function						
RHR (bpm)	63 ± 8	65 ± 12	62 ± 10	66 ± 10	64 ± 10	0.539
SBP (mm Hg)	140 ± 18	144 ± 20	148 ± 15	147 ± 26	145 ± 20	0.594
DBP (mm Hg)	82 ± 12	84 ± 9	86 ± 9	85 ± 11	84 ± 10	0.589
Hand-grip strength (kg)	29.8 ± 11.6	32.0 ± 9.5	31.8 ± 8.7	37.1 ± 9.9	32.7 ± 10.2	0.111
Gait speed (m s^{-1})	1.26 ± 0.23[d]	1.45 ± 0.28	1.44 ± 0.24	1.53 ± 0.19[a]	1.42 ± 0.25	0.004
Sit-to-stand (s)	13.49 ± 3.12[d]	10.28 ± 2.26	11.68 ± 2.89	10.79 ± 2.89[a]	11.56 ± 3.02	0.002
TUGT (s)	7.65 ± 1.46	7.01 ± 1.8	7.10 ± 1.60	6.49 ± 0.71	7.06 ± 1.48	0.090
SCT (W)	323.8 ± 90.0[d]	369.4 ± 99.5	386.0 ± 101.3	440.1 ± 131.3[a]	379.8 ± 112.7	0.008
1RM leg press (kg)	99.5 ± 31.4	101.2 ± 23.9	113.1 ± 27.6	114.1 ± 30.7	107.0 ± 28.8	0.214
1RM chest press (kg)	32.9 ± 13.9[d]	39.3 ± 17.1	37.8 ± 13.3	46.9 ± 14.5[a]	39.2 ± 15.3	0.027
Chester step test (bpm)	117.5 ± 16.8	123.1 ± 9.9	125.2 ± 13.1	119.7 ± 12.9	121.4 ± 13.5	0.247
MoCA	26 ± 3	26 ± 2	27 ± 2	27 ± 2	27 ± 2	0.710
Blood markers						
Total cholesterol (mmol L^{-1})	5.56 ± 0.76	5.51 ± 0.74	5.11 ± 1.17	5.41 ± 1.45	5.38 ± 1.05	0.580
HDL-C (mmol L^{-1})	1.64 ± 0.46	1.63 ± 0.50	1.37 ± 0.38	1.31 ± 0.36	1.49 ± 0.44	0.067
LDL-C (mmol L^{-1})	3.45 ± 0.72	3.46 ± 0.78	3.25 ± 0.93	3.54 ± 1.25	3.41 ± 0.92	0.824
Triglycerides (mmol L^{-1})	1.02 ± 0.34	0.93 ± 0.36	1.06 ± 0.42	1.21 ± 0.80	1.05 ± 0.50	0.501
Glucose (mmol L^{-1})	5.63 ± 0.52	5.38 ± 0.48	5.51 ± 0.84	5.94 ± 1.12	5.60 ± 0.79	0.246
Insulin (mU L^{-1})	4.33 ± 1.47	3.95 ± 1.14	4.50 ± 1.82	5.03 ± 1.78	4.43 ± 1.58	0.343
HOMA-IR	1.09 ± 0.42	0.95 ± 0.30	1.12 ± 0.56	1.36 ± 0.66	1.12 ± 0.51	0.617

1RM, one-repetition maximum; BMI, body mass index; DBP, diastolic blood pressure; HDL-C, high-density lipoprotein cholesterol; HOMA-IR, homeostatic model assessment to quantify insulin resistance; LBM, lean body mass; LDL-C, low-density lipoprotein cholesterol; M/F, male/female; MoCA, Montreal cognitive assessment; RHR, resting heart rate; SBP, systolic blood pressure; SCT, stair-climbing test; TUGT, timed up-and-go test.

P values are reported from one-way ANOVA by group. When $P < 0.05$, post-hoc pairwise comparisons with Tukey's correction were used to determine where differences existed between groups as indicated by [a]$P < 0.05$ vs CON, [b]$P < 0.05$ vs AER, [c]$P < 0.05$ vs RES, [d]$P < 0.05$ vs CEX for the annotated group.

batch-analyzed for insulin (Mercodia, Sweden) and total cholesterol, HDL-C, LDL-C, triglycerides, and glucose (all Randox Daytona, Crumlin, UK). HOMA-IR was calculated based on the fasting glucose and insulin concentrations.[24]

Participants then consumed a small snack (cereal bar plus banana) and were allowed water ad libitum. Hand-grip strength of the dominant hand was then measured to the nearest 0.5 kg using a hydraulic hand dynamometer

(JAMAR, Duluth, MN, USA). Next, lower body physical function was assessed using the 8 foot (2.4 m) Timed Up-and-Go Test (TUGT),[25] and Short Physical Performance Battery (SPPB)[26] consisting of habitual gait speed (3 m), standing balance (non-tandem and tandem), and five repetition sit-to-stand. Cognitive function was then assessed using Montreal Cognitive Assessment Test (MoCA).[27] Lastly, aerobic fitness was assessed using the Chester Step Test.[28]

On day 2, participants reported to the exercise training facility (Medfit Proactive Healthcare) for the assessment of leg power by Stair Climbing Test (SCT),[29] and lower and upper limb strength by 1 repetition maximum (1RM) on leg press and chest press machines, respectively (Milon, Germany). Prior to the assessment at PRE, a first familiarization session was performed wherein the correct lifting technique was demonstrated and practiced, after which maximum strength was estimated using the multiple repetitions testing procedure. This informed the assessment of 1RM, which was performed in a second session undertaken 1 week after the familiarization session.

2.3 | Training intervention

The 12-week exercise training intervention consisted of three exercise sessions per week (Monday, Wednesday, Friday) of ~40 minutes per session including a standardized warm-up and cool-down. All training sessions were supervised and performed on the Milon Circle (Milon, Germany), a smart card-enabled circuit featuring a combination of eight fully automated strength (six) and aerobic (two) exercise machines depending on designation to AER, RES, and CEX (Table 2). Heart rate was monitored continuously via telemetry throughout each training session (Polar H7, Finland). Warm-up for all sessions consisted of 5 min of low-intensity treadmill walking followed by calisthenics to mobilize the upper and lower limbs.

Aerobic exercise training (AER) consisted of a Cross Trainer and Stationary Cycle Ergometer. Participants completed 4 minutes on one modality followed by 1-minute passive recovery before completing 4 minutes on the other modality followed by 1-minute passive recovery. This was repeated for three rounds of each modality in each session (6 × 4 minutes exercise) for AER. The power output was adjusted to elicit a target intensity of 80% of age-predicted maximum heart rate (%HR_{max}) for each 4-minute bout. This intensity was targeted consistently throughout the training intervention to insure a progressive overload was continuously provided.

Resistance exercise training (RES) consisted of six exercise machines (Leg Press, Seated Row, Chest Press, Lat Pulldown, Leg Extension, and Tricep Dips). Participants completed 15 tempo-controlled repetitions of one exercise in a 60-seconds period followed by 30 seconds of rest before proceeding to the next exercise. Four rounds of the six exercise circuit were completed in each session for RES. Participants began the training intervention at ~60% of 1RM, but once an exercise could be completed comfortably for the 60 seconds period, an ~5% increment in weight to be lifted was added for the next training session to insure a progressive overload was provided throughout the training intervention.[4]

Concurrent exercise training (CEX) consisted of a combination of aerobic and resistance training that was time-matched by having half of AER and half of the RES training volume. In each session, participants performed three of the 4-minute bouts of aerobic exercise and two rounds of the six resistance exercise circuit. The aerobic and resistance components of the concurrent training program were merged wherein participants completed three resistance training exercises, followed by one 4-minute bout of aerobic training, and repeated this pattern. Therefore, across each of AER, RES, and CEX, each training session consisted of 24 minute of active exercise.

2.4 | Statistical analysis

Data were analyzed using GraphPad Prism 7 (GraphPad Software, Inc., USA) and are presented as mean ± SD for baseline data, training attendance and heart rate, and mean difference (lower 95% confidence interval of difference, higher 95% confidence interval of difference) for data expressed as percentage change from baseline. Differences between groups at baseline (PRE) for all parameters were compared using a one-way analysis of variance (ANOVA). Two-way (group × time) repeated measures ANOVAs were performed to determine changes, if any, in response to training and differences, if any, between groups in those responses. When main or interaction effects were indicated, post-hoc pairwise comparisons were performed using Tukey's multiple comparisons test. For all null hypothesis statistical testing, significance was accepted at $P < 0.05$. Apart from and independent of the outcome of the repeated measures ANOVA, standardized differences in the mean were used to assess magnitudes of effects for differences at POST between groups in the response to each training intervention. These effect sizes were calculated using Cohen's d and interpreted using thresholds of 0.2, 0.5, and 0.8 for small, moderate, and large, respectively, and are reported in Table S2.

3 | RESULTS

Attendance at the exercise training sessions averaged 88 ± 7% throughout the 12 week period (Figure 1A) and did not differ by training group at 88 ± 7%, 90 ± 7%, and

Table 2. Overview of the training intervention for respective groups

	Training group			
	CON	AER	RES	CEX
Number of weekly training sessions	0	3	3	3
Type of exercise				
Aerobic	None	Exercises: Cross Trainer Cycle Ergometer Intensity: ~80% HR_{max} Duration: Cross Trainer 4 min Recovery 1 min Cycle Ergometer 4 min Recovery 1 min Repeat ×3 sets	None	Exercises: Cross Trainer Cycle Ergometer Intensity: ~80% HR_{max} Duration: Cross Trainer 4 min Recovery 1 min Cycle Ergometer 4 min Recovery 1 min Repeat ×1.5 sets
Resistance	None	None	Exercises: Leg Press Seated Row Chest Press Lat Pulldown Leg Extension Tricep Dips Intensity: ~60% 1RM Volume: 1 min per exercise 30-s recovery per exercise Repeat ×4 sets	Exercises: Leg Press Seated Row Chest Press Lat Pulldown Leg Extension Tricep Dips Intensity: ~60% 1RM Volume: 1 min per exercise 30-s recovery per exercise Repeat ×2 sets
Total weekly active exercise time (min)	0	72	72	72

86 ± 6% for AER, RES, and CEX, respectively. Heart rate averaged 79 ± 6%, 66 ± 10%, and 74 ± 8% of HR_{max} for AER, RES, and CEX, respectively (Figure 1B). Across all parameters measured during the study, there was no statistically significant change in CON at either MID or POST compared to PRE.

For hand-grip strength, a main effect of time ($P < 0.001$), but no group ($P = 0.52$) or interaction ($P = 0.38$) effects, was observed. The change in hand-grip strength was small in AER (4.9%; −1.4, 11.2), whereas larger increases were observed at POST in RES (7.9%; 1.6, 14.1) and CEX (11.0%; 4.8, 17.3; Figure 2A). Accordingly, the improvements in hand-grip strength were greatest in CEX with effect sizes interpreted as small compared to AER ($d = 0.49$) and RES ($d = 0.24$; Table S2). Main effects of time ($P < 0.001$) and group ($P = 0.010$), and a group × time interaction effect ($P = 0.042$), were observed for gait speed. Gait speed was increased in all three training groups by MID, that is, AER, 10.9% (1.9, 19.9; $P = 0.014$); RES, 10.3% (1.3, 19.3; $P = 0.021$); and CEX, 16.8% (7.8, 25.6; $P < 0.001$), but this increase was only maintained at POST in CEX (16.8%; 7.8, 25.8; $P < 0.001$; Figure 2B). The between-group difference at POST in CEX represented a moderate effect compared to AER ($d = 0.58$), and a large effect compared to RES ($d = 0.94$; Table S2). For the sit-to-stand test, a main effect of time ($P < 0.001$), but no group ($P = 0.80$) or interaction ($P = 0.30$) effects, were observed. Performance in the sit-to-stand test was improved at POST in RES and CEX with completion times decreasing by 10.1% (−20.1, −0.1; $P = 0.049$) and 15.4% (−25.4, −5.3; $P = 0.001$), respectively (Figure 2C). The change in sit-to-stand performance in RES was trivial compared to CON ($d = 0.11$) and AER ($d = 0.07$), but a small effect size was observed for the improvement in CEX compared to AER ($d = 0.36$) and RES ($d = 0.31$; Table S2). Main effects of time ($P < 0.001$) and group ($P = 0.010$), and a group × time interaction effect ($P = 0.042$), were observed for TUGT.

Performance in the TUGT was improved at POST in all three training groups, that is, AER, −10.4% (−17.1, −3.8; $P < 0.001$); RES, −8.9% (−15.5, −2.2; $P = 0.005$); and CEX, −18.1% (−24.7, −11.4; $P < 0.001$; Figure 2D). The difference between AER and RES was trivial ($d = 0.10$), but the greater improvements in CEX were interpreted as a moderate effect compared to AER ($d = 0.73$) and RES ($d = 0.64$).

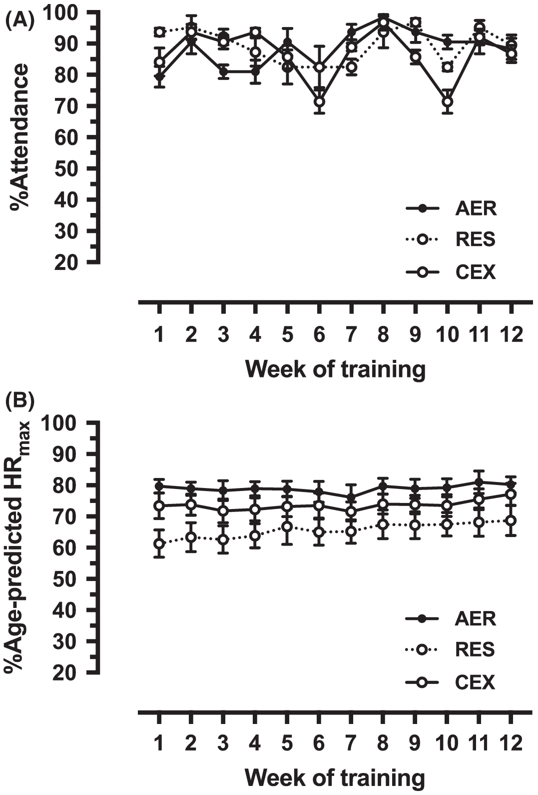

Figure 1. Rates of attendance and intensity of exercise training across the training groups AER, RES, and CEX. A, Week by week representation of attendance rates as percentage of sessions attended. B, Week by week representation of exercise intensity as %HR$_{max}$. Data are mean ± 95% confidence intervals

For resting heart rate, a main effect of time ($P = 0.005$), but no group ($P = 0.19$) or interaction ($P = 0.62$) effects, were observed. The change in resting heart rate was small in RES (−0.9%; −7.0, 5.2), whereas larger reductions were observed at POST in AER (−6.6%; −12.7, −0.5) and CEX (−7.2%; −13.3, −1.1; Table S1). Accordingly, compared to RES, the effect sizes were small (AER: $d = 0.44$) and moderate (CEX: $d = 0.49$), but the difference between AER and CEX was trivial ($d = 0.05$; Table S2). No main effect of group ($P = 0.98$) or interaction effect ($P = 0.92$) was observed for systolic blood pressure, and despite a main effect of time ($P = 0.005$), post-hoc comparisons did not reveal differences within groups at any time point (Table S1). Effect sizes for between-group differences in systolic blood pressure were trivial (Table S2). For diastolic blood pressure, a main effect of time ($P = 0.003$), but no group ($P = 0.83$) or interaction ($P = 0.97$) effects, were observed. Diastolic blood pressure was lower at POST in RES (−4.8%; −9.5, −0.1; $P = 0.048$; Table S1). This effect was small compared to AER ($d = 0.23$), and trivial compared to CEX ($d = 0.13$; Table S2). Main effects of time ($P < 0.001$) and group ($P = 0.030$), and a group × time interaction effect ($P = 0.008$), were observed for aerobic fitness. Aerobic fitness was improved at both MID in AER (6.2%; 2.0, 10.3; $P = 0.002$) and RES (6.3%; 2.2, 10.4; $P = 0.001$), and POST in AER (7.8%; 3.7, 12.0; $P < 0.001$) and RES (9.1%; 4.9, 13.2; $P < 0.001$), but not at either time point in CEX (Table S1). The difference between AER and RES was a trivial effect ($d = 0.12$), but was interpreted as moderate (AER, $d = 0.70$) and large (RES, $d = 1.15$) effects compared to CEX (Table S2). Cognitive function was improved at MID (6.2%; 2.6, 9.8; $P < 0.001$) and POST (7.3%; 3.7, 10.9; $P < 0.001$) in AER, at POST in RES (5.1%; 1.5, 8.7; $P = 0.003$), and at MID (4.5%; 0.8, 8.1; $P = 0.010$) and POST (7.9%; 4.3, 11.5; $P < 0.001$) in

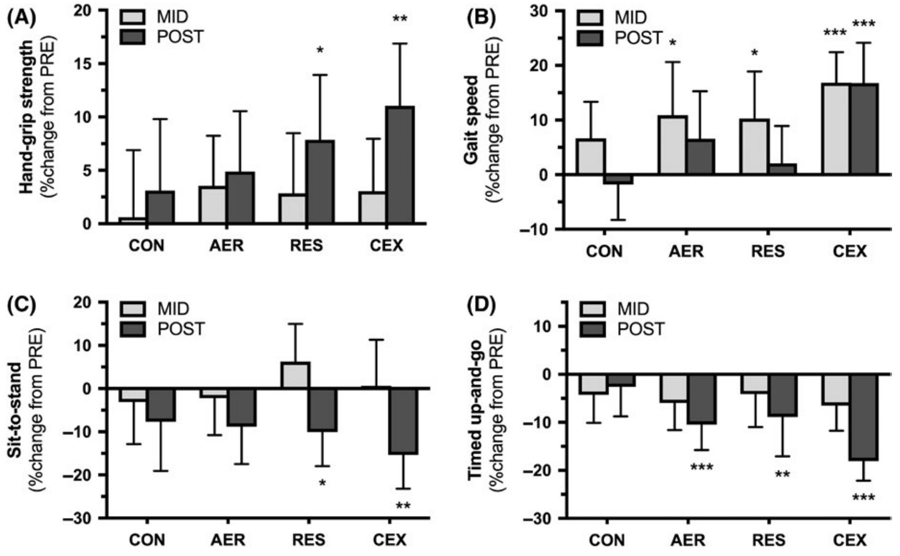

Figure 2. Changes in selected assessments of physical function in response to 12 wk of exercise training. A, Hand-grip strength; B, Gait speed; C, Five repetition sit-to-stand test; D, Timed up-and-go test. Columns are means representing % change from baseline (PRE) at 6 wk (MID) and 12 wk (POST) with error bars representing 95% confidence intervals. * Symbols denote significant difference from PRE for the respective training group; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$

CEX (Table S1). The difference between AER and CEX was a trivial effect ($d = 0.07$), but was interpreted as small effects (AER, $d = 0.35$; CEX, $d = 0.38$) compared to RES (Table S2). No changes in blood-borne markers of metabolic health (cholesterol, HDL-C, LDL-C, triglycerides, glucose, insulin, and HOMA-IR) were observed within or between groups at either MID or POST (Table S1).

For upper limb strength, main effects of time ($P < 0.001$) and group ($P < 0.001$), and a group × time interaction effect ($P < 0.001$), were observed for 1RM chest press. 1RM chest press was unchanged in AER (6.4%; −0.9, 13.7), but increased in RES and CEX at both MID (RES: 26.3% [19.0, 33.6; $P < 0.001$]; CEX: 16.0% [8.7, 23.3; $P < 0.001$]) and POST (RES: 36.8% [29.5, 44.1; $P < 0.001$]; CEX: 20.9% [13.6, 28.2; $P < 0.001$]), with the improvement at POST being greater in RES than CEX ($P = 0.008$; Figure 3A), and representing a moderate effect ($d = 0.77$; Table S2). For lower limb strength, main effects of time ($P < 0.001$) and group ($P < 0.001$), and a group × time interaction effect ($P < 0.001$), were observed for 1RM leg press. 1RM leg press was increased in all training groups at both MID and POST (all $P < 0.001$; Figure 3B), with the largest increase observed at CEX POST (47.5%; 39.8, 55.2) being greater than AER POST (27.2%; 19.5, 34.9), RES POST (21.7%; 14.0, 29.4) and CEX MID (34.5%; 26.8, 42.3; all $P < 0.001$ vs CEX POST). The greater improvements observed in CEX represented large effects compared to AER ($d = 0.91$) and RES ($d = 1.34$; Table S2). For leg power, a main effect of time ($P < 0.001$), but no group ($P = 0.29$) or interaction ($P = 0.20$) effects, was observed for the stair-climbing test. Leg power was greater at MID (7.3%; 1.9, 12.8) and POST (7.2%; 1.8, 12.7) in AER (both $P < 0.01$), and at POST in RES (8.3%; 2.8, 13.8; $P = 0.001$) and CEX (11.0%; 5.5, 16.5; $P < 0.001$; Table S1). The difference between AER and RES was a trivial effect ($d = 0.09$), but the greater improvements in CEX were interpreted as small effects compared to AER ($d = 0.34$) and RES ($d = 0.24$; Table S2).

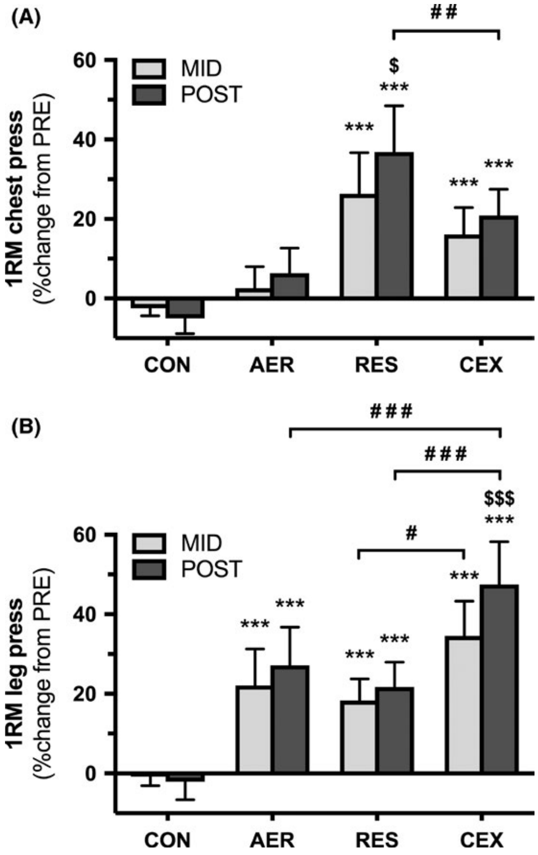

Figure 3. Changes in upper and lower limb muscle strength assessed by 1RM in response to 12 wk of exercise training. A, Chest press; B, Leg press. Columns are means representing % change from baseline (PRE) at 6 wk (MID) and 12 wk (POST) with error bars representing 95% confidence intervals. * Symbols denote significant difference from PRE for the respective training group; *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$. $ symbol denotes significant difference from MID to POST within the respective training group; $, $P < 0.05$; $$$, $P < 0.001$. # symbols denote significant difference at the same time point between the respective training groups; #, $P < 0.05$; ##, $P < 0.01$; ###, $P < 0.001$

Main effects of time ($P = 0.038$) and group ($P = 0.032$), and a group × time interaction effect ($P = 0.006$), were observed for arm LBM. Arm LBM was unchanged in AER (−0.4%; −2.9, 2.0), but was increased at MID in CEX (2.4%; 0.1, 4.8; $P = 0.049$), and at POST in RES (3.3%; 0.9, 5.7; $P = 0.005$; Figure 4A). The increase in arm LBM in RES was interpreted as a small ($d = 0.24$) and moderate ($d = 0.62$) effects compared to CEX and AER, respectively (Table S2). Leg LBM was unchanged (time, $P = 0.95$; group, $P = 0.066$; interaction, $P = 0.15$; Figure 4B), as were arm fat mass (time, $P = 0.42$; group, $P = 0.34$; interaction, $P = 0.61$) and leg fat mass (time, $P = 0.072$; group, $P = 0.25$; interaction, $P = 0.34$; Table S1). For trunk fat mass, main effects of time ($P = 0.037$) and group ($P = 0.013$) were observed, and the group × time interaction effect approached significance ($P = 0.065$). Changes in trunk fat were small in AER (−2.0%; −5.0, 0.9) and RES (0.1%; −2.9, 3.0), whereas decreases were larger in CEX at both MID (−4.1%; −7.1, −1.2) and POST (−4.2%; −7.2, −1.3; Figure 4C). Accordingly, the reduction in trunk fat mass in CEX was interpreted as a small ($d = 0.41$) and moderate ($d = 0.62$) effects compared to AER and RES, respectively (Table S2). For percentage body fat, main effects of time ($P < 0.001$) and group ($P = 0.002$), and a group × time interaction effect ($P = 0.003$), were observed. Body fat was decreased at POST in RES (−1.8%; −3.4, −0.3; $P = 0.018$), and at both MID and POST in AER (MID: −2.1% [−3.7, −0.5; $P = 0.005$]; POST: −3.5% [−5.1, −2.0; $P < 0.001$]) and CEX (MID: −2.3% [−3.8, −0.7; $P = 0.003$]; POST: −2.0%

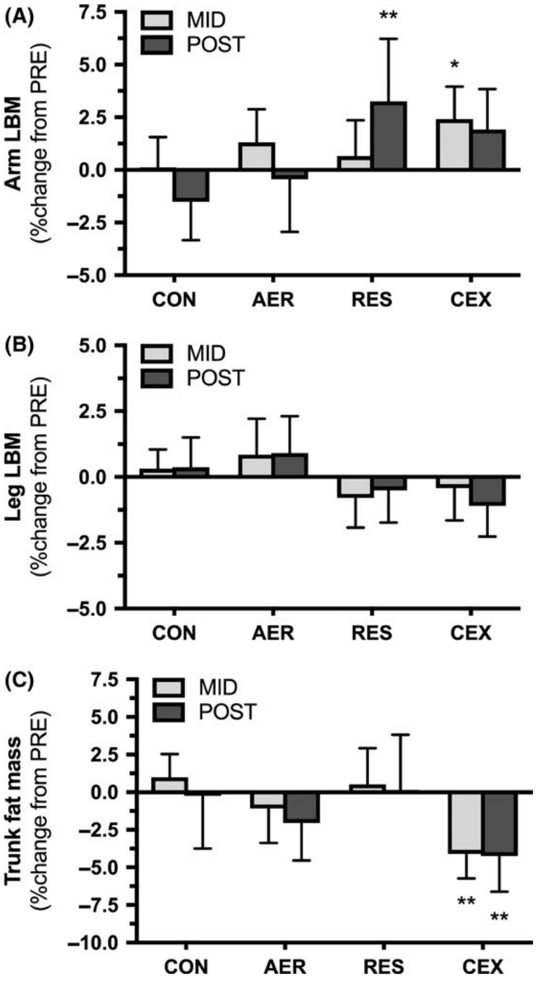

Figure 4. Changes in body composition assessed by DXA scan in response to 12 wk of exercise training. A, Arm lean body mass (LBM); B, Leg lean body mass; C, Trunk fat mass. Columns are means representing % change from baseline (PRE) at 6 wk (MID) and 12 wk (POST) with error bars representing 95% confidence intervals. * symbols denote significant difference from PRE for the respective training group; *, $P < 0.05$; **, $P < 0.01$

[−3.6, −0.4; $P = 0.009$]; Table S1). The reduction in percentage body fat was greatest in AER and interpreted as a small effects compared to RES ($d = 0.43$) and CEX ($d = 0.49$; Table S2).

4 | DISCUSSION

This present study takes the novel approach of groups being time-matched in the training intervention in addition to the inclusion of a time course design. The main findings are that, in older adults, when time-matched, concurrent exercise training is as efficacious for the improvement of a broad range of health-related parameters and is more efficacious for increasing gait speed and lower limb strength, and decreasing trunk fat than either aerobic or resistance exercise training alone. However, concurrent exercise training was less efficacious for improving upper limb strength compared to resistance exercise training alone, and in contrast to aerobic or resistance exercise training, did not improve aerobic fitness.

The observation that CEX resulted in similar improvements in health-related outcomes compared to AER or RES alone is in agreement with other studies of middle-aged to older adults.[6,7,9,10,14,30] However, several mode-specific training responses were also observed in the present study. For instance, outcomes related to upper limb function, namely hand-grip strength, 1RM chest press, and arm LBM, were unaffected by AER, but were improved by both RES and CEX. Clearly, this is an example of the specificity of adaptation given the relatively minor contribution of upper limb activity to the aerobic exercise modes employed. Given that a composite of upper and lower body strength predicts all-cause mortality in adults over 60 years,[31] and that regional muscle strength (ie, upper and lower limb) displays differential patterns of risk for mortality and hospitalization,[32] these data reinforce the prescription for upper limb resistance exercise training to be included to support aerobic exercise training for healthy aging.[4,5]

Notably, CEX was more efficacious than either AER or RES alone for changes in gait speed, lower limb strength, and trunk fat. Given the time-matched design, rather than there being any interference effect of concurrent training, these data suggest that there is a potentiation effect on these parameters. Gait speed at a given age is strong predictor of longevity,[33] but declines by 1% to 2% per decade when <62 years old and this decline accelerates to 12% to 16% per decade when >62 years.[34] Gait speed was increased by ~17% in CEX after 6 and 12 weeks, but improvements in AER and RES were only obvious after the first 6 weeks before, unexpectedly, declining toward pre-training levels at 12 weeks. A meta-analysis recently reported that RES (24 studies, n = 613) improved gait speed by 9.3%, and CEX (19 studies, n = 486) improved gait speed by 8.4%.[35] Our data are somewhat greater than the latter and also suggest that CEX is important for maintaining improvements in gait speed produced by exercise training. Similarly, the greater improvement in lower limb strength observed after 12 weeks in CEX, compared to both AER and RES, strongly supports the prescription of CEX in this population given the well-established declines in muscle strength with age.[36] This differential response to CEX is most notable for the fact that the quantity of resistance exercise performed in CEX was exactly half that of RES. This is similar to a previous report with a similar design,[9] and when concurrent groups have trained aerobic and resistance on separate days and yielded positive outcomes for strength.[10,11,14,30] However, the contribution of the aerobic exercise component to improvements in lower limb strength in the CEX group should not be discounted. The aerobic exercise stimulus in CEX comprised of 4-min intervals alternately on a cross trainer and cycle ergometer and, therefore, was primarily lower limb aerobic exercise, which itself is a stimulus to improve leg strength.[11,22]

In contrast to the effect on lower limb strength in the present study, RES produced greater improvements than CEX in upper limb strength after 12 weeks. This is similar to previous research in healthy older men wherein the training volume of the resistance exercise training group was double that of the concurrent exercise training group.[11] In contrast, in previous concurrent exercise training studies where the concurrent volume represented the combined volume of the aerobic and resistance exercise training groups, the resistance and concurrent exercise training groups improved in similar magnitudes for both elderly men,[12] and middle age to older men.[30] The training volume (ie, number of exercises, sets, repetitions) and, therefore, total time under tension is well-established as an important determinant of improvement in strength in response to resistance exercise training in older adults.[37] In contrast to the aforementioned lower limb stimulus provided by the aerobic exercise component in CEX, which we suggest would have influenced lower limb strength outcomes, the lack of upper limb aerobic exercise stimulus in CEX makes it unsurprising that there were greater gains in upper limb strength in RES. Simply put, the resistance exercise training stimulus for the upper limbs in RES was double that of CEX. Therefore, in concurrent exercise training prescription, the training volume of respective training modes influences the magnitude of improvement, and clearly, there are differential effects of training modes that need to be understood for optimal prescription in older adults.

Paradoxically, aerobic fitness was not improved in CEX despite improvements being observed after 12 weeks of AER and RES. The increase in aerobic fitness with RES is not unexpected in this population,[38] with improvements likely to occur due to improvements in the capillary-to-fiber ratio and mitochondria enzyme activity.[39] The duration of rest periods between sets is an important determinant for improving aerobic fitness by RES. Shorter rest periods resulting in a greater requirement on pathways of aerobic energy provision could potentially provide a greater stimulus to aerobic adaptations.[38] Indeed, the training stimulus in RES comprised of 60-seconds active exercise sets with short rest periods of 30 seconds, so this circuit-style approach to training may have contributed to the outcome observed. Conversely, the possible explanations for the lack of improvement in CEX are many and varied. For instance, this may be because the stimulus to aerobic adaptation provided by either exercise mode alone needs to exceed a threshold that was not provided by CEX in the respective modes.[38,40] Alternatively, it may be demonstration of an interference effect by CEX on aerobic fitness outcomes, which will require further examination in older adults. If confirmed, these data highlight important considerations for exercise prescription if maximizing training-induced improvements in aerobic fitness is a primary goal. Another explanation may be that initial values for any component of fitness are an important determinant of the adaptive response to training,[41] particularly in older cohorts.[38] Although not statistically different at PRE, the CEX group had higher levels of aerobic fitness at PRE by ~5%, which may be another contributor to the observed outcomes. Lastly, the nature of the aerobic fitness test may have had a bearing on the results. Performing a laboratory-based maximum effort, incremental test to exhaustion is the gold standard for assessment of aerobic fitness. However, this type of test was not feasible in the present study due to financial and time constraints given the large number of participants being evaluated. Although the submaximal test employed, the Chester Step Test, has been demonstrated as reliable and valid for the assessment of aerobic fitness,[28] it has not previously been established as sensitive to change in response to exercise training in older adults.

The marked effect on reducing trunk fat observed after 6 and 12 weeks of CEX compared to a lack of change in AER and RES is a notable finding from the present study. Reducing trunk fat, as a surrogate for abdominal adiposity, is a key factor for improving insulin sensitivity through exercise training in older adults.[6] The efficacy of CEX for reducing abdominal fat is similar to previous findings.[6] In that study, participants performed almost twice the training volume during concurrent training versus either mode alone in contrast to our time-matched design. However, we did not intervene at the level of energy intake, nor was the energy expenditure of training truly matched between groups, so future work should investigate whether the observed change is due to unexpected behavioral changes affecting energy intake or expenditure, or perhaps intrinsic adaptations to the stimulus provided by CEX. Surprisingly, this training intervention did not alter blood lipid profile or markers of metabolic health. Body mass reduction may be necessary for improvements in lipid profile,[42] so the lack of change in body mass herein may explain this outcome. Moreover, previous work with aerobic or resistance training,[43,44] or that included concurrent training,[45] did not observe changes in blood markers. Indeed, the HOMA-IR data indicate that this study cohort was not insulin resistant, so a relatively healthy metabolic profile may have been less sensitive to change.

In contrast to the marked improvement in leg power and strength and the aforementioned increase in arm LBM, LBM of the legs was unchanged in any group. Notwithstanding the importance of sets, reps, intensity, and time under tension, this may be explained in part by the duration of the intervention as meta-analyses highlight the importance of training program duration as a key determinant of observing change in LBM,[37,46] For example, 20.5 weeks of resistance training (compared to the present study's 12 weeks) produces an increase in whole-body LBM of ~1.1 kg.[46] Alternatively, the lack of nutrition intervention in the present study may have influenced this outcome, given that combining protein supplementation with resistance training generally enhances gains in LBM for older adults compared to training alone.[47] Lastly, the participant cohort recruited did not have a defined deficit in LBM (eg, pre-sarcopenia, sarcopenia), so the magnitude of change would have been unlikely to be as great as that observed previously in such cohorts. Despite the lack of change in leg LBM, improvements in strength, power, and other indices of lower limb function support the prescription of CEX in older adults given the importance of muscle strength and power in functional capacity.[48]

The time course design with assessments after 6 and 12 weeks of training was chosen specifically to provide information that might inform practitioners about how and when to assess, re-assess and prescribe training in this population depending on an individual's goal(s). For example, a MoCA score of below 26 is indicative of mild cognitive impairment,[27] with 27% (23/84) of our participants below that mark at baseline assessments. Exercise training improved cognitive function independent of exercise mode, but improvements were detected earlier (ie, at MID) in AER compared to RES and CEX. Clearly, some changes were observed as early as 6 weeks of training (eg, gait speed, upper, and lower limb strength), whereas others were unchanged until 12 weeks (eg, hand-grip strength, TUGT, sit-to-stand, and aerobic fitness). With increasing interest in so-called "exercise non-responders," the controversies around that definition, and the clear evidence for dose-responsiveness depending on the parameter of interest,[49,50] the present study describes temporal patterns of adaptation that must be considered in that paradigm in older adults.

An important methodological caveat is the uneven gender distribution between groups. Because gender-specific differences in the training response were not a focus of this work, we did not undertake a block randomization procedure, which resulted in a greater number of males in the CEX group. Moreover, it was not appropriate to undertake a post-hoc gender analysis because the study was not powered to do so a priori. In mitigation, the reporting of percentage change data throughout means that relative, rather than absolute, within- and between-group differences are described. That said, generally there are no gender-specific differences in the magnitude of response to aerobic or resistance exercise training in older adults.[49,51] Therefore, despite this caveat of gender distribution, we suggest that this is not a confounding factor in the observed outcomes.

5 | PERSPECTIVE

In summary, positive impacts on a variety of health-related parameters were observed in each of the training groups, but CEX was more efficacious for several outcomes such as gait speed, leg strength, and trunk fat. This supports previous research demonstrating greater efficacy of concurrent exercise training in middle- to older-aged populations,[6,9,10,19] but importantly even when groups are time-matched, in contrast to previous work. These results highlight the importance of exercise regimens incorporating both aerobic and resistance training for older adults. However, the lack of improvement in aerobic fitness in CEX requires further investigation. Our time-matched design incorporated just 24 minutes of exercise per session, an important feature given that time constraints are often cited as an obstacle to exercise training.[52] The exemplary adherence rate to the exercise program (87%) and no reported injuries cannot necessarily be generalized to unsupervised exercise. Translation into unsupervised or home-based exercise is one avenue for future work, as is investigation of optimal nutrition support to augment concurrent exercise training outcomes when defined deficits exist, for example, in LBM or cognitive function. We anticipate the observed mode- and time course-specific responses will inform practitioners on training program design for older adults, but acknowledge that further work is needed to optimize prescription in this population.

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REFERENCES

1. Booth FW, Roberts CK, Laye MJ. Lack of exercise is a major cause of chronic diseases. *Compr Physiol*. 2012;2:1143-1211.
2. Morley JE, Anker SD, von Haehling S. Prevalence, incidence, and clinical impact of sarcopenia: facts, numbers, and epidemiology-update 2014. *J Cachexia Sarcopenia Muscle*. 2014;5:253-259.
3. Pedersen BK, Saltin B. Exercise as medicine - evidence for prescribing exercise as therapy in 26 different chronic diseases. *Scand J Med Sci Sports*. 2015;25(Suppl 3):1-72.
4. Chodzko-Zajko WJ, Proctor DN, Fiatarone Singh MA, et al. American College of Sports Medicine position stand. Exercise and physical activity for older adults. *Med Sci Sports Exerc*. 2009;41:1510-1530.

5. Cadore EL, Pinto RS, Bottaro M, Izquierdo M. Strength and endurance training prescription in healthy and frail elderly. *Aging Dis*. 2014;5:183-195.
6. Davidson LE, Hudson R, Kilpatrick K, et al. Effects of exercise modality on insulin resistance and functional limitation in older adults: a randomized controlled trial. *Arch Intern Med*. 2009;169:122-131.
7. Sigal RJ, Kenny GP, Boule NG, et al. Effects of aerobic training, resistance training, or both on glycemic control in type 2 diabetes: a randomized trial. *Ann Intern Med*. 2007;147:357-369.
8. Hickson RC. Interference of strength development by simultaneously training for strength and endurance. *Eur J Appl Physiol Occup Physiol*. 1980;45:255-263.
9. Wood RH, Reyes R, Welsch MA, et al. Concurrent cardiovascular and resistance training in healthy older adults. *Med Sci Sports Exerc*. 2001;33:1751-1758.
10. Karavirta L, Hakkinen K, Kauhanen A, et al. Individual responses to combined endurance and strength training in older adults. *Med Sci Sports Exerc*. 2011;43:484-490.
11. Izquierdo M, Ibanez J, Hakkinen K, Kraemer WJ, Larrion JL, Gorostiaga EM. Once weekly combined resistance and cardiovascular training in healthy older men. *Med Sci Sports Exerc*. 2004;36:435-443.
12. Cadore EL, Pinto RS, Lhullier FL, et al. Physiological effects of concurrent training in elderly men. *Int J Sports Med*. 2010;31:689-697.
13. Cadore EL, Pinto RS, Pinto SS, et al. Effects of strength, endurance, and concurrent training on aerobic power and dynamic neuromuscular economy in elderly men. *J Strength Cond Res*. 2011;25:758-766.
14. Holviala J, Hakkinen A, Karavirta L, et al. Effects of combined strength and endurance training on treadmill load carrying walking performance in aging men. *J Strength Cond Res*. 2010;24:1584-1595.
15. Ferrari R, Kruel LF, Cadore EL, et al. Efficiency of twice weekly concurrent training in trained elderly men. *Exp Gerontol*. 2013;48:1236-1242.
16. Farinatti PT, Geraldes AA, Bottaro MF, Lima MV, Albuquerque RB, Fleck SJ. Effects of different resistance training frequencies on the muscle strength and functional performance of active women older than 60 years. *J Strength Cond Res*. 2013;27:2225-2234.
17. Wilhelm EN, Rech A, Minozzo F, et al. Concurrent strength and endurance training exercise sequence does not affect neuromuscular adaptations in older men. *Exp Gerontol*. 2014;60:207-214.
18. Cadore EL, Izquierdo M, Alberton CL, et al. Strength prior to endurance intra-session exercise sequence optimizes neuromuscular and cardiovascular gains in elderly men. *Exp Gerontol*. 2012;47:164-169.
19. Izquierdo M, Hakkinen K, Ibanez J, Kraemer WJ, Gorostiaga EM. Effects of combined resistance and cardiovascular training on strength, power, muscle cross-sectional area, and endurance markers in middle-aged men. *Eur J Appl Physiol*. 2005;94:70-75.
20. Church TS, Blair SN, Cocreham S, et al. Effects of aerobic and resistance training on hemoglobin A1c levels in patients with type 2 diabetes: a randomized controlled trial. *JAMA*. 2010;304:2253-2262.
21. Ho SS, Dhaliwal SS, Hills AP, Pal S. The effect of 12 weeks of aerobic, resistance or combination exercise training on cardiovascular risk factors in the overweight and obese in a randomized trial. *BMC Public Health*. 2012;12:704.
22. Theodorou AA, Panayiotou G, Volaklis KA, et al. Aerobic, resistance and combined training and detraining on body composition, muscle strength, lipid profile and inflammation in coronary artery disease patients. *Res Sports Med*. 2016;24:171-184.
23. Greig CA, Young A, Skelton DA, Pippet E, Butler FM, Mahmud SM. Exercise studies with elderly volunteers. *Age Ageing*. 1994;23:185-189.
24. Matthews DR, Hosker JP, Rudenski AS, Naylor BA, Treacher DF, Turner RC. Homeostasis model assessment: insulin resistance and beta-cell function from fasting plasma glucose and insulin concentrations in man. *Diabetologia*. 1985;28:412-419.
25. Mathias S, Nayak US, Isaacs B. Balance in elderly patients: the “get-up and go” test. *Arch Phys Med Rehabil*. 1986;67:387-389.
26. Guralnik JM, Simonsick EM, Ferrucci L, et al. A short physical performance battery assessing lower extremity function: association with self-reported disability and prediction of mortality and nursing home admission. *J Gerontol*. 1994;49:M85-M94.
27. Nasreddine ZS, Phillips NA, Bedirian V, et al. The Montreal Cognitive Assessment, MoCA: a brief screening tool for mild cognitive impairment. *J Am Geriatr Soc*. 2005;53:695-699.
28. Sykes K, Roberts A. The Chester step test—a simple yet effective tool for the prediction of aerobic capacity. *Physiotherapy*. 2004;90:183-188.
29. Lafortuna CL, Agosti F, Marinone PG, Marazzi N, Sartorio A. The relationship between body composition and muscle power output in men and women with obesity. *J Endocrinol Invest*. 2004;27:854-861.
30. Sillanpaa E, Hakkinen A, Nyman K, et al. Body composition and fitness during strength and/or endurance training in older men. *Med Sci Sports Exerc*. 2008;40:950-958.
31. Ruiz JR, Sui X, Lobelo F, et al. Association between muscular strength and mortality in men: prospective cohort study. *BMJ*. 2008;337:a439.
32. Guadalupe-Grau A, Carnicero JA, Gomez-Cabello A, et al. Association of regional muscle strength with mortality and hospitalisation in older people. *Age Ageing*. 2015;44:790-795.
33. Studenski S, Perera S, Patel K, et al. Gait speed and survival in older adults. *JAMA*. 2011;305:50-58.
34. Himann JE, Cunningham DA, Rechnitzer PA, Paterson DH. Age-related changes in speed of walking. *Med Sci Sports Exerc*. 1988;20:161-166.
35. Hortobagyi T, Lesinski M, Gabler M, VanSwearingen JM, Malatesta D, Granacher U. Effects of three types of exercise interventions on healthy old adults’ gait speed: a systematic review and meta-analysis. *Sports Med*. 2015;45:1627-1643.
36. Frontera WR, Hughes VA, Lutz KJ, Evans WJ. A cross-sectional study of muscle strength and mass in 45- to 78-yr-old men and women. *J Appl Physiol*. 1991;71:644-650.
37. Borde R, Hortobagyi T, Granacher U. Dose-response relationships of resistance training in healthy old adults: a systematic review and meta-analysis. *Sports Med*. 2015;45:1693-1720.
38. Ozaki H, Loenneke JP, Thiebaud RS, Abe T. Resistance training induced increase in VO2max in young and older subjects. *Eur Rev Aging Phys Act*. 2013;10:107-116.
39. Hagerman FC, Walsh SJ, Staron RS, et al. Effects of high-intensity resistance training on untrained older men. I. Strength, cardiovascular, and metabolic responses. *J Gerontol A Biol Sci Med Sci*. 2000;55:B336-B346.

40. Huang G, Gibson CA, Tran ZV, Osness WH. Controlled endurance exercise training and VO2max changes in older adults: a meta-analysis. *Prev Cardiol*. 2005;8:217-225.
41. Haskell WLJB. Wolffe Memorial Lecture. Health consequences of physical activity: understanding and challenges regarding dose-response. *Med Sci Sports Exerc*. 1994;26:649-660.
42. Leon AS, Sanchez OA. Response of blood lipids to exercise training alone or combined with dietary intervention. *Med Sci Sports Exerc*. 2001;33:S502-S515; discussion S528-509.
43. Blumenthal JA, Emery CF, Madden DJ, et al. Effects of exercise training on cardiorespiratory function in men and women older than 60 years of age. *Am J Cardiol*. 1991;67:633-639.
44. Smutok MA, Reece C, Kokkinos PF, et al. Aerobic versus strength training for risk factor intervention in middle-aged men at high risk for coronary heart disease. *Metabolism*. 1993;42:177-184.
45. Boardley D, Fahlman M, Topp R, Morgan AL, McNevin N. The impact of exercise training on blood lipids in older adults. *Am J Geriatr Cardiol*. 2007;16:30-35.
46. Peterson MD, Sen A, Gordon PM. Influence of resistance exercise on lean body mass in aging adults: a meta-analysis. *Med Sci Sports Exerc*. 2011;43:249-258.
47. Cermak NM, Res PT, de Groot LC, Saris WH, van Loon LJ. Protein supplementation augments the adaptive response of skeletal muscle to resistance-type exercise training: a meta-analysis. *Am J Clin Nutr*. 2012;96:1454-1464.
48. Reid KF, Fielding RA. Skeletal muscle power: a critical determinant of physical functioning in older adults. *Exerc Sport Sci Rev*. 2012;40:4-12.
49. Churchward-Venne TA, Tieland M, Verdijk LB, et al. There are no nonresponders to resistance-type exercise training in older men and women. *J Am Med Dir Assoc*. 2015;16:400-411.
50. Montero D, Lundby C. Refuting the myth of non-response to exercise training: ‘non-responders’ do respond to higher dose of training. *J Physiol*. 2017;595:3377-3387.
51. Kohrt WM, Malley MT, Coggan AR, et al. Effects of gender, age, and fitness level on response of VO2max to training in 60-71 yr olds. *J Appl Physiol*. 1991;71:2004-2011.
52. Cohen-Mansfield J, Marx MS, Guralnik JM. Motivators and barriers to exercise in an older community-dwelling population. *J Aging Phys Act*. 2003;11:242-253.

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