Effects of Eccentrically Biased versus Conventional Weight Training in Older Adults

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ABSTRACT

RAJ, I. S., S. R. BIRD, B. A. WESTFOLD, and A. J. SHIELD. Effects of Eccentrically Biased versus Conventional Weight Training in Older Adults. *Med. Sci. Sports Exerc.*, Vol. 44, No. 6, pp. 1167–1176, 2012. **Introduction**: We compared the effects of eccentrically biased (EB) and conventional (CONV) resistance training on muscle architecture, one-repetition maximum (1RM), isometric strength, isokinetic force–velocity characteristics, functional capacity, and pulse wave velocity in older men and women. **Methods**: Twenty-eight older adults participated in the study (mean ± SD: age = 68 ± 5 yr). Of these, 13 were allocated to a waitlist control, 10 of whom progressed to training (CONV, n = 12; EB, n = 13). Training was twice a week for 16 wk. EB involved three sets of 10 concentric lifts at 50% of 1RM with the eccentric portion of repetitions performed unilaterally, alternating between limbs with each repetition. CONV involved two sets of 10 repetitions at 75% of 1RM. EB and CONV were matched for total work. Isokinetic knee extensor strength was assessed across a range of velocities (0–360°·s^{-1}). Functional capacity was assessed via a 6-m fast walk test, a timed up and go test, stair climb and descent power test, and vertical jump test. Vastus lateralis and gastrocnemius medialis architecture were assessed using ultrasonography. **Results**: Both EB and CONV improved 1RM (Δ23%–35%, P < 0.01). Compared to the control group, both training regimens improved 6-m fast walk (Δ5%–7%, P < 0.01) and concentric torque at 60 and 120°·s^{-1} (Δ6%–8%, P < 0.05). Significant improvements were evident in EB for isometric and concentric torque at 240 and 360°·s^{-1} (Δ6%–11%, P < 0.05), vastus lateralis thickness (Δ5%, P < 0.05), and stair climb (Δ5%, P < 0.01). Timed up and go (Δ5%, P < 0.01), stair descent (Δ4%, P < 0.05), and vertical jump (Δ7%, P < 0.01) improved in CONV. Pulse wave velocity, pennation angle, and fascicle length remained unchanged in both training groups. **Conclusions**: EB seems superior to CONV at increasing torque at high contraction velocities, whereas CONV seems more effective at improving some functional performance measures and vertical jump. This has important implications for preserving functional capacity. **Key Words:** ELDERLY, EXERCISE, STRENGTH, FUNCTION

Muscular strength and power declines with age, the proposed major reasons for this being changes to the neuromuscular system and muscle architecture and skeletal muscle atrophy (8,19). The decline in power rather than the concurrent loss of strength *per se* seems to have the most profound effect on functional capacity in older adults (32) because it is associated with a slowing of walking speeds and increased risk of falling (9,30). As a means of combating these declines, training interventions using conventional high-intensity resistance training, which involves both concentric and eccentric muscle actions performed against a constant external load, have been used and demonstrated to have significant positive effects on several aspects of performance and health (17). However, while typically very effective at increasing muscle mass and strength, this traditional mode of resistance training seems to be less effective at increasing muscle power generation during high-speed contractions (25,33), which are critical for the older adult. Therefore, the effectiveness of alternative strength and power training regimens require investigation.

One of these alternative modalities is eccentric resistance training, which has been reported to increase muscle fascicle lengths in elderly resistance trainers (35). This adaptation should also favorably alter the muscle's force–velocity characteristics by increasing the maximum torque and power generation at higher contraction speeds (40). In addition, there is evidence that eccentric resistance training provides a more effective stimulus for muscle growth than concentric training (36). So, given these proposed advantages, eccentric resistance training may be of particular value to older adults with regard to increasing walking speed, lowering the risk of falling and improving functional capacity.

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Another aspect favoring eccentric resistance training is that it allows participants to perform the same amount of work at a lower RPE than traditional concentric training (22,28,31), a factor that may make it more attractive to those who have been sedentary for many years. From a cardiovascular perspective, there is reason to believe that eccentric training may have more favorable effects on arterial stiffness, at least in young people, than concentric training (29), thereby providing further advantages for its use in a population group already prone to cardiovascular disease. The favorable effect of eccentric contractions may be mediated by lesser blood pressure responses than are seen in the concentric phase of conventional lifting (20). So underloading the concentric phase of resistance training, as occurs in many reported studies, may therefore have beneficial effects on cardiac afterload (22).

The eccentric resistance training typically used in human studies involves loads being raised by research assistants or machines and then lowered (eccentrically) by the participants (35). Although this form of training can be undertaken in research contexts, it is impractical in fitness centers where the general population typically exercises. Therefore, a more practical way of obtaining overload during the eccentric portion of exercises needs to be used. One of these is "eccentrically biased" resistance training, during which the loads are lifted (concentrically) with two limbs and then lowered (eccentrically) with one. This form of training is therefore eccentrically biased because it involves a relatively underloaded concentric phase and an overloaded eccentric phase. An example would involve lifting ~50% of the bilateral one-repetition maximum (1RM) and then lowering it unilaterally, which, in doing so, would equate to ~100% of the unilateral 1RM. To date, however, there are no studies comparing the effectiveness of eccentrically biased training to conventional resistance training in older adults.

We hypothesized that eccentrically biased resistance training (EB) would lead to a greater increase in fascicle length and muscle thickness of the knee extensors and plantar flexors while also increasing concentric knee extensor strength of older adults at fast contraction speeds to a greater extent than conventional resistance training (CONV). We also sought to compare the effects of EB and CONV on functional capacity and pulse wave velocity (PWV).

METHODS

Participants. Twenty-eight community-dwelling older adults (17 men and 11 women) participated in this study. Of these, seven men and six women were assigned to the waitlist control group (mean ± SD: age = 67 ± 5 yr, body mass = 78.7 ± 13.7 kg, height = 167.0 ± 8.6 cm), 10 of whom progressed to one of the two training groups. Seven men and five women performed CONV (age = 68 ± 5 yr, body mass = 77.8 ± 15.5 kg, height = 168.3 ± 11.6 cm), and eight men and five women performed EB (age = 68 ± 5 yr, body mass = 77.4 ± 13.4 kg, height = 167.8 ± 8.8 cm). Participants were excluded from the study if they had relevant cardiovascular or orthopedic problems or if they had undertaken any resistance training in the preceding 6 months. Written informed consent was obtained from all participants before entry into the study, which was approved by the local human research ethics committee.

Study design. A randomized controlled design was used for this study. To reduce any potential bias of sex and age, participants were stratified according to age (60–70 and 71–80 yr old) and gender before being randomly assigned to CONV, EB, or a waitlist control group. Participants randomized to EB and CONV underwent pretraining testing of isometric and isokinetic knee extensor strength, quadriceps and medial gastrocnemius (GM) muscle architecture, arterial stiffness, and functional capacity. Before baseline testing, participants attended the laboratory on two occasions to be familiarized with the isometric and isokinetic strength and functional capacity tests. The familiarization sessions and test session were separated by 7–14 d. Participants then commenced the 16-wk resistance training program, after which they underwent posttraining testing. Participants randomized to the waitlist control group underwent precontrol testing and were then instructed to maintain their regular level of physical activity and avoid heavy resistance training for 16 wk before postcontrol testing. They were then randomized to either EB or CONV and performed 16 wk of resistance training before posttraining testing.

Resistance training. EB and CONV participants performed resistance training twice weekly on nonconsecutive days for 16 wk. Both programs consisted of the 45° leg press, toe press, bench press, and latissimus dorsi pull-down exercises. For the toe press, participants sat on the leg press machine with knees fully extended and with the balls of their feet on the bottom edge of the foot-plate, lifted, and lowered the resistance with the plantar flexors. Bench press was performed using a Smith machine and lat pull-downs were performed on a pin-loaded machine with a "V-bar" handgrip, composed of two parallel handles approximately 9 cm apart.

At the first training session, participants were familiarized with each exercise and were instructed on proper technique. Participants then performed a 1RM test for each exercise. After each successful lift, participants were given at least 1 min to recover before the next attempt. No more than five lifts were needed to determine 1RM. 1RM tests were repeated 2 wk later, then every 3 wk subsequently, and training weights were adjusted accordingly. When 1RM tests were performed, one less set than usual of each exercise was performed.

CONV participants performed two sets of each exercise, with 3-min rests between sets. Each set involved 10 completely bilateral repetitions at 75% of the 1RM. For EB, participants performed three sets of each exercise, with 3-min rests between sets. Each set involved 10 concentric lifts performed bilaterally with 50% of the 1RM. Participants then lowered the weight unilaterally, alternating between left and right limbs with each repetition, thus performing five

TABLE 1.

Training Method	Contraction Mode	Sets	Reps	Relative Intensity[a] (%)	Volume Load[b]
CONV	Concentric	2	10	75	1500
	Eccentric (bilateral)	2	10	75	1500
EB	Concentric	3	10	50	1500
	Eccentric (unilateral)	3	5	100	1500

[a] Relative intensity = percent of 1RM.
[b] Volume load = sets × repetitions × relative intensity.

unilateral eccentric contractions per limb per set. The difference in the number of sets used by CONV and EB in the current study was necessary to match the volume of work performed by each training group. The training protocols were designed to ensure that participants in EB and CONV performed the same amount of work for each limb relative to individual 1RM (Table 1). Actual total concentric work for each limb was calculated by multiplying the actual relative intensity (% of 1RM) by the number of repetitions performed in each set, then summing concentric work performed in each set during the whole training period. Actual total work (concentric and eccentric) for each limb was calculated by multiplying actual concentric work by 2.

RPE. The Borg (5) RPE scale with values from 6 to 20 was used to obtain RPE after each set of exercise throughout the 16 wk. Mean RPE for each exercise for each participant was then calculated. Mean RPE for each exercise in weeks 4, 8, 12, and 16 of training was also calculated.

PWV. Arterial stiffness was quantified from the PWV before strength and functional capacity tests. Reliability analyses on the data from the control group revealed an ICC (95% confidence interval (CI)) of 0.835 (0.427–0.953) and 95% ratio limits of agreement (LOA) of 23.29%. Participants lay supine for 20 min before digital pulse detectors were strapped to their right index finger and right second toe. A three-lead ECG was obtained concurrently to use as a reference point for each pulse. Data were collected for 15 min and sampled at 1000 Hz. The difference between the distances from the sternal notch to the index finger and the sternal notch to the second toe was taken as the distance traveled by the pulse wave. Five pulse waves, separated by 3 min, were selected for analysis. The mean time taken for the five separate pulse waves to travel from the finger to the toe was used to calculate PWV. Timing was made from the "foot" of the waveforms (13). All PWV data were analyzed by a single investigator.

Muscle architecture. Real-time B-mode ultrasonography (LOGIQ I; GE Healthcare, Wauwatosa, WI) with a 42-mm-long 10-MHz linear array transducer was used to measure fascicle pennation angle, fascicle length, and muscle thickness of the vastus lateralis (VL) and GM muscles on a single randomly chosen limb. The reliability of the following protocol for measuring VL and GM architecture has been previously demonstrated by our laboratory (34). A single investigator acquired the images from all participants. A second investigator, who was blinded to the identity of the participants, was then used to analyze the images.

Ultrasound images were obtained from sites 62.5% along the length between the anterior superior iliac spine and the superior aspect of the patella in the midsagittal (VL site 1) and midcoronal (VL site 2) planes of the thigh. Participants were seated on the edge of the bench with knee angles fixed at 90°, a position associated with minimal fascicle curvature (4).

GM architecture and thickness were measured 30% of the distance between the lateral malleolus of the fibula and the lateral condyle of the tibia while participants lay prone on the bench with their feet hanging off the edge (26) in a modified night splint that fixed the ankle at 15° of dorsiflexion. Consistent positioning of the ultrasound transducer before and after training was obtained by use of a transparent plastic sheet onto which the examination sites and any permanent skin blemishes were marked (4). Three ultrasound images from each site were recorded digitally and analyzed using freely available software (ImageJ 1.38x; National Institutes of Health, Bethesda, MD).

Quadriceps thickness was defined as the distance between the superficial aponeurosis and the femur, and GM muscle thickness was defined as the distance between the superficial and deep aponeuroses. Pennation angle was determined between the muscle fascicles and the deep aponeurosis, and fascicle length was measured between its insertions on the superficial and deep aponeuroses. Where the fascicles extended beyond the recorded image, their length was estimated from muscle thickness and fascicle pennation angle using equation 1:

$$L_f = T \ \sin\Theta^{-1} \qquad [1]$$

where L_f is fascicle length, T is muscle thickness, and Θ is pennation angle.

Isokinetic and isometric testing. Isokinetic and isometric knee extensor strength of a randomly chosen limb was determined on a Biodex System 4 Quick Set dynamometer (Biodex Medical Systems, Shirley, NY). Reliability analyses on 23 healthy community-dwelling older adults (13 men and 10 women, mean age = 67.2 ± 5.6 yr), 13 of whom participated in the current study, revealed that the ICC (95% CI) for the dynamometer strength tests were as follows: isometric = 0.991 (0.978–0.996), $60°\cdot s^{-1}$ = 0.976 (0.943–0.990), $120°\cdot s^{-1}$ = 0.982 (0.958–0.992), $240°\cdot s^{-1}$ = 0.984 (0.962–0.993), $360°\cdot s^{-1}$ = 0.984 (0.960–0.993). The 95% ratio LOA for the isometric, 60, 120, 240, and $360°\cdot s^{-1}$ dynamometer tests were 9.87%, 20.28%, 20.92%, 18.21%, and 14.91%, respectively (previously unpublished data).

Participants sat upright in the dynamometer secured by waist and torso straps. The dynamometer's axis of rotation was visually aligned with the lateral epicondyle of the femur. The dynamometer's ankle pad was positioned above the medial malleolus. The position of the seat base, seat back, and length of lever arm were recorded at the first familiarization session and replicated for the subsequent familiarization and testing sessions. Participants were instructed to hold onto handles positioned on either side of the seat during contractions.

A standard warm-up of the quadriceps, involving two sets of six concentric efforts at $30°\cdot s^{-1}$, was carried out before each session. Participants rested 1 min between the warm-up and the commencement of the test. The test consisted of maximal concentric contractions at 60, 120, 240, and $360°\cdot s^{-1}$ and isometric contractions ($0°\cdot s^{-1}$). One of five different test sequences, each with a different order of contraction speeds, was randomly assigned to participants at the first familiarization session and used for all subsequent sessions. Isokinetic contractions were performed between knee joint angles of 105° to 5°, with 0° representing full extension. Isometric contractions were performed at a knee joint angle of 60°. Participants performed five contractions at each speed with 30-s rest between each contraction and 1-min rest between speeds. Participants were given loud verbal encouragement and visual feedback of the torque signal in each repetition.

Torque, corrected for limb weight, was sampled at a frequency of 1000 Hz (PowerLab 4/25; AD Instruments, Bella Vista, New South Wales, Australia) and stored on computer. Only torques from the isokinetic portion of each dynamic contraction were analyzed on a computer software program (Chart 5; AD Instruments). The torque data from the five contractions performed at each velocity were averaged and used for statistical analysis.

Functional and vertical jump tests. Five functional tests were undertaken. They were the 6-m fast walk test (6MFWT), the timed up and go test (TUG), stair climb and stair descent power tests, and the vertical jump test. Reliability analyses on 23 healthy community-dwelling older adults (13 men and 10 women, mean age = 67.2 ± 5.6 yr), 13 of whom participated in the current study, revealed that the ICC (95% CI) were as follows: 6MFWT = 0.952 (0.886–0.980), TUG = 0.979 (0.951–0.991), stair climb = 0.997 (0.992–0.999), stair descent = 0.989 (0.974–0.995), and vertical jump = 0.988 (0.971–0.995). The 95% ratio LOA for the 6MFWT, TUG, stair climb, stair descent, and vertical jump tests were 14.32%, 10.36%, 7.28%, 13.72%, and 13.53%, respectively (previously unpublished data).

The 6MFWT, performed between two sets of light gates, involved the timing of participants as they walked as quickly as possible (11,15).

The TUG test measures the time taken for an individual to rise from a chair, walk 3 m to touch a marker on a wall, turn 180°, return to the chair, and sit down (6). Time was recorded with a stopwatch. Participants were instructed not to use their hands when rising from or sitting back down on the chair.

The stair climb and descent power tests involved participants climbing and descending a flight of stairs as quickly as possible (19). Stair climb and descent time were assessed separately using a stopwatch. The flight of stairs used in this study composed of 16 steps, each with a height of 15 cm. The participants were not allowed to hold the handrails during this test. Stair climb and descent power were calculated using the following equation:

$$\text{power (W)} = \frac{mgd}{t} \qquad [2]$$

where m is the mass (kg) of the participant, g is acceleration ($m\cdot s^{-2}$) due to gravity, d is vertical displacement (m), and t is stair climb or descent time (s).

The vertical jump test was performed on a force plate (Kistler Type 9286AA; Kistler Instruments, Winterthur, Switzerland). Participants were instructed to stand on the force plate with both feet shoulder-width apart, perform a countermovement by bending the knees, then jump as high as possible. Arm swing was allowed during performance of the jump. Vertical jump height and peak jumping power were estimated from vertical take-off velocity derived from impulse data using data analysis software (BioWare 3; Kistler Instruments). Methods for signal sampling are described elsewhere (7).

Participants performed each functional and vertical jump test three times during familiarization and test sessions. The average of the three results from each test was used for statistical analysis. All functional capacity and vertical jump tests were supervised by the same investigator.

Statistical analyses. Normality of the data was determined using the Kolmogorov–Smirnov test, and nonnormal data were natural log-transformed. One-way ANOVA was used to evaluate whether there were any differences between groups for any of the variables at baseline. Repeated-measures ANOVA were used to evaluate differences in RPE for each exercise between weeks 4, 8, 12, and 16. Two-way (group × time) ANOVA was used to evaluate any effect of the exercise interventions on arterial stiffness, muscle architecture, isometric and isokinetic strength, angle of peak torque, functional capacity, and 1RM. Two-way (group × velocity) ANOVA was also used to evaluate if the exercise interventions differed in their efficacy at differing isokinetic speeds. *Post hoc* tests with a Bonferroni correction were used to further analyze significant main interactions. Two-tailed unpaired t-tests were used to evaluate whether there were any differences in RPE and work performed between training groups. Data are presented as mean ± SD. Results were considered significant at $P < 0.05$, and statistical analyses were performed using IBM SPSS Statistics 19.0 (IBM, Somers, NY). *A priori* power analysis based on the most conservative effect size of 0.34 regarding dynamometer tests of strength (torque data at $60°\cdot s^{-1}$) revealed that 13 participants were needed per group to obtain statistical power of 0.95 (10).

RESULTS

Three participants assigned to the waitlist control group decided not to participate in the resistance training intervention. The other 10 participants from the waitlist control group were randomly assigned to either EB or CONV after

TABLE 2. Estimates of total work for each limb.

	Group	Total Work (AU)	P
Leg press	CONV	76,320 ± 6147	0.17
	EB	79,507 ± 4876	
Toe press	CONV	74,623 ± 8296	0.18
	EB	78,463 ± 5396	
Bench press	CONV	75,244 ± 6098	0.77
	EB	73,866 ± 15,012	
Lat pull-down	CONV	75,673 ± 5199	0.34
	EB	77,685 ± 5122	

Data presented as mean ± SD. *P* values are for two-tailed independent *t*-tests performed to compare total work performed both groups.
AU, arbitrary units.

the control period. There were no significant differences between the three groups regarding any variables at baseline.

Resistance training data. Estimates of total work performed by each limb for leg press, toe press, bench press, and latissimus dorsi pull-downs were not significantly different between EB and CONV (Table 2). EB and CONV participants completed 95.9% and 95.8% of the total planned training sessions, respectively. Changes in 1RM as a result of training are summarized in Table 3. Significant time effects were observed for changes in 1RM for all exercises ($P < 0.01$). *Post hoc* tests revealed significant differences ($P < 0.01$) between pretraining and posttraining 1RM for all exercises in both exercise groups. There were no significant group × time effects for 1RM between EB and CONV for any exercise, indicating that there was no significant difference between training modalities regarding changes in 1RM.

RPE. Mean RPE for each set tended to be higher in CONV than EB for all exercises. This difference was nonsignificant for leg press (12.8 ± 1.6 vs 12.5 ± 1.4, respectively, $P = 0.59$) and toe press (13.3 ± 1.8 vs 12.2 ± 1.4, $P = 0.11$) but significant for bench press (14.8 ± 2.0 vs 13.3 ± 1.4, $P < 0.05$) and latissimus dorsi pull-downs (15.1 ± 2.2 vs 12.8 ± 1.2, $P < 0.01$). RPE did not change significantly between weeks 4, 8, 12, and 16 in CONV for all exercises ($P > 0.05$). RPE did not change significantly between weeks 4, 8, 12, and 16 in EB for leg press, bench press, and latissimus dorsi pull-downs. A significant time effect was observed for toe press in EB ($P < 0.05$). *Post hoc* tests revealed that RPE was significantly lower in week 16 than week 4 for toe press in EB (11.8 ± 1.5 in week 16 vs 12.6 ± 1.9 in week 4).

TABLE 3. Changes in 1RM as a result of training.

	Group	Before Training	After Training	% Difference
Leg press 1RM (kg)	CONV	159 ± 38	195 ± 45	23*
	EB	171 ± 51	211 ± 61	23*
Toe press 1RM (kg)	CONV	200 ± 50	263 ± 64	31*
	EB	196 ± 37	265 ± 54	35*
Bench press 1RM (kg)	CONV	36 ± 13	46 ± 15	30*
	EB	37 ± 14	47 ± 14	24*
Lat pull-down 1RM (kg)	CONV	48 ± 17	58 ± 18	23*
	EB	50 ± 14	61 ± 15	24*

Data presented as mean ± SD.
% Difference, percentage difference between pretraining and posttraining data.
* Significant difference between before and after training, $P < 0.01$.

TABLE 4. Changes in PWV and functional capacity.

	Group	Before Training	After Training	% Difference
PWV ($m \cdot s^{-1}$)	CONV	14.5 ± 10.3	16.0 ± 10.8	10
	EB	10.8 ± 3.7	12.1 ± 7.4	12
	Control	11.7 ± 4.2	13.3 ± 5.5	14
6MFWT (s)	CONV	2.79 ± 0.57	2.66 ± 0.61	−5*
	EB	2.79 ± 0.32	2.60 ± 0.29	−7*
	Control	2.74 ± 0.40	2.86 ± 0.38	4**
TUG (s)	CONV	4.55 ± 0.81	4.34 ± 0.64	−5*
	EB	4.51 ± 0.43	4.39 ± 0.38	−3
	Control	4.58 ± 0.54	4.50 ± 0.48	−2
Stair climb power (W)	CONV	400 ± 117	412 ± 121	3
	EB	433 ± 138	456 ± 141	5*
	Control	404 ± 101	410 ± 99	1
Stair descent power (W)	CONV	376 ± 83	392 ± 81	4**
	EB	366 ± 105	380 ± 111	4
	Control	362 ± 62	360 ± 60	−1
Vertical jump height (cm)	CONV	25.4 ± 9.1	27.3 ± 8.6	7*
	EB	28.1 ± 5.7	28.9 ± 5.3	3
	Control	25.9 ± 4.9	25.2 ± 6.0	−2
Peak jumping power (W)	CONV	985 ± 466	1055 ± 499	7
	EB	1085 ± 453	1085 ± 458	0
	Control	1083 ± 344	1040 ± 422	−4

Data presented as mean ± SD
% Difference, percentage difference between pretraining and posttraining data.
* Significant difference between before and after training or after control, $P < 0.01$.
** Significant difference between before and after training or after control, $P < 0.05$.

PWV. PWV data for the three groups are summarized in Table 4. The three groups did not differ significantly at baseline. No significant time ($P = 0.38$) or group × time ($P = 0.30$) effects were observed.

Muscle architecture. Muscle architecture data for all three groups are summarized in Table 5. The three groups did not differ significantly in any architecture measurements

TABLE 5. Muscle architecture data.

	Group	Before Training	After Training	% Difference
GM Θ (°)	CONV	19.9 ± 3.6	20.6 ± 2.7	4
	EB	19.6 ± 1.4	18.9 ± 3.2	−3
	Control	19.9 ± 3.5	18.0 ± 2.7	−10*
GM L_f (cm)	CONV	5.56 ± 0.97	5.38 ± 0.81	−3
	EB	5.67 ± 0.76	5.92 ± 0.83	4
	Control	5.85 ± 1.07	6.17 ± 1.25	5
GM thickness (cm)	CONV	1.87 ± 0.28	1.87 ± 0.21	0
	EB	1.89 ± 0.24	1.89 ± 0.25	0
	Control	1.94 ± 0.25	1.87 ± 0.29	−3
VL site 1 thickness (cm)	CONV	3.88 ± 0.46	3.96 ± 0.47	2
	EB	4.03 ± 0.62	4.22 ± 0.68	5*
	Control	4.18 ± 0.74	3.95 ± 0.55	−6*
VL site 2 thickness (cm)	CONV	4.71 ± 0.50	4.71 ± 0.62	0
	EB	4.49 ± 0.53	4.64 ± 0.52	3
	Control	4.50 ± 0.49	4.47 ± 0.46	−1
VL Θ (°)	CONV	12.9 ± 2.8	11.9 ± 3.6	−8
	EB	11.5 ± 4.4	11.9 ± 3.1	3
	Control	11.9 ± 3.2	11.1 ± 3.5	−7
VL L_f (cm)	CONV	11.1 ± 2.6	11.5 ± 3.6	4
	EB	12.3 ± 3.8	12.9 ± 5.1	5
	Control	12.3 ± 4.3	12.1 ± 4.5	−2

Data presented as mean ± SD.
Θ, pennation angle; L_f, fascicle length; % difference, percentage difference between pretraining and posttraining or postcontrol data.
* Significant difference between before and after training or after control, $P < 0.05$.

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TABLE 6. Knee extensor isometric and isokinetic torque data.

Velocity	Group	Before Training (N·m)	After Training (N·m)	% Difference
Isometric	CONV	160 ± 40	166 ± 46	4
	EB	175 ± 38	187 ± 44	7*
	Control	162 ± 40	162 ± 41	0
$60°{\cdot}s^{-1}$	CONV	126 ± 36	135 ± 39	7*
	EB	129 ± 30	137 ± 32	6*
	Control	125 ± 25	128 ± 29	2
$120°{\cdot}s^{-1}$	CONV	101 ± 31	109 ± 32	8**
	EB	101 ± 24	108 ± 26	7**
	Control	98 ± 19	101 ± 20	3
$240°{\cdot}s^{-1}$	CONV	75 ± 26	77 ± 26	3
	EB	74 ± 21	78 ± 22	5*
	Control	70 ± 16	72 ± 18	3
$360°{\cdot}s^{-1}$	CONV	59 ± 21	60 ± 24	1
	EB	56 ± 16	62 ± 19	11**
	Control	56 ± 12	56 ± 11	0

Data presented as mean ± SD.
% Difference, percentage difference between pretraining and posttraining or postcontrol data.
* Significant difference between before and after training or after control, $P < 0.05$.
** Significant difference between before and after training or after control, $P < 0.01$.

at baseline. A significant group × time effect was observed for VL site 1 thickness ($P < 0.01$). *Post hoc* tests revealed that VL site 1 thickness increased significantly by 5% in EB ($P < 0.05$), whereas thickness did not change significantly in CONV ($P = 0.41$) and decreased significantly by 6% in the control group ($P < 0.05$). No significant main effects were observed for other muscle architecture measures in either muscle.

Knee extensor torque–velocity relationship. The knee extensor torque data are presented in Table 6. Change (Δ) in torque at each velocity in each group is illustrated in the Supplemental Digital Content (see Figure, SDC 1, showing the change in torque for knee extensors for conventional training [CONV], eccentrically biased training [EB], and the control group, http://links.lww.com/MSS/A138).

The main group effect for the mean change in torque (post − pre, for all velocities combined) showed a trend between the groups with (mean) control = 1.6 N·m, CONV = 5.2 N·m, and EB = 7.6 N·m. The difference between these means bordered on being statistically significant between the control group and EB ($P = 0.13$).

The main effect for the amount of change in torque (post − pre, Δ torque) differed between velocities. Essentially, the five velocities formed two clusters. The three slower velocities (0, 60, and $120°{\cdot}s^{-1}$) displayed a greater change in torque (mean of all three groups) than the two faster velocities (240 and $360°{\cdot}s^{-1}$). The amount of change (Δ torque) was 5.9, 6.3, and 6.3 N·m for the three slower velocities and 2.8 and 2.3 N·m for the two faster velocities. These differences were statistically significant ($P < 0.05$) between $120°{\cdot}s^{-1}$ and the two faster velocities (240 and $360°{\cdot}s^{-1}$). For the two other slower velocities (0 and $60°{\cdot}s^{-1}$), the difference with the two faster velocities (240 and $360°{\cdot}s^{-1}$) displayed the same trend (see means) but did not reach statistical significance.

Further analyses revealed that the differences in the change in torque (i.e., the three slower velocities displaying greater overall increases in torque than the two faster velocities) were largely attributable to the differences in delta torque displayed at different velocities in CONV, where the differences between velocities within the group were statistically significant ($P < 0.05$). This was due to CONV producing relatively large changes at the three slowest velocities, but little or no improvement at the two fastest velocities. Conversely, in EB, the Δ torque at different velocities did not differ statistically because they all displayed an improvement of similar and relatively large magnitude, and in the control group, the Δ torque at different velocities again did not differ statistically because the changes were also consistent but of small magnitude or nonexistent across all velocities.

Further analysis of the difference between groups revealed a group × velocity interaction with the change in torque being statistically significant ($P < 0.05$) at $360°{\cdot}s^{-1}$, with EB producing a greater change in torque at this fastest velocity than either CONV or control.

Regarding the two-way (group × time) ANOVA performed using the absolute torque values, significant time effects were detected for torque during isometric contractions and all concentric contraction speeds ($P \leq 0.01$). A significant group × time effect was also detected for torque during concentric contractions at $360°{\cdot}s^{-1}$ ($P < 0.05$). *Post hoc* tests revealed that for isometric contractions, torque increased significantly in ECC by 7% ($P < 0.01$). For contractions at $60°{\cdot}s^{-1}$, torque increased significantly in both ECC and CONV by 6% and 7%, respectively ($P < 0.05$). For contractions at $120°{\cdot}s^{-1}$, torque increased significantly in both ECC and CONV by 7% and 8%, respectively ($P < 0.01$). For contractions at $240°{\cdot}s^{-1}$ and $360°{\cdot}s^{-1}$, torque increased significantly only in ECC by 5% ($P < 0.05$) and 11% ($P < 0.01$), respectively.

A significant group × time effect ($P < 0.05$) was detected for angle of peak torque during contractions at $240°{\cdot}s^{-1}$. *Post hoc* tests revealed that the angle of peak torque during contractions at $240°{\cdot}s^{-1}$ decreased significantly (Δ5%, $P < 0.05$) in the control group but did not change significantly in CONV ($P = 0.36$) or EB ($P = 0.225$). No significant main effects ($P > 0.05$) were observed for angle of peak torque at all other contraction speeds.

Functional and vertical jump tests. Functional and vertical jump tests data are summarized in Table 4. Significant time ($P < 0.05$) and group × time ($P < 0.01$) effects were detected for the 6MFWT. *Post hoc* tests revealed that 6MFWT time decreased significantly ($P < 0.01$) in both EB and CONV but increased significantly in the control group ($P < 0.05$). A significant time effect was detected for the TUG ($P < 0.01$). *Post hoc* tests revealed that TUG time decreased significantly in CONV ($P < 0.01$) and approached significance in EB ($P = 0.08$). There was no significant change in the control group ($P = 0.25$). When data were pooled across experimental groups, a significant improvement in TUG performance (4.54 s before vs 4.41 s after, $P < 0.01$) was observed from before to after condition. A significant time effect was detected for the stair climb power test ($P < 0.01$). *Post hoc* tests revealed that stair climb power increased significantly only in EB ($P < 0.01$) with no significant change in CONV ($P = 0.10$) or the control group ($P = 0.53$). When data were pooled across experimental groups, a significant improvement in stair climb power (417 W before vs 430 W after, $P < 0.01$) was observed from before to after condition. A significant time effect was detected for the stair descent power test ($P < 0.05$). Stair descent power increased significantly in CONV ($P < 0.05$) and approached significance in EB ($P = 0.06$). There was no significant change in the control group ($P = 0.96$). When data were pooled across experimental groups, a significant improvement in stair descent power (373 W before vs 382 W after, $P < 0.05$) was observed from before to after condition. A significant group × time effect was detected for the vertical jump height ($P < 0.05$). *Post hoc* tests revealed that vertical jump height increased significantly in CONV ($P < 0.01$) but did not change significantly in EB ($P = 0.33$) or the control group ($P = 0.22$). No significant time ($P = 0.83$) or group × time ($P = 0.525$) effects were detected for peak jumping power.

DISCUSSION

This is the first study to compare eccentrically biased resistance training, a more practically applicable training modality than eccentric-only resistance training, and conventional training in older adults. The main findings are as follows: (i) EB and CONV lead to similar increases in 1RM strength; (ii) EB leads to increases in strength across a range of isokinetic contraction velocities, whereas CONV leads to strength gains only at slower contraction velocities; (iii) EB and CONV induce similar improvements to the performance of several functional capacity assessments, but CONV was more effective than EB for increasing vertical jump height; (iv) EB and CONV seem to have no significant effect on arterial stiffness; (v) EB may be more effective than CONV at increasing muscle mass; and (vi) RPE is similar to or lower in EB than in CONV training.

The changes to the torque–velocity relationship of the knee extensors after training confirm our hypothesis that EB would be more effective than CONV at increasing torque production during faster concentric contractions. The observed increase in torque production at isometric and slower concentric contractions (0, 60, and $120°\cdot s^{-1}$) but not at the faster velocities (240 and $360°\cdot s^{-1}$) in CONV is expected because the relatively heavy weights demanded that concentric contractions in all exercises, specifically the leg press, were performed at relatively slow speeds. This finding is consistent with the concept of velocity specificity in resistance training (2). The significant increase in torque at fast concentric contractions (240 and $360°\cdot s^{-1}$) is encouraging for its application to training programs for older adults. This increased torque at fast contraction speeds may be an advantage when rapid movements of the limbs are necessary, such as recovering from a stumble or trip (44). The increase in torque across all concentric contraction velocities and during isometric contractions after EB is intriguing because it does not conform to the concept of velocity specificity. The previously reported elongation of muscle fascicles after eccentric-only resistance training (35) would conceivably increase muscle force and power output at relatively high shortening velocities, although we did not observe increases in fascicle lengths. It is therefore difficult to pinpoint a reason for the positive effects of eccentric resistance training on high-velocity concentric strength in EB. However, the increase in VL thickness in EB may partly explain this observation. One issue arising from the EB training modality is that of the bilateral strength deficit. The influence of the bilateral strength deficit would mean that participants in the EB group possibly performed slightly less work overall during the training program in the eccentric phase, which was performed unilaterally, than those in the CONV group. This is because the 1RM tests were performed bilaterally, meaning that the unilateral 1RM may have been slightly underestimated, especially at the start of the training program. Also, the bilateral strength deficit is reduced with training and it may have declined less in the EB group, who performed the bilateral concentric phase of exercises at 50% of 1RM compared to 75% of 1RM in the CONV group. This could have potentially biased the bilateral tests toward the CONV group and the unilateral tests toward the EB group. However, both groups performed bilateral concentric phases so the effects of the training should not have differed too drastically between groups. To illustrate this, torque still increased at all contraction speeds in EB while only increasing at slow contraction speeds in CONV. In addition, 1RM strength, which was performed bilaterally, increased to a similar degree in both EB and CONV groups.

Although more functional capacity measures improved significantly in CONV than EB, performance improvements in the TUG and stair descent power test in EB approached significance ($P = 0.08$ and $P = 0.06$, respectively), thereby suggesting that the two training modalities might be similarly effective at improving functional performance. It was surprising to observe a significant decline in 6MFWT performance in the control group after only 16 wk in this healthy community-dwelling older adult population. However, similar declines in function have been observed in the control groups of other studies (38,39), so this finding is not a unique anomaly and may be indicative of real functional declines. Another interesting observation was that the increase in knee extensor strength across all contraction velocities in EB did not translate into better performance in the vertical jump test than CONV. However, it should be noted that older adults perform vertical jumps with relatively low joint angle velocities (12), and conventional resistance training has been shown to have a positive effect on vertical jump performance in older men (18). Also, participants in CONV lifted heavier loads in the concentric phase, which were possibly more specific to body mass, than those in EB, and vertical jump is a movement with a bilateral stretch shorten cycle that finishes with a concentric effort rather more similar to the CONV training than the EB. This may suggest that velocity and contraction mode specificity are important for this task. Nevertheless, it could be argued that the superior improvements in vertical jump performance, which is a bilateral method of assessing power, in CONV is more functionally significant than the increases in unilateral, isokinetic strength seen in the EB group.

The lack of familiarization before 1RM testing is a limitation of the current study and may have overestimated 1RM gains as a result of training. However, the percentage increase in leg press 1RM (23% for CONV and EB), for example, is similar to the increase (23%) in leg press 5RM observed by Reeves et al. (35) after 14 wk of conventional training in nine older adults (mean age = 67 ± 2 yr) with 2 wk of familiarization before 1RM testing. Also, the similar increases in 1RM strength in both training groups indicate that both modalities are equally effective at increasing maximal strength, and the improvements in isokinetic and isometric strength and functional capacity measures in both groups independently illustrate the effectiveness of the CONV and EB training protocols used in this study.

GM and VL muscle fascicle length and pennation angle did not change significantly in either training group. This is in contrast to the observations of Reeves et al. (35), who reported increases in VL fascicle length and pennation angle after 14 wk of either eccentric-only or conventional resistance training performed three times a week by older adults. However, there were significant decreases in GM pennation angle and VL thickness at site 1 and nonsignificant decreases in GM fascicle length, VL pennation angle, and VL fascicle length in the control group in the current study. 3 the degree of deterioration in muscle architecture measures in the control group is surprising, the fact that the reliability of these muscle architecture measures has been recently demonstrated (34) makes this observation difficult to explain. Also, the lack of change in angle of peak torque in the training groups supports our finding of a lack of change in fascicle lengths in CONV and EB (3). These observations may suggest that both training modalities had a protective effect against the potentially detrimental age-related changes in GM and VL muscle architecture and that the increases in torque at fast contraction speeds in EB may be due to mechanisms other than changes in fascicle length. Nevertheless, the fact that fascicle length was only measured at one site on each muscle is a limitation of the current study because it is recognized that muscular adaptation to training may be heterogeneous along the length of a muscle and may differ between vastii (27). Regarding muscle thickness, the fact that EB brought about an increase in VL thickness whereas thickness in CONV did not change and thickness in the control group decreased over time is consistent with numerous previous studies which suggest that eccentric resistance training is more effective at increasing muscle hypertrophy than concentric training (16,37,43). The lack of change in GM thickness with both training modalities is consistent with the finding that soleus muscle protein synthesis responds relatively poorly to an acute bout of resistance training when compared with VL protein synthesis (41).

The lower RPE in upper body exercises in EB compared with CONV concurs with the findings of Reeves et al. (35), who compared conventional training to eccentric-only training in older adults. Lower RPE may be important for resistance training program compliance. The lack of change in RPE over time in both training groups for most exercises is expected because of the adjustment of training weights with every 1RM test conducted throughout the training program, so that participants exercised at the same intensity throughout the programs. The decrease in RPE over time in EB for toe press is most likely due to participants becoming more familiar with performing the exercise, rather than an actual decrease in exertion, due to the unusual nature of the exercise.

The finding that neither training modality had a significant effect on central and peripheral arterial PWV supports the findings of Maeda et al. (21), who found that 12 wk of isokinetic (concentric and eccentric) leg resistance training had no effect on carotid and femoral artery PWV in healthy young females. On the other hand, Okamoto et al. (29) reported higher brachial–ankle PWV after 8 wk of concentric-only resistance training but no change after eccentric-only resistance training in older men. Other studies have found evidence of decreased central arterial compliance as a result of conventional resistance training in men (23,24). One reason for this discrepancy could be that previous studies that observed increases in arterial stiffness after weight training measured central arterial stiffness, whereas the method used in the current study takes into account central as well as peripheral arteries. Heffernan et al. (14) found that peripheral arterial stiffness decreased in the exercised limb after weight training. Therefore, the differential changes in central and peripheral arterial stiffness may have masked overall changes in arterial stiffness in the current study. The index of arterial stiffness used in the current study is one of several methods to describe arterial stiffness (13), and there are limitations to this method. For example, the method of measuring the distance traveled by the pulse wave does not take into account differences in body shape and assumes that the aorta is straight. Although this method has been validated by Tsai et al. (42), more research may be needed before the effects of EB and CONV on arterial stiffness are more clearly understood.

CONCLUSIONS

This study suggests that eccentrically biased resistance training is a viable alternative to conventional resistance training for older adults. Although improvements in 1RM and functional capacity were similar for both training modalities, quadriceps thickness and torque at higher isokinetic velocities increased only after EB. While longer-term studies are required, these findings suggest that EB may be particularly valuable for a population that is prone to sarcopenia and falls (9). Generally, lower RPE in eccentrically biased training may also have implications for program compliance. Furthermore, although eccentric-only training is impractical in a real-world gym setting owing to the consistent need for assistance from a spotter to aid with the lifting of the weights, this study has demonstrated that eccentrically biased training can be successfully performed without assistance, using resistance training machines that are widely available.

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