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Cardiopulmonary responses to eccentric and concentric resistance exercise in older adults

Alberto F. Vallejo, Edward T. Schroeder, Ling Zheng, Nicole E. Jensky, Fred R. Sattler

University of Southern California, Biokinesiolgy, Los Angeles, CA, USA

Address correspondence to: A. F. Vallejo. Email: avallejo@usc.edu

Abstract

Background: in older ambulatory persons, exercise strategies that are expected to generate beneficial muscle adaptations with low cardiopulmonary demands are needed.
Objective: we hypothesised that eccentric resistance exercise would be less demanding on the cardiovascular and pulmonary systems than bouts of concentric resistance exercise.
Design: the effects of eccentric and concentric resistance exercise were compared during leg squats at a submaximal intensity known to increase muscle mass.
Subjects: 19 older persons (15 women/four men, age 65±4 years) and 19 young reference controls (10 women/nine men; age 25±2 years) were enrolled.
Methods: participants completed eccentric-only and concentric-only exercise bouts 5–7 days apart.
Results: cardiovascular and pulmonary measures were collected from subjects during bouts consisting of three sequential sets of 10 repetitions at 65% of their voluntary concentric 1-repetition maximum force (68±16 kg for older participants and 94±36 kg for young participants). Peak heart rate (119±10 versus 155±16 b.p.m.), systolic blood pressure (129±18 versus 167±14 mmHg), cardiac index (7.8±2.0 versus 9.2±1.5 l/min/m^2) and expired ventilation (20.5±5.7 versus 29.8±9.1 l/min) were significantly lower during eccentric than during concentric bouts in the older subjects, respectively (P<0.001 for all comparisons). Similarly, peak heart rate, systolic blood pressure, cardiac index and expired ventilation were significantly lower during eccentric bouts in the young control subjects.
Conclusions: eccentric resistance exercise produced less cardiopulmonary demands and may be better suited for older persons with low exercise tolerance and at risk of adverse cardiopulmonary events.

Keywords: *resistance exercise, cardiopulmonary demands, leg squats, elderly*

Introduction

Progressive resistance exercise is an effective means to increase skeletal muscle strength in older persons even into advanced age. Indeed, Fiatarone *et al.* showed that 3- to 4-fold increases in skeletal muscle strength could be achieved with resistance exercise in selected octogenarians and nonagenarians [1, 2]. Of importance, such improvements translated to enhanced skeletal muscle power [3], which has been correlated with improved gait acceleration, stair climbing speed, improved get up and go times, and other functional measures (stair descent time, Berg balance test) in older persons [4, 5].

However, the metabolic demands and safety of this type of strenuous exercise for a broader population of community dwelling older persons with age-related cardiopulmonary

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impairments and other illnesses such as hypertension, elevated cholesterol, diabetes, etc. are unknown. Limited evidence suggests that eccentric-based resistance exercise may be more metabolically efficient and therefore could be more tolerable as well as potentially safer for older persons [6–8]. Unlike traditional resistance exercise in which most of the work is done during concentric contractions as the muscle actively shortens to provide movement against a load, eccentric muscle contractions involve force exertion during active lengthening of the muscle [9]. Several studies suggest that eccentric exercise can improve skeletal muscle performance, with a lower demand for oxygen compared with concentric exercise. However, these studies were largely conducted in young persons using cycle ergometry [10, 11], which is not an optimal means to augment skeletal muscle mass and strength.

We hypothesised that eccentric resistance exercise should be better suited for older persons at risk for sarcopenia (loss of muscle mass) and age-related cardiopulmonary impairments since eccentric exercise appears to require less ATP utilisation [12] and should, therefore, be less demanding on the heart and lungs for these persons. Previous studies of eccentric resistance exercise were conducted in young normal volunteers and utilised an overload training stimulus with eccentric exercise intensities of 100–130% of the maximal capacity for concentric muscle force [13–16]. For older individuals, such an overload is unlikely to be tolerable or safe. The purpose of this study was, therefore, to determine if cardiopulmonary requirements are, in fact, less with eccentric than concentric resistance exercise at the same submaximal workload expected to generate skeletal muscle hypertrophy and enhance strength in typical community-dwelling older men and women. Young, healthy persons served as controls.

Methods

Measures of cardiac and pulmonary responses were assessed during rigorous eccentric and concentric resistance exercise in older adults (60–80 years old), with a young healthy population (21–30 years old) as a reference control group.

Screening

All subjects provided written informed consent approved by the Institutional Review Board of the University of Southern California. To screen and exclude potential subjects with severe cardiopulmonary limitations including increased risk of coronary ischaemia during exercise testing, older participants underwent a peak VO_2 exercise stress test on a cycle ergometer with electrocardiographic (ECG) and blood pressure monitoring. Peak VO_2 was the maximum VO_2 when the subject could not continue the exercise because of leg fatigue. Blood tests including comprehensive blood and chemistries were done to exclude persons with catabolic disease, such as uncontrolled diabetes, liver disease and renal failure, and to assess fasting lipids. Whole-body DEXA scans (Hologic QDR-4500, version 7.2 software, Waltham, MA) were performed to quantify lean body and fat mass (coefficient of variation for repeated measures was <1% for lean and fat mass).

Exercise protocol

Prior to the exercise test bouts, maximal voluntary force (1-repetition maximum) for the concentric leg squats was determined on two separate occasions (5–7 days apart) to determine the workload for the testing sessions. At the first testing bout (5–7 days after the last 1-repetition maximum testing session), participants performed either eccentric or concentric leg squats (three sets of 10 repetitions) at 65% of the 1-repetition maximum by random assignment. This intensity was based on prior studies showing that eccentric exercise at 50–75% intensity (relative to the concentric 1-repetition maximum) produced significant strength gains that were of similar magnitude to higher intensities (100–125%) in a young population [17, 18]. Participants returned 5–7 days after the first exercise trial to perform an exercise bout using the opposite contraction type.

For the exercise bouts, a Smith squat rack was modified with a pulley system to enable study participants to perform isolated eccentric or concentric leg squats, using a bench to delimit the lower boundary (Figure 1). A pulley system allowed the investigator to raise or lower the weight, thereby allowing participants to perform only eccentric or concentric muscle actions. The velocities of the eccentric or concentric movements were standardised to 2 s using a metronome. Participants were allowed 2 min rest periods between the three sets.

Figure 1. Modified Smith rack. A traditional Smith rack was modified with pulleys in order to isolate the eccentric and concentric muscle actions during the parallel knee squat exercise.

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Primary measures

Heart rate cardiac index and expired ventilation were assessed 5 min before, during and 5 min after completion of the exercise. Heart rate was determined using a dedicated limb lead ECG monitor. After establishing resting blood pressure, blood pressure was measured manually immediately before and at the completion of each exercise set. Expired ventilation (l/min) was measured using a Medgraphics Cardio II gas analysis module (Breeze Suite software version 6.0 A).

Statistical considerations

Demographics and baseline characteristics for older participants were compared with those of young participants using independent *t*-tests for means and Fishers exact test for proportions (Table 1). For the primary outcome measures, a repeated measures analysis of variance (ANOVA; age, gender for between-subject factors, exercise mode for within-subject factors) was performed for each exercise type (eccentric and concentric leg squats). For the entire population, within-subjects effects (exercise mode), between-subjects effects (age, gender), between-subjects interaction effects (age × gender) and interaction effects (exercise × age, exercise × gender, exercise × age × gender) were tested. The *a priori* plan was that if gender did not affect the outcomes, results would not be presented by gender. All *post hoc* tests were performed with Bonferroni adjustment. Analysis of covariance (ANCOVA) was used to compare mean differences of cardiovascular measures statistically between young and old groups or between eccentric and concentric exercise type, with adjustment for workload. Data in the text and tables are presented as means±1 SD. Statistical testing was performed using a two-sided 5% level of significance (1.25% for each *post hoc t*-test) and Statistical Analysis System version 8.0 (SAS Institute, Inc., Cary, NC).

Statistical power calculations

Due to the potential heterogeneity of older populations, conservative assumptions were used to prevent a type II (beta) error. Based on our prior pilot experiments, our primary assumption was that the difference in peak heart rate would be 20 b.p.m., namely a difference between a concentric mean of 130 b.p.m. and an eccentric mean of 150 b.p.m. with a common standard deviation of change of ~16 b.p.m. These assumptions required a sample size of 12 participants for each age group to provide a power of 85% to detect the expected changes with a two-sided alpha of <0.05.

Table 1. Study population characteristics

	Older participants (n = 19)	Young participants (n = 19)	P-value
Age (range)	65±4	25±2	<0.001
Gender			
Female	15	10	0.09
Male	4	9	
Ethnicity			
Hispanic	17	4	
Non-Hispanic White	2	4	<0.001*
Asian Pacific Islander	0	11	
History of diabetes	5	0	<0.001*
Hypertension	12	0	<0.001*
Body composition			
Weight (kg)	75±12	70±15	0.053
Body mass index (kg/m^2)	29±4	25±4	0.005
Total lean body mass (kg)	44±10	50±11	0.08
Appendicular LBM[a] (kg)	18±5	23±6	0.09
Trunk fat (kg)	16±5	7±4	<0.001
Blood counts and chemistries			
Haemoglobin (g/dl)	14±1	14±1	0.63
Blood urea bitrogen (mg/dl)	15±5	14±3	0.28
Aspartate aminotransferease (U/l)	25±9	29±26	0.51
Total cholesterol (mg/dl)	217±42	186±36	0.02
Triglycerides (mg/dl)	169±77	75±45	<0.001
HDL-cholesterol (mg/dl)	50±11	62±15	0.009
LDL-cholesterol (mg/dl)	132±39	109±33	0.06
Exercise performance measures			
VO_2 peak (ml/kg/min)	25.5±3.9	NT	NA
Leg squats (kg) for 1-RM[b]	68±16	94±36	<0.001

*P-values by Fisher's exact test.
[a]Lean body mass
[b]One-repetition maximum

Results

Study participants

Nineteen older persons with a mean age of 65±4 years were enrolled in the study; of these, 15 were women and four were men. Nineteen young persons with a mean age of 25±2 years were enrolled; of these, 10 were women and nine were men. Characteristics of the two groups of study participants were generally comparable (Table 1), with the exception that there were a greater number of Hispanic participants in the older group and a greater number of Asian Pacific Islanders enrolled in the young group. As expected, body mass index (BMI), trunk fat by DEXA, total and high-density lipoprotein (HDL) cholesterol, and fasting triglycerides were significantly greater in the older participants (P<0.05). One-repetition maximum strength was significantly lower in the older participants. The peak or VO_{2max} of 25.5±3.9 ml/kg/min in the 19 older subjects was consistent with the effects of ageing in a community-dwelling ambulatory older population and not consistent with values expected for a group with severe cardiopulmonary limitations due to overt heart or lung diseases.

Although there were more female participants in the older group, there were no significant differences for gender across the entire population of 38 participants or within either of the age groups by ANOVA for any of cardiopulmonary measures. Thus, the results were not displayed by gender.

Cardiopulmonary outcomes

For the older participants, the peak heart rate, systolic blood pressure, diastolic blood pressure, cardiac index, and the work of breathing as measured by expired ventilation were significantly higher (P<0.001) during the concentric compared

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with the eccentric bout of resistance exercise (Table 2). These same differences were demonstrated in the young cohort. In addition, when comparing the young with the older group, the older participants had significantly higher peak responses ($P<0.001$) for heart rate, cardiac index and expired ventilation during both the eccentric and concentric bouts.

Figure 1 shows the absolute changes from baseline to peak response for three of the measured parameters during the resistance exercise sessions. The left panel shows that changes in heart rate, systolic blood pressure and cardiac index were significantly lower during the eccentric than concentric bouts for both age groups. Moreover, changes during concentric bouts were different between the age groups ($P<0.05$). The change in heart rate and cardiac index differed during the eccentric bouts between the age groups. To assess whether the differences between age groups were due to the greater absolute workload used by the young participants during the exercise bouts (Table 1), the cardiopulmonary outcomes were adjusted for the maximum load (1-repetition maximum). The significant differences between the age groups for heart rate and cardiac index were eliminated for the eccentric bouts after adjustment for workload but not for the three parameters during the concentric bouts (Figure 2, right panel). Finally, when these variables were adjusted for appendicular lean body tissue (an indirect measure of muscle mass) and ethnicity, there were no differences between the age groups ($P>0.05$, data not shown).

Table 2. Primary outcomes for parallel knee squats

	Older participants (n = 19)	Young participants (n = 19)	P-value[a]
Heart rate (b.p.m.)			
Concentric			
Baseline	68±22	62±26	0.004
Peak[b]	155±16*	116±24*	<0.001
Eccentric			
Baseline	70±10	68±6	0.02
Peak	119±10*	98±14*	<0.001
Systolic blood pressure (mmHg)			
Concentric			
Baseline	130±16	121±13	0.043
Peak	167±14*	147±11*	0.21
Eccentric			
Baseline	120±15	116±8	0.37
Peak	128±18*	122±8*	0.27
Diastolic blood pressure (mmHg)			
Concentric			
Baseline	78±4	74±9	0.06
Peak	82±8	81±4	0.49
Eccentric			
Baseline	76±5	75±5	0.70
Peak	78±5	77±5	0.54
Cardiac index (l/min/m^2)			
Concentric			
Baseline	4.8±0.4	5.4±0.5	<0.001
Peak	9.2±1.5*	12±2.4*	<0.001
Eccentric			
Baseline	4.6±0.3	5.0±0.3	<0.001
Peak	7.8±2*	10±2*	<0.001
Ventilation (l/min)			
Concentric			
Baseline	8.0±2.9	12.2±4	<0.001
Peak	29.8±9.1*	45.2±14.3*	<0.001
Eccentric			
Baseline	7.8±1.4	11.3±3.0	0.014
Peak	20.5±5.7*	29.0±9.1*	0.002

[a]Comparison of older and younger subjects.
[b]Absolute value at peak effort.
*Different from baseline ($P<0.001$).

Discussion

This is the first study to compare the metabolic effects of eccentric and concentric resistance exercise at a submaximal workload (65% of the concentric 1-repetition maximum) previously shown to produce skeletal muscle hypertrophy and to augment strength during chronic training [19]. The results demonstrated that peak cardiovascular and pulmonary responses of heart rate, systolic blood pressure, cardiac index and expired ventilation during intense bouts of eccentric resistance exercise at these workloads were significantly less compared with bouts of concentric exercise for older community-dwelling persons with medical conditions typical of ageing. The outcomes were generally similar in younger healthy participants.

With ageing, there is an increase in peripheral vascular resistance in response to exercise, causing a greater increase in systolic blood pressure compared with young participants [20]. Indeed, the older participants in this study had a greater change in systolic blood pressure and heart rate for both the eccentric and concentric exercise bouts when compared with the young participants (Figure 2). Other differences in cardiopulmonary responses between age groups may have been due to age-related cardiopulmonary limitations, alterations in skeletal muscle fibre type and number, or insulin resistance with endothelial dysfunction in the older participants, which would require greater heart rate responses to deliver a similar oxygen content to skeletal muscle to perform similar amounts of work.

Moreover, in older participants, insulin resistance is related to endothelial dysfunction with decreased capacity of large arteries to dilate and increased peripheral arteriolar resistance [21–23]. Although hypertension was controlled in our older study participants, it is not surprising that blood pressure would increase more in this group if they indeed had endothelial dysfunction even though their absolute workload was less than that for the young group. In addition, there were more Hispanics in the older group who would be expected to have greater insulin resistance and endothelial dysfunction [24]. Regardless of these factors, the important observation is that increases in systolic blood pressure and heart rate were less with eccentric than concentric bouts of exercise. Overend *et al.* also showed that maximum heart rate and mean arterial pressure were less with eccentric than concentric resistance exercise in older subjects, which further corroborates our findings [25]. However, the exercise stimulus in their study was based on torque output during isokinetic knee extension, and respiratory measures were not collected.

The absolute and relative (percentage change) increases in expired ventilation and cardiac index were greater in the young subjects, presumably due to the greater absolute workload during testing in the young participants based on

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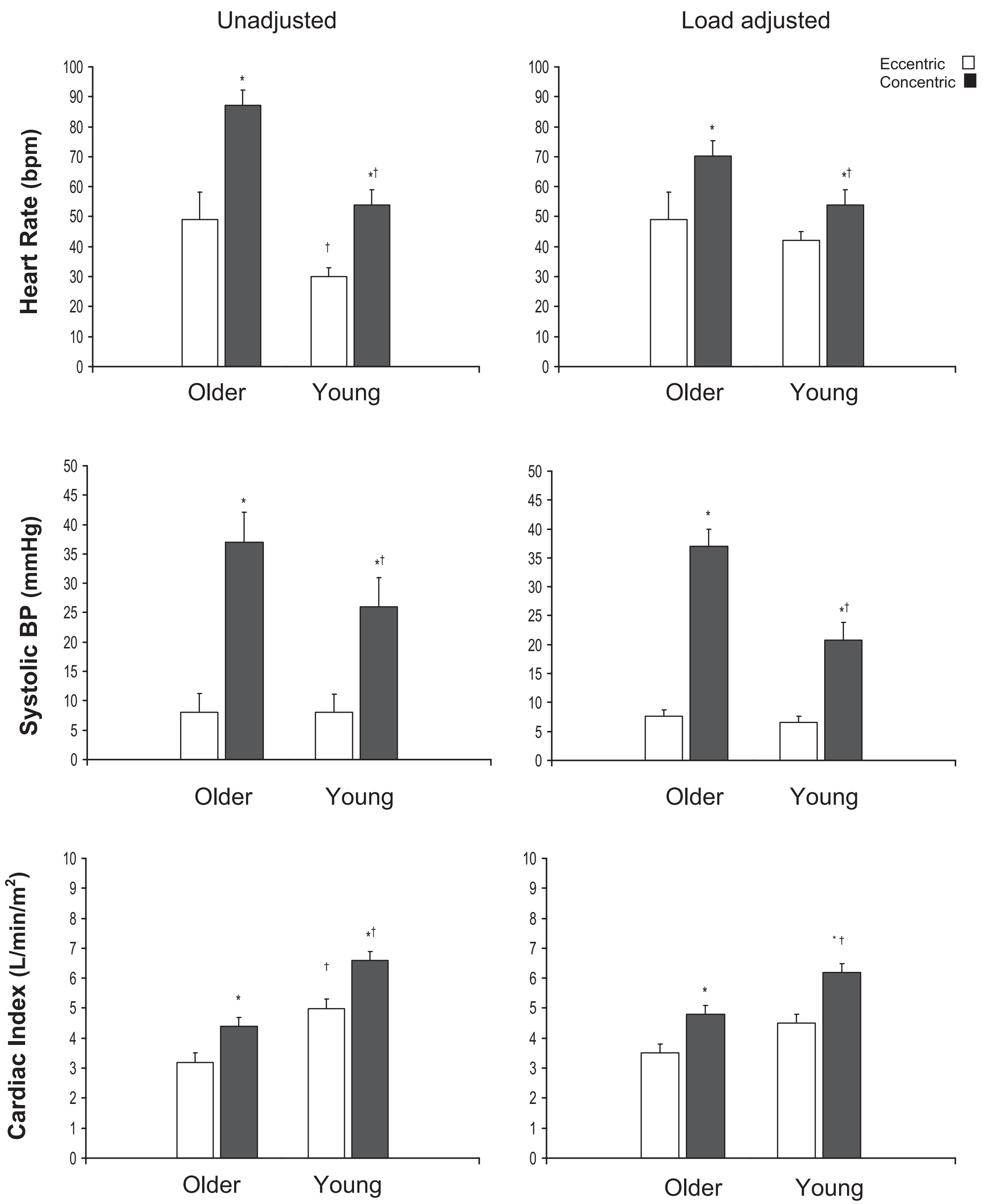

Figure 2. Changes in cardiovascular measures during leg squats. Absolute changes in heart rate, systolic blood pressure and cardiac index are shown for eccentric bouts by the open bars, and concentric bouts by the filled bars. Values are means±SE. *Significant differences between eccentric and concentric bouts for the same age group ($P<0.05$). †Significant differences for either the eccentric or concentric bouts between age groups ($P<0.05$). The left panel shows unadjusted values, whereas the right panel shows the values adjusted by workload (1-repetition maximum).

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their pre-exercise concentric 1-repetition maximum results. However, when the outcomes were adjusted for exercise intensity (1-repetition maximum workload), differences between the groups were eliminated for the eccentric exercise but persisted for the concentric exercise.

In addition to the limitations discussed above, it is possible that there were differences in force during the leg squats due to variability in acceleration (since force = mass × acceleration) during eccentric and concentric resistance exercises. Attempts were made to standardise acceleration in both modes by use of a metronome and to limit the extent of the downward motions with a bench. However, use of force plates and measurement of net joint kinetics would have confirmed that the forces during the eccentric and concentric bouts were truly similar.

Studies indicate that muscle adaptations (strength and hypertrophy) are superior with eccentric resistance exercise training compared with standard concentric-based training modes [26–28]. Because workloads at 65% of the concentric 1-repetition maximum have produced significant increases in muscle mass, strength and power [19, 29, 30], eccentric resistance exercise at the workload evaluated in this study should, therefore, produce skeletal muscle benefits when used with longitudinal training. Further, data exist that eccentric cycling in older persons may result in greater benefits in some aspects of physical function than with concentric-based exercise [6, 7]. Finally, because of the greater stresses placed on the cardiopulmonary system with concentric exercise, it is possible that some older patients with more severe cardiopulmonary limitations may not be able to tolerate concentric exercise programmes even at submaximal intensities approximating 65%.

We speculate that eccentric resistance exercise should be better tolerated in older persons with overt cardiopulmonary impairments such as chronic lung disease, coronary ischaemia or cardiomyopathy. Indeed, Meyer *et al.* showed that right heart catheterisation measures were similar during eccentric and concentric cycle ergometry in middle-to-older aged patients with coronary disease despite a 4-fold greater work output with eccentric aerobic exercise [8]. Although aerobic exercise is not an effective way to increase skeletal muscle mass or physical strength, that study supports our findings that eccentric exercise *per se*, whether resistance based or aerobic, is more metabolically efficient and may be safer and better tolerated at the same workload in older persons. Based on our findings, future studies should evaluate whether eccentric training at submaximal intensities produces greater or at least comparable gains in muscle mass, strength, power and physical function for populations with low exercise tolerance (i.e. from ageing or catabolic illness such as cancer or AIDS) or those who have cardiopulmonary limitations due to chronic lung disease or heart failure.

Key points

In older relatively healthy men and women,

- Heart rate, blood pressure and cardiac index responses were less with eccentric compared with concentric resistance exercise.
- Ventilation responses were less with eccentric compared with concentric resistance exercise.
- Similar differences between eccentric and concentric exercise were observed in young controls.
- Eccentric resistance exercise should be investigated for older persons with severe cardiopulmonary limitations.

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