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Stretch-Shortening Cycle Potentiation and Resistance Training-Induced Changes in Walking Economy/Ease and Activity-Related Energy Expenditure in Older Women

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Abstract

Hunter, GR, Singh, H, Martins, C, Baranauskas, MN, and Carter, SJ. Stretch-shortening cycle potentiation and resistance training-induced changes in walking economy/ease and activity-related energy expenditure in older women. *J Strength Cond Res* 35(5): 1345–1349, 2021—Use of elastic energy to improve economy and ease of walking may be important for older adults. The purpose of this investigation was to determine whether baseline (i.e., untrained) stretch-shortening cycle potentiation (SSCP) was associated with potential changes in free-living activity-related energy expenditure (AEE) after supervised exercise training. Sedentary, post-menopausal women ($n = 64$) between 60 and 74 years of age were evaluated before and after 16 weeks of combined aerobic and resistance training. Assessments included: (a) body composition (dual-energy X-ray absorptiometry), (b) resting energy expenditure (indirect calorimetry), (c) submaximal and maximal walking (treadmill/indirect calorimetry), (d) total energy expenditure (doubly labeled water), and (e) one repetition maximum performed on an incline leg press and SSCP (calculated as the difference between concentric and countermovement leg press throw). Results indicated that baseline SSCP was related ($r = -0.29$; $p < 0.02$) to changes in AEE. However, subjects who possessed a high baseline SSCP did not increase SSCP or AEE, whereas subjects with low to moderate baseline SSCP demonstrated a significant increase in both SSCP (low +0.54 and moderate +0.47 $m \cdot s^{-1}$) and AEE (low +158 and moderate +333 $kcal \cdot d^{-1}$) post-training (all p less than 0.05). Our findings suggest that among subjects with low to moderate baseline SSCP, 16 weeks of combined aerobic and resistance training can increase SSCP and free-living AEE. However, subjects with high baseline SSCP may require tailored exercise to increase SSCP and possibly AEE.

Key Words: elastic energy, physical activity, strength, weight training

Introduction

Insufficient physical activity, especially among older adults, contributes to a range of detrimental health consequences including obesity, cardiometabolic dysregulation, and poor quality-of-life (23). Alternatively, aerobic or resistance exercise training have been frequently shown to promote greater engagement in spontaneous free-living physical activity (9). However, there is considerable variation to the extent from which exercise training can invoke a positive shift in activity-related energy expenditure (AEE) (9,12,24). Prior work has demonstrated that some exercise training programs result in no change (1) or even a decrease (4,31) in AEE. Still, even among exercise programs that successfully increase AEE, considerable between-subject variation exists in response to the exercise training (3). Indeed, some subjects exhibit marked increases, whereas others do not change—despite similar improvement in aerobic fitness and muscle strength (3). Hence, it is of interest to identify modifiable factors that may be responsive to exercise training and thus possibly influential to AEE.

Walking economy and ease are known factors related to increased physical activity engagement, and accordingly AEE (2,7). In recent work, our group has reported a negative relationship between net oxygen uptake ($\dot{V}O_2$; inverse of economy) during steady-state walking and stretch-shortening cycle potentiation (SSCP) among older adults (27). The implications being that SSCP may favorably affect physical activity engagement through improved walking economy (7,22,27); however, it remains unclear if baseline (i.e., untrained) SSCP is related to potential changes in AEE. During walking and running, previous work shows that the muscle-tendon complex of the ankle joint resembles a *spring-like* mechanism, wherein stored elastic energy at foot contact is rapidly released during push off (5,6,17). This feature might lower the energy requirement for locomotion, and in turn, improve walking economy through enhanced utilization of stored elastic energy (i.e., ↑SSCP) (25). However, the use of SSCP varies considerably between younger (22) and older adults (27). Taken together, it is possible that

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variation in the functionality of SSCP may be influential to free-living AEE. Given the inherent synchrony between the muscle-tendon complex for walking, it is probable that exercise training interventions can influence the potential for improving SSCP. However, it currently remains unclear as to whether the magnitude of improvement (attributed to exercise training) in walking economy/ease, SSCP, and AEE are influenced by baseline SSCP. The primary purpose of the present work was to determine whether baseline SSCP was related to changes in walking economy/ease, SSCP, and AEE among a cohort of older women. It is hypothesized that subjects with low to moderate baseline SSCP will increase SSCP and AEE to a greater extent than those with higher baseline SSCP.

Methods

Experimental Approach to the Problem

Secondary analyses were performed on prior work designed to evaluate the cardiometabolic effects of 16 weeks of combined aerobic and resistance training (13).

Subjects

Sixty-four postmenopausal women between 60 and 74 years of age were evaluated before and after 16 weeks of supervised exercise training. All subjects were nonsmokers and self-reported sedentary, as defined by exercising less than one time per week. In compliance with guidelines established by the Declaration of Helsinki, all study procedures were approved by the University of Alabama at Birmingham institutional review board. Verbal and written informed consent was obtained from all subjects before testing.

Procedures

Instrumentation: Body Composition. Total body fat percent was estimated before and after the intervention period using customary procedures for dual-energy X-ray absorptiometry (Lunar DPX-L densitometer; LUNAR Radiation, Madison, Adult Software v1.33, WI).

Instrumentation: Resting Oxygen Uptake. After an overnight fast, resting oxygen uptake ($\dot{V}O_2$) was measured for 40 minutes through open-circuit, indirect calorimetry (DeltaTrac II: Sensor Medics, Yorba, CA). The final 20 minutes of the measurement period were used for resting $\dot{V}O_2$.

Instrumentation: Free-Living Total Energy Expenditure. Doubly labeled water (DLW) was used to measure total energy expenditure, as previously described (29). Briefly, subjects provided a baseline urine sample. A loading dose of DLW (10% $H_2{}^{18}O$ and 8% ${}^2H_2O$) was administered at a ratio equating to approximately 1.1 grams per kilogram body mass. To permit proper isotopic dilution, 2 additional urine samples were collected at +3 and +4 hours post-DLW dosing. Fourteen days later, 2 urine samples were collected in the morning hours. Urine samples were evaluated in duplicate using isotope ratio-mass spectrometry. Based on the equation by Speakman et al. (28), CO_2 rates (rCO_2) were determined using a fixed constant for the dilution space ratio (1.0427): $rCO_2\ (mol \cdot d^{-1}) = 0.4554N\ (1.01K_0 - 1.04K_h)$, where N is total body water (mol) and K_0 and K_h are $H_2{}^{18}O$ and ${}^2H_2O$ turnover rates (day^{-1}), respectively. Using the rCO_2, TEE was calculated from the following equation from Weir (30): TEE $(kcal \cdot d^{-1}) = 3.9\ (rCO_2/FQ) + 1.1\ rCO_2$, where rCO_2 is rate of CO_2 production ($L \cdot d^{-1}$) and food quotient (0.88). The coefficient of variation for total energy expenditure in our laboratory is 4.3%. Activity-related energy expenditure (AEE) was calculated by subtracting 10 percent of the TEE (for thermogenesis related to eating) and REE from TEE (AEE = TEE – [0.1 × TEE] – REE) (26).

Instrumentation: Maximal oxygen Uptake ($\dot{V}O_2max$) and Walking Economy. To measure $\dot{V}O_2$max, a graded exercise test consistent with a modified-Balke protocol (Max − 1 Cart; Physio-Dyne Instrument Corporation, Quogue, NY) was performed on a treadmill to voluntary exhaustion. Heart rate was continuously measured using a 12-lead electrocardiogram. The highest 20-second $\dot{V}O_2$ was considered $\dot{V}O_2$max ($mL \cdot kg^{-1} \cdot min^{-1}$). On a separate day, walking net $\dot{V}O_2$ (inverse of walking economy) was measured during a submaximal treadmill test at a fixed walking speed of 0.89 $m \cdot s^{-1}$. Average $\dot{V}O_2$ and heart rate for the fourth minute were used to confirm steady-state. If $\dot{V}O_2$ or heart rate increased during the fourth minute (above that during the third minute), an additional fifth minute was used. Net $\dot{V}O_2$ was calculated by subtracting resting $\dot{V}O_2$ from steady-state $\dot{V}O_2$.

Instrumentation: Maximum Muscle Strength Assessment. Subjects performed a 1 repetition maximum (1RM) test after the initial 2 exercise sessions (to permit overall familiarization). Notably, we have previously revealed a high test-retest reliability for measurements performed in our laboratory involving strength assessments (8). Determination of muscle strength included the incline leg press, squat, leg extension, leg curl, elbow flexion, lateral pull-down, bench press, and military press. Lower-back extension and bent leg sit-ups were performed with no weight according to methods previously described (8).

Instrumentation: Stretch-Shortening Cycle Potentiation. An electronic goniometer was attached to the knee of the subject before testing. The leg press sled was connected to a linear position transducer. Both the electric goniometer and linear position transducer were synced with a National Instruments system with a customized LabVIEW (Laboratory Virtual Instrument Engineering Workbench, v7.1) software program connected to a 16-channel 12-bit data acquisition system. Before each test, calibration of linear position transducer and goniometer was performed. Data were collected at 1 kHz. A low-pass fourth-order Butterworth filter was applied with a cutoff frequency of 50 Hz. The transducer tracked the position of the leg press sled. Using finite-difference technique, the displacement data of sled were used to calculate velocity (22). After a 3-minute warm-up on a cycle ergometer, a ballistic leg press was performed with a weight equivalent to 100% of the subject's body mass at baseline and post-training. Concentric only (CO) velocity during a *static* leg press throw was evaluated after holding the weight for 3 seconds at a 90° knee joint angle, after which subjects extended their knees and hips as rapidly as possible. Velocity was also measured during a countermovement (CM) leg press throw, wherein subjects initiated the move with their legs straightened and then lowered the weight to a 90° knee joint angle. To confirm the correct position upon lowering, the computer provided an audible signal indicating 90° knee joint angle had been reached. Immediately, upon hearing the signal, subjects extended their knees and hips as rapidly as possible. The difference between CM and CO velocities was defined as SSCP. After initial statistical inquiries, subjects were stratified by tertiles based on baseline SSCP (low group $\leq 0.09\ m \cdot s^{-1}$, $n = 21$; middle group, >0.09 and $\leq 0.14\ m \cdot s^{-1}$, $n = 22$; and high group, $>0.14\ m \cdot s^{-1}$, $n = 21$).

Instrumentation: Exercise Training. Subjects performed aerobic and resistance training wherein the order of exercise mode alternated each training session. Subjects completed a 3–4-minute warm-up on a treadmill or cycle ergometer followed by 3–4 minutes of stretching before each exercise session. Subjects stretched muscles to maximum comfort—holding the stretch for 8–10 seconds. Stretching exercises included: standing calf stretch, standing quadriceps stretch, seated hamstring stretch, standing inner groin stretch, buttocks stretch, and cat trunk stretch. All training sessions were supervised by an exercise physiologist in a facility dedicated to research. The mode of aerobic exercise included a treadmill or cycle ergometer with at least 50% of training completed on the treadmill. Week one commenced with 20 minutes of continuous aerobic exercise corresponding to ≈67% of maximal heart rate (MHR; previously measured during the modified-Balke protocol). Subjects wore a heart rate monitor during exercise training sessions to assure target heart rate. Weekly volume and intensity gradually increased so that at the end of week 10, subjects were continuously training for 40 minutes at an intensity of ≈80% of MHR. The resistance training protocol began with 2 sets of 10 repetitions at an intensity matching 60% of measured 1RM with 90–120-second rest period between sets. Resistance training progressed to 80% 1RM at week 8 (8), whereas between-set recovery was kept to 60–120 seconds.

Statistical Analyses

Data are reported as means and standard deviations unless noted otherwise. Data were assessed for normality using the Shapiro-Wilk test. Univariate analysis of variance (ANOVA) was used to evaluate between-group differences in age, whereas independent ANOVAs with repeated-measures for time (i.e., pre-/post-) were used to detect group differences for separate variables. Among the repeated-measured ANOVAs performed, Mauchly's test indicated that the assumption of sphericity was not violated in any instance. Dependent *t*-tests with Bonferroni correction (based on number of group pairwise comparisons) were used to examine critical *post hoc* comparisons. Substantive differences were assessed using partial eta squared (η_p^2) and Cohen's *d* as a measure of effect size for ANOVAs and *post hoc* comparisons, respectively. Effect sizes were qualitatively considered using the following: (η_p^2) 0.01 as small, 0.06 as medium, and 0.14 as large, and (*d*) 0.2 as small, 0.5 as moderate, and 0.8 as large (19). Equal variance was confirmed for all variables with the Levene test. Bivariate relationships were determined using Pearson product-moment correlations on variables of interest. After preliminary inquiries, a negative relationship between baseline SSCP and changes in AEE were detected. To further elucidate this observation, subjects were subsequently stratified by tertiles based on baseline SSCP (low group <0.09 m·s^{-1}, $n = 21$; middle group, >0.09 and <0.14 m·s^{-1}, $n = 22$; and high group, >0.14 m·s^{-1}, $n = 21$). All data were analyzed using the Statistical Package for the Social Sciences (SPSS v 25.0; IBM, Armonk, NY). Statistical significance was set a priori with a *p*-value equal to or less than 0.05.

Results

Figure 1 illustrates the unadjusted relationship between baseline SSCP and changes in AEE ($r = -0.29$; $p < 0.02$). Table 1 contains mean values for all study variables divided into tertiles for SSCP. Apart from SSCP, no significant between-group differences were found among other reported variables. Significant time effects were observed for body weight (reduced, $\eta_p^2 = 0.064$), percent body fat (reduced, $\eta_p^2 = 0.317$), $\dot{V}O_{2max}$ (increased, $\eta_p^2 = 0.102$), leg press strength (increased, $\eta_p^2 = 0.549$), net walking $\dot{V}O_2$ (reduced, $\eta_p^2 = 0.124$), walking heart rate (reduced, $\eta_p^2 = 0.450$), and AEE (increased, $\eta_p^2 = 0.121$). Changes in SSCP ($\eta_p^2 = 0.250$) and AEE ($\eta_p^2 = 0.119$) displayed the only time-by-group interactions (SSCP $\eta_p^2 = 0.205$ and AEE $\eta_p^2 = 0.067$).

Further *post hoc* evaluations revealed the low ($d = 0.545$) and middle ($d = 0.583$) SSCP groups decreased net walking $\dot{V}O_2$. Walking heart rate also significantly decreased in the low ($d = 0.545$), middle ($d = 0.636$), and high ($d = 0.818$) groups. SSCP increased in the low ($d = 0.14$) and middle SSCP ($d = 0.11$) groups, and additionally, the low ($d = 0.383$) and middle ($d = 1.100$) groups increased AEE.

Discussion

The purpose of this investigation was to determine whether baseline (i.e., untrained state) SSCP in older women related to changes in AEE after 16 weeks of combined aerobic and resistance training. Results indicated that subjects who possessed a high SSCP before training did not increase AEE, whereas subjects with low, and to a greater extent moderate, SSCP before training increased AEE post-training. These differences in physical activity gain occurred despite similar increases in aerobic fitness and strength for all groups post-training. Importantly, women with lower SSCP before training showed an increase in SSCP and walking economy (i.e., decreased net $\dot{V}O_2$ during the submaximal walk), whereas those with the highest baseline SSCP *did not* increase either SSCP or walking economy. These results demonstrate that older women who possess low SSCP before training (i.e., baseline) are able to increase SSCP, increase walking economy, and increase AEE, whereas older women who possess relatively higher SSCP before training may not exhibit positive changes in SSCP, walking economy, or free-living physical AEE. These findings are suggestive that increases in SSCP can favorably influence walking economy/ease and participation in free-living physical activity. Further work is needed to determine whether other training modalities (i.e., plyometrics) can elicit similar effects.

Increased utilization of elastic energy leads to greater force-generation without adding to the metabolic burden (25). This elastic energy-induced force-generation may enhance economy of walking. Fukunaga et al. (5,6) and Kubo et al. (16,17) have shown that the muscle-tendon complex of the ankle joint is stretched during single support and then rapidly recoiled during the push-off. Thus, the muscle-tendon complex of the ankle joint acts as a *spring-like* mechanism through the storage and release of elastic-strain energy during locomotion. Longer Achilles tendons have higher compliance in the muscle-tendon complex and greater ability to store and use mechanical energy (18). Thus, the spring-like action of the muscle-tendon complex reduces the energy needed for muscle shortening (i.e., concentric contraction) during walking and running. Consistent with this premise, we have previously shown that economy during running (14) and walking (27) is positively associated with SSCP, and that Achilles tendon length is positively associated with improved walking economy (21)—likely attributed to enhanced SSCP.

Low levels of physical activity partially contribute to increased obesity and poor metabolic health (15). This may be especially the case for older adults. Previously, we have shown that ease of

Table 1
Study variables in the low, middle, and high SSCP groups.*

	Low SSCP (n = 21)	Middle SSCP (n = 22)	High SSCP (n = 21)	p
Age (y)	64 ± 4	66 ± 4	64 ± 3	G = 0.09
Body mass (kg)				T < 0.04
Baseline	72.8 ± 9.0	72.4 ± 9.4	75.5 ± 14.8	G = 0.84
Post-training	72.1 ± 7.8	71.6 ± 9.8	74.6 ± 13.1	T × G = 0.99
Body fat (%)				T < 0.01
Baseline	42.9 ± 5.7	41.9 ± 4.6	43.1 ± 7.7	G = 0.74
Post-training	41.5 ± 5.4	40.4 ± 5.6	42.0 ± 7.7	T × G = 0.77
$\dot{V}O_2$max (ml·kg^{-1}·min^{-1})				T < 0.02
Baseline	21.6 ± 4.1	24.2 ± 3.5	22.4 ± 5.7	G = 0.13
Post-training	21.9 ± 5.0	25.3 ± 3.9	23.8 ± 5.2	T × G = 0.48
Leg press strength adjusted for body weight (kg·kg^{-1}·d^{-1})				T < 0.01
Baseline	2.90 ± 0.64	2.77 ± 0.63	2.82 ± 0.78	G = 0.60
Post-training	3.50 ± 0.90	3.25 ± 0.66	3.66 ± 1.05†	T × G = 0.06
Net walking $\dot{V}O_2$ (ml·kg^{-1}·min^{-1})				T < 0.02
Baseline	7.4 ± 1.0	7.7 ± 1.1	6.9 ± 1.3	G = 0.33
Post-training	6.8 ± 1.2‡	7.0 ± 1.3‡	6.7 ± 1.9	T × G = 0.43
Walking heart rate (b·min^{-1})				T < 0.01
Baseline	102 ± 13	100 ± 13	105 ± 12	G = 0.46
Post-training	96 ± 9‡	93 ± 14‡	96 ± 10‡	T × G = 0.43
SSCP (m·s^{-1})				T = 0.21
Baseline	0.050 ± 0.019	0.107 ± 0.017	0.212 ± 0.061	G < 0.01
Post-training	0.104 ± 0.061‡	0.151 ± 0.068‡	0.155 ± 0.087†	T × G < 0.01
AEE (kcal·d^{-1})				T < 0.01
Baseline	484 ± 381	556 ± 240	637 ± 285	G = 0.22
Post-training	642 ± 442‡	889 ± 365‡	645 ± 249†	T × G < 0.02

*SSCP = stretch-shortening cycle potentiation; AEE = activity-related energy expenditure.
†Different from pooled low SSCP and middle SSCP Groups $p < 0.05$.
‡Denotes significant *post hoc* difference from baseline.

walking (i.e., decreased heart rate for a given workload) enhances physical activity in older adults (7,10,11), whereas improved walking economy improves ease of locomotion (11,20). Indeed, modifiable lifestyle factors such as exercise training represent one of the most effective strategies to combat the loss of function with advancing age. SSCP has been previously shown to be associated with free-living physical activity, possibly by affecting walking economy and ease of locomotion. This is supported by recent evidence revealing a positive relationship between SSCP and walking economy in older women (27). Subjects in this study who had relatively high SSCP before training did not increase SSCP, walking economy, or AEE. Alternatively, subjects with a comparatively moderate SSCP before training increased SSCP, walking economy, and AEE—suggesting that improvements in SSCP may be important for improved AEE after exercise training. However, it also implies there may be a ceiling effect for SSCP. For example, improvement in SSCP (due to combined aerobic and resistance training) was not observed in the high SSCP group *and* the high SSCP group did not increase AEE after post-training. It is possible that improvements in SSCP above a certain level may necessitate tailored, more specific exercise training to enhance walking economy and perhaps AEE in older women.

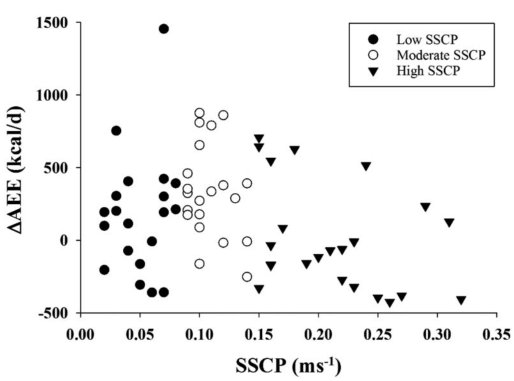

Figure 1. Unadjusted relationship between baseline SSCP and change (Δ) in AEE ($r = -0.29$, $p < 0.02$). Note that low/moderate baseline SSCP tended to exhibit a larger increase in free-living AEE post-training. SSCP = stretch-shortening cycle potentiation; AEE = activity-related energy expenditure.

In conclusion, our findings suggest that among subjects with low to moderate baseline SSCP, 16 weeks of combined aerobic and resistance training can increase SSCP and free-living AEE. However, subjects with high baseline SSCP may require tailored exercise to increase SSCP and possibly AEE.

Practical Applications

These results suggest that measurement of SSCP may be of value among older adults. Although it is advisable for older adults to incorporate both aerobic and resistance exercise training, additional research should determine whether inclusion of plyometrics may enhance SSCP and possibly AEE in older adults.

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