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Increased strength and decreased flexibility are related to reduced oxygen cost of walking

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Abstract

Purpose was determine effects resistance training/weight loss induced changes in muscular strength and flexibility have on net walking oxygen uptake (netVO$_2$). Sixty-seven premenopausal women lost 12 kg. Before weight loss subjects were assigned to diet (WL) or diet/3 days per week resistance training (WLRT). Resting energy expenditure, oxygen uptake while walking at 4.84 km h^{-1} on the flat and up 2.5% grade, isometric knee extension strength, and flexibility of the knee extensors and plantar flexors were measured. Strength increased in WLRT (+36 N) but not in WL (−24 N). NetVO$_2$ decreased significantly while flat walking (7.3%) and 2.5% grade walking (5.7%) in WLRT, but not in WL. Delta strength was negatively while delta knee extensor and plantar flexor flexibility were positively related to delta netVO$_2$. Decreases in walking and grade netVO$_2$ were independently and positively related to increased knee extension strength and decreased knee extensor and plantar flexor flexibility.

Keywords

Oxygen uptake; Resistance training; Weight loss walking economy

Introduction

Prevalence of obesity and overweight continues to increase in the United States (Flegal et al. 2002) despite more than a decade of intense research/public health effort designed to decrease its prevalence. An understanding of factors that might influence weight gain and thus development of obesity is important. We have previously shown that muscle metabolic economy (muscle force/muscle ATP use) is inversely related to subsequent 1-year weight gain (Larew et al. 2003) suggesting increased exercise economy may be advantageous for weight maintenance.

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Weight loss is normally associated with loss of muscular strength (Walsh et al. 2004). Optimizing maintenance of muscle function are normally considered to be desirable outcomes of weight loss programs. Exercise training, especially high intensity resistance exercise training has been shown to be beneficial in maintaining muscular strength during weight loss (Ballor et al. 1988; Daly et al. 2005; Bryner et al. 1999).

Locomotion (either walking or running) economy is generally considered to be the net oxygen uptake (oxygen uptake above resting) required during walking or running, with high economy associated with low net oxygen uptake (Jung 2003). A number of factors are known to positively affect exercise economy including muscle fiber type (type I muscle fibers are more economical than type II muscle fibers) (Hunter et al. 2001; Coyle et al. 1992) and the ability to store and reuse elastic energy from eccentric muscle contractions (Cavanagh and Kram 1985; Anderson 1996). Consistent with the concept that less flexible joints may facilitate the elastic stretch during the eccentric phase of biped locomotion, nonpathalogical muscle tightness has been reported to be inversely related to running oxygen uptake (Jones 2002; Craib et al. 1996; Gleim et al. 1990) and walking oxygen uptake (Gleim et al. 1990).

A number of studies have shown that locomotion economy increases following resistance training (Johnston et al. 1997; Paavolainen et al. 1999; Hoff et al. 2006). Although the reasons for these improvements are unclear, it has been hypothesized that increased strength may improve economy by several different mechanisms: (1) increasing the use of elasticity because of improved neuromuscular function, (Jung 2003; Paavolainen et al. (1999); (2) improving muscle coordination (Carson 2006); and (3) changing motor recruitment patterns to include less dependence on inefficient fast twitch muscle fibers (Jung 2003; Hunter et al. 2004a).

Although it has been reported that weight loss might be associated with an increase in muscle metabolic economy (Rosenbaum et al. 2003), especially during exercise, little is known concerning the interaction of exercise training and weight loss on factors that are related to locomotion economy, such as flexibility and strength. Therefore, the primary purpose of this study was to determine what effects a combination of exercise training and weight loss has on muscular flexibility, strength, and walking economy and to determine whether changes in strength and flexibility predict changes in walking economy. We hypothesized that the combination of weight loss and resistance training will be associated with more increase in strength and walking economy than weight loss without resistance training. We also hypothesized that individual changes in flexibility will be negatively associated and changes in strength will be positively associated with changes walking economy.

Methods

Prior to commencing weight loss 66 African American and European American overweight (body mass index more than 27 and less than 30 kg/m^2) premenopausal women were matched for age, weight, and body composition and randomly assigned to two groups; resistance training and no exercise training. After assignment to groups, subjects participated in a diet induced weight loss program designed to reduce weight to a BMI of less than 25 kg/m^2. Food was provided (3,349 kJ (800 kcal) day^{-1}, 55% carbohydrate, 22% fat, and 23% protein) during weight loss. Average time of weight loss was ~21 weeks. Both prior to and after weight loss women were weight stable for 4 weeks prior to evaluation and were on a controlled diet (furnished by the General Clinical Research Center kitchen) within the range of 20–22% of energy as fat, 18–22% as protein, and 58–62% as carbohydrate for 2 weeks before testing. Subjects assigned to the exercise groups were required to continue training during the weight loss and the 4-week weight stabilization period post weight loss (an average of 25 total weeks). All women were nonsmokers and reported experiencing menses at regular intervals. Since metabolism may be affected by menstrual cycle, all testing was performed in the follicular phase of the menstrual cycle (within 10 days of menses). In order to further control for potential confounders that may affect subjects' energy expenditure, subjects were admitted to the General Clinical Research Center for 4 days during the time of baseline and post-intervention testing. Procedures followed were in accordance with the ethical standards of the institution committee on human experimentation and the 1964 Declaration of Helsinki. Before participating in the study, the women provided informed consent to the protocol, which was approved by the University of Alabama at Birmingham Institutional Review Board and Human Services Regulation for Protection of Human Research Subjects.

Resting energy expenditure (REE)

Three consecutive mornings after an overnight stay in the General Clinical Research Center and 12 h fast, REE was measured immediately after awakening between 6:00 and 7:00 a.m. Subjects were required to remain awake and measurements were made in a quiet, softly lit, well ventilated room. Temperature was maintained between 22 and 24°C. With the women lying supine on a comfortable bed, measurements were made with the participant's head enclosed in a plexiglass canopy. After resting for 15 min, REE was measured for 30 min with a computerized, open-circuit, indirect calorimetry system with a ventilated canopy (Delta Trac II, Sensor Medics, Yorba Linda, CA, USA). The last 20 min of measurement was used for analysis. Oxygen uptake (VO_2) and carbon dioxide production (CO_2) were measured continuously and values were averaged at 1 min intervals. VO_2 values used in the determination of exercise net oxygen uptake (i.e. exercise $VO_2 -$ resting VO_2) were means of the three resting measurements. Coefficient of variation for the repeat VO_2 was <4%.

Fitness testing

Fitness testing was done in a fasted state on one day starting at 7:30 a.m. Order of testing was strength, followed by flexibility 15 min following the strength test, and followed by walking at 4.84 km h^{-1} approximately 1 h after the strength test.

Strength

Knee extension strength was measured isometrically using methods previously described (Hunter et al. 1995). Forces were measured using a universal shear beam load cell (LCC 500; Omega Engineering, Stamford, CT, USA). Force was measured at 70° knee extension on the right lower leg at the level of the lateral malleolus. Subjects were restrained across the upper legs and hips with padded straps. After three trials, three maximal isometric contractions were recorded with 60 s rest between each trial. Test retest reliability for these tests in our lab has a coefficient of variation of <4%.

Flexibility

Flexibility was measured using adaptations of methods described by Norkin and White (1995). One investigator stabilized and stretched the tendon/muscle complexes while a second investigator measured angles with a goniometer. Flexibility of the ankle dorsi and plantar flexors was done with the subject lying supine and the knee extended. Goniometer fulcrum was placed over the lateral aspect of the lateral malleolus. The proximal arm was aligned with the head of fibula and the distal arm was aligned parallel to the lateral aspect of the fifth metatarsal. Measurement of plantar flexor flexibility occurred with the investigator pushing on the plantar surface of the foot toward a dorsiflexion position. Measurement of dorsiflexor flexibility occurred with the investigator pushing on the dorsum of the foot toward a plantar flexion position. The knee was stabilized to prevent movement and pressure was not placed on the toes throughout measurement of dorsiflexor and plantar flexor flexibility. Measurement of flexibility of the knee extensors occurred with the subjects lying supine and the leg extending off the end (approximately 6 inc. superior to knee) of a specially designed table. The center of the fulcrum of the goniometer was placed over the lateral epicondyle of the femur with the proximal arm aligned with the greater trochanter and the distal arm was aligned with lateral malleolus. Gripping the lower leg just above the ankle one investigator pushed the lower leg toward a more flexed position while the other investigator maintained hip position. In all flexibility evaluations the investigator stopped the stretch when a firm end feel was noted (Norkin and White 1995).

Submaximal oxygen uptake

Submaximal oxygen uptake (VO_2) was obtained in the steady state, during the third and fourth minutes while walking at 4.84 km h^{-1} on the treadmill at zero grade (FWK). Immediately following the 4.84 km h^{-1} walk a 4 min walk of 4.84 km h^{-1} at a grade of 2.5% (GWK) was completed. If VO_2 or heart rate increased from the third to the fourth minute, a fifth minute of walking ensued to insure steady state. Net oxygen uptake was considered walking economy and was determined by subtracting resting oxygen uptake from the average oxygen uptake during the third and fourth minutes of the two submaximal walks or in the case where VO_2 increased between the third and fourth minute the average of the fourth and fifth minute. Steady state (no increase in VO2 over previous minute) was achieved in all subjects. Walking speed and grade were selected as normal walking pace that is below ventilatory threshold for this group of sedentary premenopausal women.

Resistance training

After a warm-up on the treadmill or bike ergometer for 5 min and 3–5 min of stretching, subjects performed the following exercises: squats, leg extension, leg curl, elbow flexion, triceps extension, lateral pull-down, bench press, military press, lower back extension, and bent leg sit-ups. One set of ten repetitions was performed during the first 4 weeks, after which two sets of ten repetitions were performed for each exercise with 2 min rest between sets. The training was progressive with intensity based on 65% of the maximum weight an individual could lift (1 RM) and progressing to 80% of 1 RM during the sixth week of training. Strength was evaluated every 3 weeks and adjustments in training resistance were made based on the most current 1RM.

Statistics

A 2 (race) × 2 (exercise group) × 2 (time) with repeated measures on time analysis of variance (ANOVA) was used to determine whether there were racial and exercise group differences with weight loss on all variables of interest. No race by time, race by group, or race by group by time interactions were present so only a 2 (group) by 2 (time) with repeated measures on time are reported. Simple Pearson Product correlations were run to determine relationships between changes in fitness (strength and flexibility) and changes in walking net economy. Multiple regression was used to model changes in walking economy. *T* tests with Bonferroni corrections were used for post hoc analysis where appropriate and significance was set at a probability of less than 0.05 for all statistical tests.

Results

Table 1 contains descriptive variables. Significant time effects for both body mass ($P < 0.01$) and BMI ($P < 0.01$) indicate subjects decreased body mass and BMI significantly. No significant group for age, body mass, or BMI was found indicating no biasing in group assignment and no time by group interaction for body mass or BMI shows that weight loss between groups was similar.

No significant strength or flexibility time effects were found (Table 2). Although there was no time by group interaction for either of the flexibility measures there was a significant time by group interaction for knee extension strength ($P < 0.05$) with post hoc tests showing the WLRT group increasing strength ($P < 0.05$) and the WL group tending to decrease strength ($P > 0.05$).

No time main effect was found for any of the submaximum oxygen uptakes (Table 3). However, there were significant time by group interactions for gross VO_2 during the FWK ($P < 0.04$) and net VO_2 during both the FWK ($P < 0.02$) and GWK (0.02). Post hoc analysis of the gross VO_2 during the FWK ($P < 0.05$) and the net VO_2 during both FWK ($P < 0.05$) and GWK ($P < 0.05$) revealed that the WLRT group decreased submaximum VO_2 (increased walking economy). No significant change in VO_2 was found for the WL group.

The overweight to post overweight change (delta) for strength and both submaximum net VO_2 test results were significant and negatively correlated ($r = -0.33$ for the FWK and −0.34 for the GWK both <0.01, Table 4). The delta for plantar flexor flexibility was significantly related to both the FWK net VO_2 delta ($r = 0.32$, $P < 0.01$) and GWK VO_2 delta ($r = 0.31$, $P < 0.01$). The delta for knee extensor flexibility was significantly related to the grade walk net VO_2 delta ($r = 0.30$, $P < 0.01$) but only approached significance for the FWK net VO_2 walk delta ($r = 0.18$, $P < 0.08$). Delta dorsiflexor flexibility was not significantly related to delta FWK net VO_2 ($r = 0.18$, $P < 0.08$) but was significantly related to delta GWK net VO_2 ($r = 0.30$, $P < 0.01$).

Both delta net VO_2 during the FWK and delta net VO_2 during the GWK were modeled by multiple regression using the knee extension strength measure and each of the three flexibility measures. Dorsiflexor flexibility did not enter as a significant correlate in either model (partial $r = 0.04$, $P = 0.78$ and partial $r = 0.06$, $P = 0.61$ respectively). In addition, models developed with dorsiflexor flexibility included had identical multiple Rs with those in which dorsiflexor flexibility was not included. Therefore, the models reported do not contain dorsiflexor flexibility. In the first model (Table 5, Multiple $R = 0.53$, $P < 0.01$) delta knee extension strength (partial $r = -0.37$, $P < 0.01$), delta knee extensor flexibility (partial $r = 0.26$, $P < 0.03$) and delta plantar flexor flexibility (partial $r = 0.36$, $P < 0.01$) were independently related to delta FWK VO_2. As in the model for the delta FWK, delta knee extension strength (partial $r = -0.40$, $P < 0.01$) delta knee extensor flexibility (partial $r = 0.38$, $P < 0.01$) and delta plantar flexor flexibility (partial $r = 0.38$, $P < 0.01$) were all independently related to delta grade walk (multiple $R = 0.61$, $P < 0.01$).

Discussion

The results of this study indicate that resistance training during weight loss not only induces modest increases in strength but results in increased walking economy. The increase in walking economy (decrease in net oxygen uptake), both on the flat and up a small grade, was independently and positively related to delta knee extension strength, but negatively related to delta knee extensor flexibility, and delta plantar flexor flexibility. Since high muscular strength and metabolic economy during a submaximum task have been shown to be independently related to long term weight maintenance (Larew et al. 2003), it seems reasonable to expect the resistance training induced increases in strength and walking economy to be beneficial for increasing the ease of being physically active and thus long term weight maintenance. Our previous findings that strength is positively (Walsh et al. 2004) while heart rate and perceived exertion in tasks of daily living are negatively related to activity related energy expenditure and participation in free living energy expenditure (Hunter et al. 2004a, b) are supportive of the hypothesis that ease of exercise may increase the likelihood that individuals have a more active lifestyle.

Since there was no significant change in either knee extensor or plantar flexor flexibility in either the WL or the WLRT group it is difficult to speculate on what effects training induced changes in flexibility may have on walking economy. The inverse relationship found between change in joint flexibility and changes in walking economy found in this study as well as the cross-sectional relationships between joint flexibility and running economy (Jones 2002; Craib et al. 1996; Gleim et al. 1990) and walking economy (Gleim et al. 1990) found in other studies suggests that increases in knee and ankle flexibility may have a negative effect on walking and running economy. However, at least one study has shown that a chronic 10 week stretching program does not adversely affect running economy (Nelson et al. 2001).

It is possible the inverse relationship between locomotion economy and flexibility may be due to an improved use of elastic energy generated from stretch shortening potentiation in the less flexible individuals. It has also been hypothesized that the need for activation of unproductive active musculature may be minimized at a less flexible joint (Martin and Morgan 1992). It is interesting that both delta plantar flexor and knee extensor flexibility were independent correlates of delta walking economy suggesting that stiffness in each joint had an independent affect on muscle activation during the two walking tasks. Dorsiflexor flexibility was not significantly correlated with either walking on the flat or up a slight grade in this study. In addition, delta dorsiflexor flexibility was not a significant independent correlate of delta walking economy. If low flexibility and thus greater joint stiffness does increase storage and return of elastic energy during locomotion, it would seem logical that muscles that are stretched during deceleration of the support phase would have the most opportunity for storing and thus releasing elastic energy. This would include the knee extensors and plantar flexors but not the dorsiflexors, further indirectly supporting the hypothesis that non pathological joint stiffness may be beneficial in increasing the storage and reuse of elastic energy during locomotion.

It is well established that exercise training results in shifts from type IIx to type IIa muscle fibers (Adams et al. 1993; Allemeier et al. 1994; Kosek et al. 2006; Staron et al. 1994). Therefore it is highly likely the subjects who trained in this study may have experienced a shift of muscle fiber type from type IIx toward type IIa thus increasing economy. The increases in strength may have also resulted in changes in motor unit recruitment patterns and muscle coordination (Jung 2003).

Interestingly, increased exercise economy following weight loss has been previously reported (Rosenbaum et al. 2003), suggesting that exercise metabolism following weight loss is inherently reduced. As with our previous studies we did not find an increase in exercise economy following weight loss when exercise training was not included (Newcomer et al. 2001; Weinsier et al. 2000). The improvements in exercise economy found with weight loss (Rosenbaum et al. 2003) have generally been at very low exercise intensity (lower than 2 METs), much lower than the 3.5 and higher MET exercise intensities that we have used. Although strength might be expected to decrease following weight loss, it is possible the decrease in strength may be proportionately less than the decrease in weight, actually making the individuals relatively stronger following their weight loss. This appears to be the case at least in this study. The women who did not train decreased body weight approximately 16% but decreased knee extension strength only 4.3%. It is therefore possible the improvements in work economy reported following weight loss may be induced by some of the same mechanism (s) found following resistance training, i.e. changes in muscle function induced by improvements in relative strength. Why the increases in economy following weight loss only seem to occur at very low work intensities is unknown.

In conclusion, we show that walking economy at 4.84 km h^{-1} on the flat and up a 2.5% grade is increased following weight loss that includes resistance exercise training but not following weight loss that does not include exercise training. We also show that increases in walking economy following weight loss are positively and independently related to increased knee extension strength but decreased knee extensor and plantar flexor flexibility.

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Table 1

Descriptive variables

	WLRT	**WL**	***P***
Age (year)	34.6 ± 6.2	35.0 ± 5.3	Group 0.71
Body mass (kg)			
Overweight	77.1 ± 7.8	78.3 ± 7.4	Time <0.01
Post wt loss	65.6 ± 6.8	65.8 ± 6.6	Group 0.67
Difference	−11.5	−12.5	T × G 0.13
BMI (kg/m^2)			
Overweight	28.0 ± 1.2	28.3 ± 1.4	Time <0.01
Post wt loss	23.8 ± 1.1	23.8 ± 1.3	Group 0.56
Difference	−4.2	−4.5	T × G 0.28

Table 2

Fitness variables

	WLRT	**WL**	***P***
Knee extension strength (*N*)[a]			
Overweight	572 ± 179	569 ± 157	Time 0.71
Post wt loss	608 ± 147	545 ± 179	Group 0.36
Difference	+36	−24	T × G <0.05
Flexibility knee extensor (°)			
Overweight	127 ± 10	127 ± 12	Time <0.09
Post wt loss	131 ± 13	129 ± 15	Group 0.65
Difference	+4	+2	T × G 0.72
Flexibility plantar flexor (°)			
Overweight	24 ± 10	21 ± 16	Time 0.23
Post wt loss	24 ± 9	25 ± 9	Group 0.65
Difference	0	+4	T × G 0.25
Flexibility dorsiflexor (°)			
Overweight	60 ± 8	59 ± 6	Time 0.24
Post wt loss	59 ± 10	58 ± 8	Group 0.52
Difference	−1	−1	T × G 0.92

[a] Post hoc overweight to post overweight delta, $P < 0.05$

Table 3

Net oxygen uptake

	WLRT	**WL**	***P***
4.84 km h^{-1} walk VO_2 ml $kg^{-1}min^{-1}$[a]			
Overweight	12.2 ± 1.3	11.8 ± 1.4	Time 0.64
Post wt loss	11.7 ± 1.6	12.1 ± 1.3	Group 0.84
Difference	−0.5	+0.3	T × G 0.04
4.84 km h^{-1} walk net VO_2 ml $kg^{-1}min^{-1}$[a]			
Overweight	9.5 ± 1.6	9.0 ± 1.2	Time 0.18
Post wt loss	8.8 ± 1.4	9.2 ± 1.5	Group 0.83
Difference	−0.7	+0.2	T × G <0.02
Grade walk VO_2 ml kg^{-1} min^{-1}			
Overweight	14.8 ± 1.6	14.5 ± 1.7	Time 0.60
Post wt loss	14.5 ± 1.7	15.0 ± 1.8	Group 0.69
Difference	−0.3	+0.5	T × G 0.11
Grade walk net VO_2 ml $kg^{-1}min^{-1}$[a]			
Overweight	12.3 ± 1.4	11.8 ± 1.5	Time 0.38
Post wt loss	11.6 ± 1.6	12.1 ± 1.6	Group 0.94
Difference	−0.7	+0.3	T × G 0.03

[a] Post hoc overweight to post overweight delta, $P < 0.05$

Table 4

Overweight to post-overweight correlations between delta net oxygen uptake during walking and delta fitness measures ($N = 63$)

	Delta net VO_2 4.84 km h^{-1} walk	**Delta net VO_2 grade walk**
Delta knee extension strength	−0.33 ($P < 0.01$)	−0.34 ($P < 0.01$)
Delta knee extensor flexibility	0.18 ($P < 0.08$)	0.30 ($P < 0.01$)
Delta plantar flexor flexibility	0.32 ($P < 0.01$)	0.31 ($P < 0.01$)
Delta dorsi flexor flexibility	0.18 ($P < 0.08$)	0.30 ($P < 0.01$)

Table 5

Multiple regression models for estimating delta net oxygen uptake

Model	Intercept	*R*	Slope	*β*	*P*
Model 1: delta net VO_2 4.84 km h^{-1} walk (ml kg^{-1} min^{-1})		0.53			<0.01
Constant	0.465				
Delta knee extension strength (kg)			−0.0045	−0.37	<0.01
Delta knee extensor flexibility (°)			0.030	0.26	<0.03
Delta plantar flexor flexibility (°)			0.036	0.36	<0.01
Model 2: delta net VO_2 grade walk (ml kg^{-1} min^{-1})		0.61			<0.01
Constant	0.497				
Delta knee extension strength (kg)			−0.0054	−0.40	<0.01
Delta knee flexibility (°)			0.051	0.38	<0.01
Delta plantar flexor flexibility (°)			0.043	0.38	<0.01