ORIGINAL RESEARCH

Chronic Eccentric Cycling Training Improves Walking Economy in Healthy Individuals

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ABSTRACT

Background: Low muscular strength is associated with decline in ambulatory function. Progressive strength training has been demonstrated to improve physical functional outcomes. Because eccentric exercise is a potent stimulus for increasing muscle size, strength, and power, it has the potential to serve as a time-effective intervention to improve ambulatory function at a lower metabolic cost compared with traditional strength training. We examined the effect of a 6-week eccentric cycling training intervention on walking economy in healthy individuals.

Methods: Eleven healthy individuals (age = 24 ± 3 years; body weight = 71 ± 9 kg; height = 1.7 ± 0.1 m) trained on an eccentric ergometer for 6 weeks (3×/week; 10-30 min; 54%-66% of maximum heart rate). The metabolic cost of walking was assessed 1 week prior to and 1 week following eccentric cycling training. Cost of walking was determined as the net energy cost ($J \cdot kg^{-1} \cdot s^{-1}$), divided by walking speed ($m \cdot s^{-1}$) during steady-state walking at 5 walking speeds (0.7, 1.11, 1.39, 1.67, and 1.9 $m \cdot s^{-1}$).

Results: Posttraining cost of walking was significantly improved across all 5 walking speeds (0.7, 1.11, 1.39, 1.67, and 1.9 $m \cdot s^{-1}$; all $P < 0.01$) following eccentric cycling training.

Conclusion: These results demonstrate that 6 weeks of chronic eccentric cycling training was effective in improving walking economy and can be safely administered and tolerated by healthy individuals. Enhancing ambulatory function through eccentric cycling ergometry would be beneficial for both athletic and mobility-limited populations. *Journal of Clinical Exercise Physiology*. 2020;9(2):45–51.

Keywords: eccentric exercise, resistance training, mobility, ambulatory function

INTRODUCTION

The capacity to maintain functional independence while performing activities of daily living is related to an increased quality of life (1,2). Judge and colleagues (3) examined the factors that influence physical independence and reported associations between increased physical function (i.e., balance, gait speed, and muscular strength) and the ability to perform activities of daily living. Implicitly, individuals with reduced physical function because of physical inactivity, low muscle mass reserves and quality, and age-related decline, often exert considerably greater effort and/or experience higher metabolic costs while performing physical tasks such as walking, compared with healthier or younger persons (4). Therefore, implementing appropriate interventions to counteract the reduction in physical function is imperative. Traditional resistance exercise can attenuate decline in physical function. Indeed, previous investigators reported that conventional resistance exercise improved muscular strength (5–8), neuromuscular performance (5,7), balance (8,9), and ambulatory function (6,10). However, traditional resistance exercise (involving a combination of concentric and eccentric contractions) that requires elevated

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Conflicts of Interest and Source of Funding: The authors declare that they have no conflicts of interest to report. This study was supported by the New England American College of Sports Medicine (NEACSM) Undergraduate Research Grant (non-Tier 1) 2016 and the Central Connecticut Faculty-Student Research Grant 2016/17.

levels of perceived exertion may represent an obstacle in exercise tolerability and compliance in healthy sedentary individuals with low muscle mass reserves and quality.

In contrast to conventional resistance exercise, eccentric exercise is a potent stimulus for eliciting improvements in muscle size (11–15), strength (11,14,16–19), and power (12,15,20), at a substantially lower metabolic cost (17,21–25). Recently, several investigators have demonstrated that eccentric cycling can serve as a repetitive, high-force, low-metabolic cost training modality effective in producing significant hypertrophy (11,12,14), increased leg spring stiffness (20,26,27), and power (12,15,20). While these findings demonstrate the use of eccentric cycling training to improve muscle structure and muscular function, the potential for eccentric cycling training to improve ambulatory function measured as walking economy, has not been investigated. Further, exploring a training intervention with the potential to improve metabolic efficiency and ambulatory function at a relatively low metabolic cost may have use in both sedentary and active populations.

The purpose of this study was to examine the effect of 6 weeks of eccentric cycling training on walking economy in healthy individuals. We hypothesized that this training would be a tolerable and effective intervention that improves walking economy in healthy individuals.

METHODS

Experimental Approach to the Problem

In this investigation, we implemented a 6-week eccentric cycling training intervention and evaluated pretraining to posttraining changes in walking economy, measured as the metabolic cost of walking (C_w) (Figure 1). One week prior to the start of the training, participants reported to the laboratory for pretraining assessment of C_w across 5 random ordered walking speeds of 0.7, 1.11, 1.39, 1.67, and 1.9 m·s^{-1} (described below). Following the pretraining assessment of C_w, participants performed eccentric cycling training 3 times a week for 6 consecutive weeks (see training protocol below). Participants returned for the posttraining assessment of C_w 1 week after the final training session.

Subjects

We recruited healthy volunteers to participate in this investigation. Volunteers needed to be considered recreationally active as characterized by Rhea (28) (i.e., consistently active for at least 1 year, but less than 5 years). Experimental procedures used in this investigation were reviewed and approved by the Central Connecticut State University Human Studies Council. Experimental procedures were verbally explained, and all participants provided written

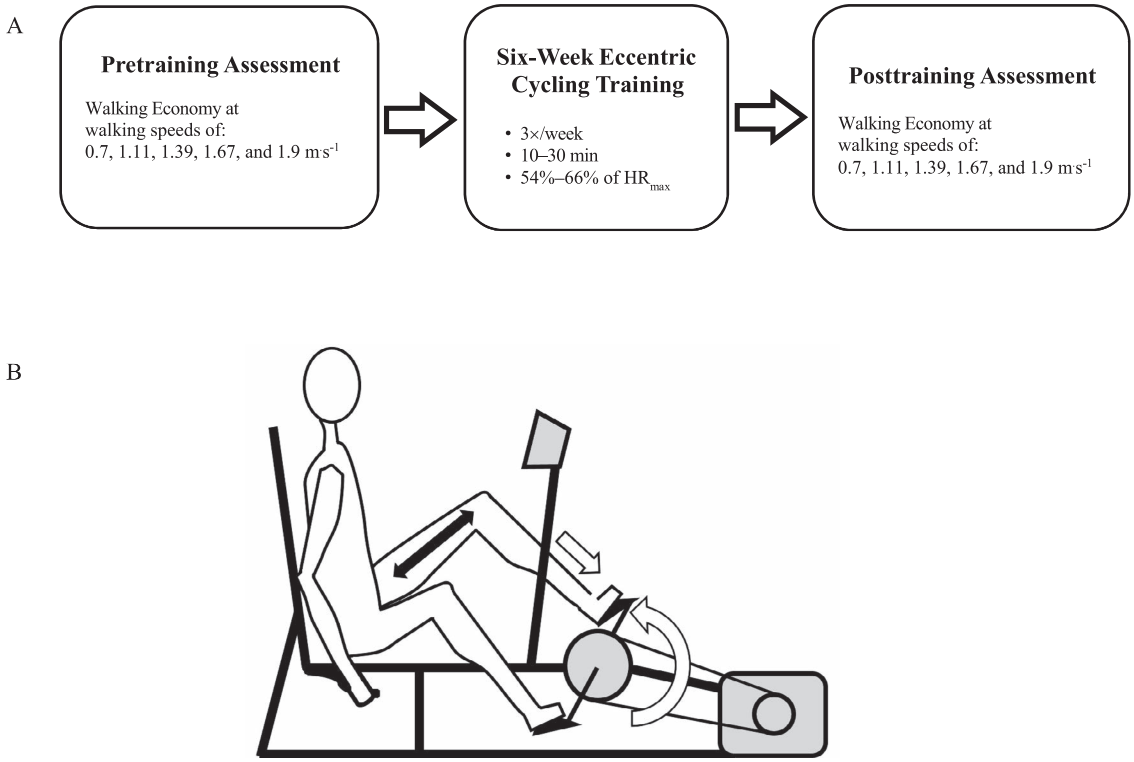

FIGURE 1. Experimental protocol (A). One week before the start of the eccentric cycling training, pretraining assessment of metabolic cost (C_w) at specified walking speeds was conducted. Next, participants performed the eccentric cycle training protocol. One week after the final training session, C_w at walking speeds were again assessed. Schematic illustrates the eccentric cycle ergometer (B). As the pedals driven backward by the electric motor rotate toward the participant (large white circular arrow), the participant resists by applying force to the pedals (small white arrow). Because the magnitude of the force produced by the motor exceeds that produced by the participant, leg extensors (black arrows on thigh) actively lengthen (eccentric muscle action).

TABLE 1. Participant characteristics (n=11).

Parameter	Mean±SD
Age (y)	24±3
Mass (kg)	71±9
Height (m)	1.7±0.1
BMI ($kg \cdot m^{-2}$)	23±3

BMI = Body mass index

informed consent. Prior to testing all participants were screened for potential risk factors for various cardiovascular, pulmonary, and metabolic diseases, as well as orthopedic limitations with Physical Activity Readiness Questionnaire and the American Heart Association/American College of Sports Medicine Health/Fitness Facility Preparticipation Screening Questionnaire (29). Participant characteristics are shown in Table 1.

Procedures

Eccentric Cycling Training

Participants performed eccentric cycling training on an isokinetic eccentric cycle ergometer constructed using a recumbent cycle ergometer frame (Stairmaster 3800, Core Health & Fitness, Vancouver, Washington) with a 2238 kW motor (Leeson Electric, Grafton, Wisconsin) that powered the cranks in reverse (Figure 1). Pedaling rate was controlled with a variable frequency drive and set at 60 rpm. Participants were instructed to resist the reverse moving pedals of the eccentric cycle ergometer at a specified training intensity based on a percentage of the participant's age-predicted maximum heart rate (HR_{max}). Specifically, training intensity progressed from 54% to 66% of HR_{max}, while training duration increased from 10 min in the first week to 30 min in the final week. This progression of eccentric cycling training protocol was adapted from previous studies (14,17,20) and is summarized in Table 2.

During each training session, mean power and total work was determined using a power meter (Schoberer Rad Messtechnik, Julich, Germany) and average heart rate (HR) was monitored using an HR monitor (Polar, FT1, Polar Electro Oy, Kempele, Finland). In addition, during the final minute of each training session, rating of perceived exertion (RPE) for the *whole body* and *legs only* was recorded using the Borg 6-20 scale (30). To ensure that the progressive training protocol was well tolerated and safely administered to avoid unnecessary muscle damage, we implemented the eccentric-negative progression algorithm recommended by LaStayo and colleagues (31). Prior to subsequent sessions of eccentric cycling, participants indicated leg muscle soreness during a static bilateral squat movement. Soreness was assessed using a visual analog scale (0-10) with 10 representing the worst pain imaginable (15,20). Reported soreness values of 0 to 4 were used as an indication that the eccentric exposure was deemed tolerable enough for the participant to continue with the progressive training program (31).

TABLE 2. Eccentric cycling training protocol.

Weeks of Training	Time (min)	% HR_{max} [a]
1	10	54
2	15	58
3	20	62
4	20	63
5	25	64
6	30	66

[a]HR_{max}: Age-predicted maximum heart rate determined as 220 – age

Walking Economy

Gas exchange data were measured using open circuit spirometry (True Max 2400, Parvo Medics, Sandy, Utah). The metabolic system was calibrated using room air and a calibration gas concentration (16.00% O_2, 4.00% CO_2, balanced N_2). Oxygen consumption ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), minute ventilation ($\dot{V}_E$), respiratory exchange ratio, and HR were recorded breath-by-breath and averaged to 15-s intervals. Prior to walking, resting metabolic cost was recorded for 5 min. Following the metabolic sampling at rest, participants performed walking on a treadmill (TrackMaster, TMX428CP, Full Vision Inc., Newton, Kansas). Participants walked at 5 randomized speeds (0.7, 1.11, 1.39, 1.67, and 1.9 $m \cdot s^{-1}$) while gas exchange data were measured. Each walking speed was maintained for 5 min to assure a metabolic steady-state was achieved (32,33), while participants reported their walking rating of perceived exertion (RPE_w) using Borg 6-20 scale during the final minute at each walking speed (30). Walking heart rate (HR_w) was recorded as the HR averaged over the final minute of each walking speed. Walking economy, defined as the energy cost of moving 1 kg of body mass 1 m ($J \cdot kg^{-1} \cdot m^{-1}$), was measured as the metabolic C_w derived from metabolic averages of $\dot{V}O_2$ and $\dot{V}CO_2$ collected during the final minute of each walking speed. Specifically, C_w was calculated using the Brockway equation, which determines energy cost ($J \cdot kg^{-1} \cdot s^{-1}$) at rest and during steady-state walking. The net energy cost of walking is determined by subtracting the energy cost at rest from the energy cost calculated for each walking speed. Finally, C_w expressed as ($J \cdot kg^{-1} \cdot m^{-1}$) is obtained by dividing net energy expenditure ($J \cdot kg^{-1} \cdot s^{-1}$) by walking speed ($m \cdot s^{-1}$) (34).

Statistical analysis

Paired sample *t* tests (IBM SPSS Statistics, v 22.0; IBM Corp, Armonk, New York) were used to evaluate the pretraining to posttraining changes in physiological variables (C_w, RPE_w, and HR_w). Effect sizes (ESs) were calculated and ES magnitudes of <0.80, 0.80 to 1.50, and >1.50, were interpreted as small, moderate, and large effects, respectively, according to the training status of the participants

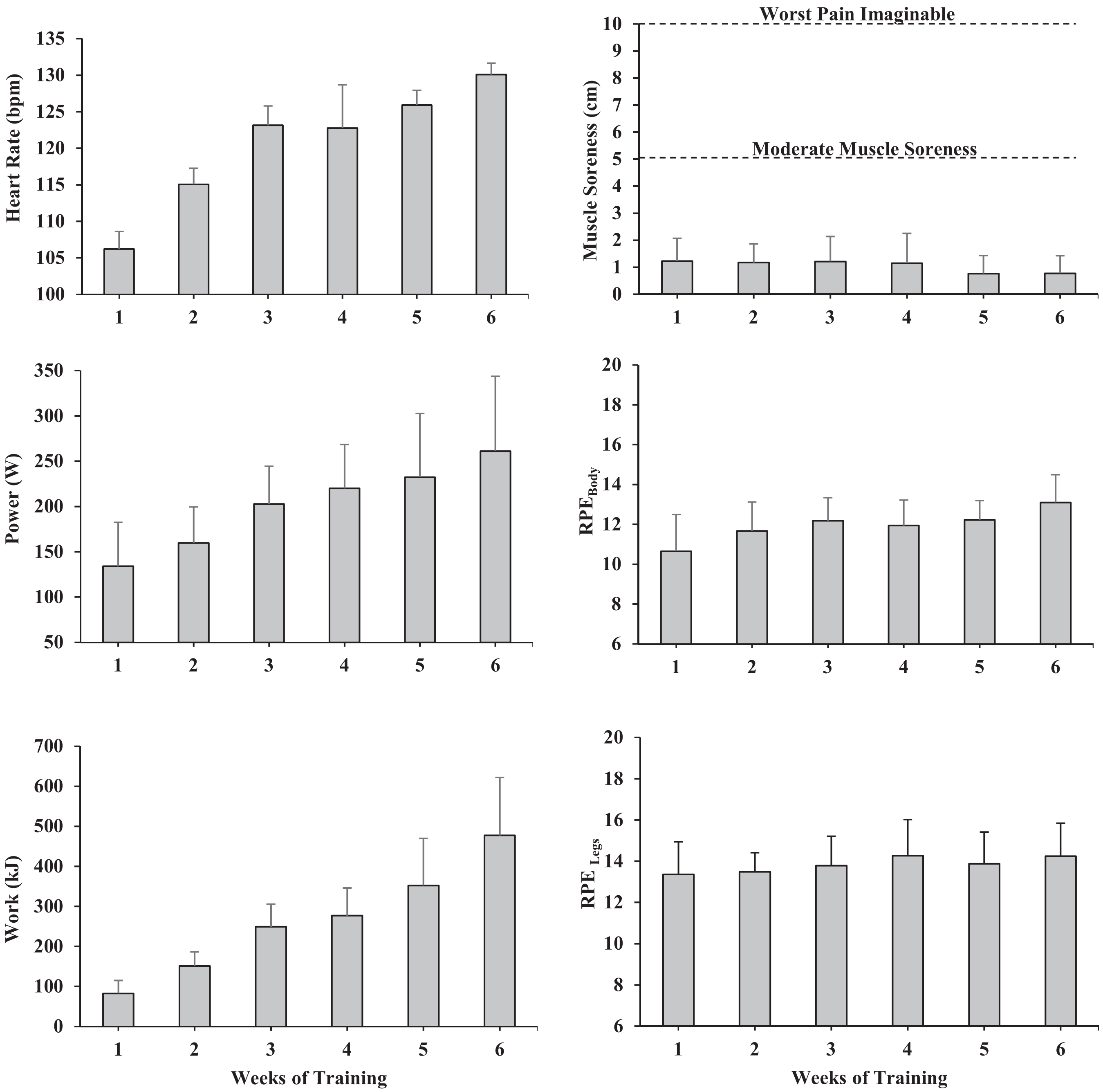

FIGURE 2. Cardiorespiratory, mechanical, and perceptual responses recorded during 6 weeks of eccentric cycling training. Values are presented as mean ± SD.

(28). Values are reported as mean ± standard deviation (SD) and alpha was set at 0.05.

RESULTS

We recruited 11 participants (10 male and 1 female). During the 6-week eccentric cycling training period, participants' average power progressed from 134 ± 49 W to 261 ± 26 W and total work progressed from 83 ± 32 kJ to 477 ± 145 kJ (Figure 2). Training HR, RPE_{body}, and RPE_{legs} increased in response to the progressive eccentric cycling training intervention (Figure 2). Participants reported low (0.8 ± 0.6 to 1.2 ± 0.8 out of 10) levels of muscle soreness throughout the eccentric cycling training period (Figure 2).

Following eccentric cycling training, posttraining C_w was significantly reduced by 15% ± 15%, 11% ± 11%, 12% ± 6%, 7% ± 7%, and 10% ± 10%, across all 5 walking speeds of 0.7, 1.11, 1.39, 1.67, and 1.9 $m \cdot s^{-1}$, respectively, compared with pretraining values (all $P < 0.01$; Table 3). Posttraining HR_w was significantly reduced by 8% ± 11%, 9% ± 11%, and 10% ± 12% while walking at 0.7, 1.11, and 1.39 $m \cdot s^{-1}$, respectively (all $P < 0.05$; Table 3). RPE_w was also significantly reduced by 15% ± 10% and 14% ± 8%

TABLE 3. Pretraining versus posttraining metabolic cost of walking (C_w), walking heart rate (HR_w), and walking rating of perceived exertion (RPE_w). Data presented as mean ± SD.

Walking Speed ($m \cdot s^{-1}$)	Pretraining	Posttraining	*P* Value	ES
C_w ($J \cdot kg^{-1} \cdot m^{-1}$)				
0.7	2.37 ± 0.50	1.97 ± 0.37	0.009	0.79
1.11	2.24 ± 0.43	1.96 ± 0.27	0.005	0.64
1.39	2.35 ± 0.33	2.04 ± 0.25	0.0001	0.91
1.67	2.72 ± 0.40	2.53 ± 0.30	0.007	0.49
1.9	3.27 ± 0.52	2.95 ± 0.68	0.005	0.61
HR_w ($b \cdot min^{-1}$)				
0.7	93 ± 9	86 ± 14	0.04	0.84
1.11	96 ± 7	88 ± 13	0.03	1.19
1.39	104 ± 12	94 ± 15	0.03	0.90
1.67	112 ± 9	105 ± 17	0.12	0.89
1.9	130 ± 16	119 ± 21	0.08	0.69
RPE_w				
0.7	7 ± 1	7 ± 1	0.55	0.28
1.11	8 ± 1	7 ± 1	0.84	0.20
1.39	8 ± 2	8 ± 2	0.14	0.35
1.67	10 ± 2	8 ± 2	0.001	0.79
1.9	11 ± 2	10 ± 2	0.0004	0.68

ES = effect size

while walking at 1.67 and 1.9 $m \cdot s^{-1}$, respectively (both $P < 0.01$; Table 3).

DISCUSSION

Researchers and clinicians have traditionally prioritized strength or resistance training in a rehabilitative plan to maintain, restore, and/or improve ambulatory function. However, traditional resistance exercise may represent an unattractive option for individuals with limited cardiovascular exercise tolerance. In contrast, eccentric exercise has been demonstrated to be a desirable alternative that allows high muscular loading with resulting low metabolic demand. Although extensive reviews by previous investigators (35,36) highlighted the superior neuromuscular adaptations elicited by eccentric training, reports of the potential for eccentric training to improve ambulatory function are limited. In this investigation, we evaluated the effect of 6 weeks of eccentric cycling training on walking economy in healthy individuals. Our main finding was that 6 weeks of eccentric cycling training improved walking economy across a spectrum of walking speeds (0.7, 1.11, 1.39, 1.67, 1.9 $m \cdot s^{-1}$). These data demonstrate that our training intervention (3×/week, 10-30 min at 54%-66% HR_{max}) served as a safe and tolerable strategy for improving walking economy in healthy individuals.

A possible mechanism underlying the reductions in walking metabolic cost and HR following chronic eccentric cycling training is likely due to neuromuscular adaptations involving compliant leg stiffness (37). Previous investigators (20,27,38) using protocols like that implemented in our investigation reported increases in leg spring stiffness. These investigators suggest a strong link between leg spring stiffness and stretch reflex mechanisms (i.e., neural adaptations associated with stretch-shortening cycle), with the stretch-shortening cycle being implicated in improved efficiency and performance in running (27). Because the dynamics of running and walking can be explained by spring-mass (39,40) and bipedal spring-mass models (37), respectively, the stretch-shortening cycle allows the temporary storage and subsequent recovery of elastic energy during cyclic movements. Effective stretch-shortening cycle during cyclic movements (characterized by accentuated muscle preactivation and a short-latency stretch reflex component) regulates stiffness in the eccentric part of the stretch-shortening cycle (41,42). Thus, an increase in leg spring stiffness following chronic eccentric training might indicate an enhanced elastic strain energy storage and recovery by this cyclic *stretch-shorten* use of muscles during locomotion (27,43), contributing to improved efficiency during running and walking.

Morphological adaptations involving propulsive power generation during walking (44–46) could also have contributed to the improvement in walk economy. Conventionally, multijoint leg extension actions play a role in power generation during walking (45). Thus, an increase in muscular strength has the potential to improve the force or power generating capacity of propulsive leg muscles that influences functional outcomes such as step length, walking speed, and walking economy. Increased muscular strength also allows participants to work at a lower percentage of their maximum strength at a given workload, reducing the reliance on anaerobic mechanisms (44). Previous investigators consistently report increased muscular strength and/or power elicited by muscular hypertrophy following eccentric training (13,15,17,47). Hence, these training-induced increases in hypertrophy and concomitant increase in muscular strength and/or power may account for improvements in walking economy observed in this investigation. Consequently, a future direction of our laboratory will be to quantify the contribution of neuromuscular adaptations to walking economy with direct measures of leg stiffness, muscle structure, and muscular power.

A limitation of our study was that our sample population of healthy individuals constrains direct clinical application of our findings. Nevertheless, previous investigators (13) implementing a similar eccentric cycling protocol reported increased muscle strength and decreased fall risk in a frail elderly population, demonstrating the potential for our findings to be reproduced in patient populations. Additionally, the limited number of commercially available eccentric cycle ergometers, manufacturing constraints, and substantial cost impede the use of eccentric cycling in physical therapy and rehabilitation centers. However, this limitation could be circumvented by constructing an eccentric cycle ergometer in house. Indeed, Elmer and Martin (48) provide a technical note on the construction of an isokinetic eccentric cycle ergometer using commonly available exercise equipment, industrial parts, and a modest amount of custom fabrication, enabling a commercially viable option for researchers and clinicians to employ eccentric cycling as an exercise modality.

Clinical Implications

To the best of our knowledge, this is the first report of improved walking economy following 6 weeks of eccentric cycling training in healthy individuals. Our results expand upon the application of eccentric exercise training for improving variables associated with strength, power, and speed performance in athletic populations (35). Additionally, our results of improved walking economy in healthy individuals also extends upon previous work (13,15,49,50) that lays the foundation for exploring the prescription of eccentric cycling training for mobility-limited patients, as well as improving a variety of age and/or medical-related conditions associated with muscular dysfunction (31). Indeed, an extensive review by LaStayo and colleagues (31) highlighted more than 20 investigations demonstrating chronic eccentric training to be a safe and feasible rehabilitative intervention for diagnostically diverse patient groups that are traditionally considered exercise intolerant. These groups include patients who are frail and elderly, those with cardiopulmonary disorders, cancer survivors, patients with metabolic disorders, and patients with neurologic conditions. Implicitly, the benefits of improved walking economy allowing for increased mobility, ease of movement, and levels of habitual physical activity, possibly translating to improvements in functional status, overall health, and quality of life, demand that this exercise modality be considered for clinical application and future studies in patient populations.

Acknowledgments: The authors would like to thank the participants who volunteered in this study for their enthusiastic efforts throughout the training intervention and the students (Andrew Weiler, Christopher Samboy, and Jonathan Huaqui) in the Biomechanics Laboratory for their assistance with the data collection.

REFERENCES

1. Chou C-H, Hwang C-L, Wu Y-T. Effect of exercise on physical function, daily living activities, and quality of life in the frail older adults: a meta-analysis. Arch Phys Med Rehabil. 2012;93(2):237–44.
2. Felce D, Perry J. Quality of life: its definition and measurement. Res Dev Disabil. 1995;16(1):51–74.
3. Judge JO, Schechtman K, Cress E, Group F. The relationship between physical performance measures and independence in instrumental activities of daily living. J Am Ger Soc. 1996;44(11):1332–41.
4. Hortobágyi T, Mizelle C, Beam S, DeVita P. Old adults perform activities of daily living near their maximal capabilities. J Gerontol A Biol Sci Med Sci. 2003;58 (5):M453–60.
5. Fiatarone MA, O'Neill EF, Ryan ND, Clements KM, Solares GR, Nelson ME, Roberts SB, Kehayias JJ, Lipsitz LA, Evans WJ. Exercise training and nutritional supplementation for physical frailty in very elderly people. N Engl J Med. 1994;330(25):1769–75.
6. Rosendahl E, Lindelöf N, Littbrand H, Yifter-Lindgren E, Lundin-Olsson L, Håglin L, Gustafson Y, Nyberg L. High-intensity functional exercise program and protein enriched energy supplement for older persons dependent in activities of daily living: a randomised controlled trial. Aus J Physiother. 2006;52(2):105–13.
7. Taaffe DR, Duret C, Wheeler S, Marcus R. Once-weekly resistance exercise improves muscle strength and neuromuscular performance in older adults. J Am Geriatr Soc. 1999;47(10):1208–14.
8. Timonen L, Rantanen T, Ryynanen O-P, Taimela S, Timonen TE, Sulkava R. A randomized controlled trial of rehabilitation after hospitalization in frail older women: effects on strength, balance and mobility. Scand J Med Sci Sports. 2002;12(3): 186–92.
9. Judge JO, Lindsey C, Underwood M, Winsemius D. Balance improvements in older women: effects of exercise training. Phys Ther. 1993;73(4):254–62.
10. Hartman M, Fields D, Byrne N, Hunter G. Resistance training improves metabolic economy during functional tasks in older adults. J Strength Cond Res. 2012;21(1):91–5.
11. Flann KL, LaStayo PC, McClain DA, Hazel M, Lindstedt SL. Muscle damage and muscle remodeling: no pain, no gain? J Exp Biol. 2011;214(4):674.
12. Gross M, Lüthy F, Kroell J, Müller E, Hoppeler H, Vogt M. Effects of eccentric cycle ergometry in alpine skiers. Int J Sports Med. 2010;31(08):572–6.
13. LaStayo PC, Ewy GA, Pierotti DD, Johns RK, Lindstedt S. The positive effects of negative work: increased muscle strength and decreased fall risk in a frail elderly population. J Gerontol A Biol Sci Med Sci. 2003;58(5):M419–24.
14. LaStayo PC, Pierotti DJ, Pifer J, Hoppeler H, Lindstedt SL. Eccentric ergometry: increases in locomotor muscle size and strength at low training intensities. Am J Physiol Regul Integr Comp Physiol. 2000;278(5):R1282.
15. Leong C, McDermott W, Elmer S, Martin J. Chronic eccentric cycling improves quadriceps muscle structure and maximum cycling power. Int J Sports Med. 2013;35(07):559–65.
16. Dibble LE, Hale T, Marcus RL, Gerber JP, LaStayo PC. The safety and feasibility of high-force eccentric resistance exercise in persons with Parkinson's disease. Arch Phys Med Rehabil. 2006;87(9):1280–2.
17. Lastayo PC, Reich TE, Urquhart M, Hoppeler H, Lindstedt SL. Chronic eccentric exercise: improvements in muscle strength can occur with little demand for oxygen. Am J Physiol Regul Integr Comp Physiol. 1999;276(2):R611.
18. Mueller M, Breil FA, Vogt M, Steiner R, Lippuner K, Popp A, Klossner S, Hoppeler H, Däpp C. Different response to eccentric and concentric training in older men and women. Eur J Appl Physiol. 2009;107(2):145–53.
19. Seger JY, Thorstensson A. Effects of eccentric versus concentric training on thigh muscle strength and EMG. Int J Sports Med. 2005;26(01/02):45–52.
20. Elmer S, Hahn S, McAllister P, Leong C, Martin J. Improvements in multi-joint leg function following chronic

eccentric exercise: functional changes following exercise. Scand J Med Sci Sports. 2012;22(5):653–61.
21. Abbott BC, Bigland B, Ritchie JM. The physiological cost of negative work. J Physiol. 1952;117(3):380–90.
22. Bigland-Ritchie B, Woods JJ. Integrated electromyogram and oxygen uptake during positive and negative work. J Physiol. 1976;260(2):267–77.
23. Bonde-Petersen F, Knuttgen HG, Henriksson J. Muscle metabolism during exercise with concentric and eccentric contractions. J Appl Physiol. 1972;33(6):792.
24. Penailillo L, Blazevich A, Numazawa H, Nosaka K. Metabolic and muscle damage profiles of concentric versus repeated eccentric cycling. Med Sci Sport Exerc. 2013;45(9):1773–81.
25. Perrey S, Betik A, Candau R, Rouillon JD, Hughson RL. Comparison of oxygen uptake kinetics during concentric and eccentric cycle exercise. J Appl Physiol. 2001;91(5):2135.
26. Reich TE, Lindstedt SL, LaStayo PC, Pierotti DJ. Is the spring quality of muscle plastic? Am J Physiol Regul Integr Comp Physiol. 2000;278(6):R1661.
27. Lindstedt SL, LaStayo PC, Reich TE. When active muscles lengthen: properties and consequences of eccentric contractions. Physiology. 2001;16(6):256.
28. Rhea MR. Determining the magnitude of treatment effects in strength training research through the use of the effect size. J Strength Cond Res. 2004;18(4):918.
29. Balady GJ, Chaitman B, Driscoll D, Foster C, Froelicher E, Gordon N, Pate R, Rippe J, Bazzarre T. Recommendations for cardiovascular screening, staffing, and emergency policies at health/fitness facilities. Circulation. 1998;97(22):2283–93.
30. Borg G. Perceived exertion as an indicator of somatic stress. Scand J Rehabil Med. 1970;2(2):92–8.
31. LaStayo P, Marcus R, Dibble L, Frajacomo F, Lindstedt S. Eccentric exercise in rehabilitation: safety, feasibility, and application. J Appl Physiol. 2014;116(11):1426–34.
32. Mian OS, Thom JM, Ardigo LP, Narici MV, Minetti AE. Metabolic cost, mechanical work, and efficiency during walking in young and older men. Acta Physiol. 2006;186(2): 127–39.
33. Whipp BJ, Wasserman K. Oxygen uptake kinetics for various intensities of constant-load work. J Appl Physiol. 1972; 33(3):351.
34. Brockway JM. Derivation of formulae used to calculate energy expenditure in man. Hum Nutr Clin Nutr. 1987; 41(6):463–71.
35. Douglas J, Pearson S, Ross A, McGuigan M. Chronic adaptations to eccentric training: a systematic review. Sports Med. 2017;47(5):917–41.
36. Hoppeler H. Moderate load eccentric exercise: a distinct novel training modality. Front Physiol. 2016;7:483.
37. Geyer H, Seyfarth A, Blickhan R. Compliant leg behaviour explains basic dynamics of walking and running. Proc Biol Sci. 2006;273(1603):2861–7.
38. LaStayo P, Pierotti D, Pifer J, Hoppeler H. Eccentric ergometry: increases in locomotor muscle size and strength at low training intensities. Am J Physiol Regul Integr Comp Physiol. 2000;278(5):1282–8.
39. Farley CT, Blickhan R, Saito J, Taylor CR. Hopping frequency in humans: a test of how springs set stride frequency in bouncing gaits. J Appl Physiol. 1991;71(6):2127–32.
40. Farley CT, Gonzalez O. Leg stiffness and stride frequency in human running. J Biomech. 1996;29(2):181–6.
41. Komi PV, Buskirk ER. Effect of eccentric and concentric muscle conditioning on tension and electrical activity of human muscle. Ergonomics. 1972;15(4):417–34.
42. Komi PV, Gollhofer A. Stretch reflex can have an important role in force enhancement during SSC-exercise. J Appl Biomech. 1997;13:451–60.
43. Lindstedt SL, Reich TE, Keim P, LaStayo PC. Do muscles function as adaptable locomotor springs? J Exp Biol. 2002;205(Pt 15):2211–6.
44. Ades PA. Weight training improves walking endurance in healthy elderly persons. Ann Int Med. 1996;124(6):568.
45. Franz JR. The age-associated reduction in propulsive power generation in walking. Exer Sports Sci Rev. 2016;44(4): 129–36.
46. Griffin TM, Roberts TJ, Kram R. Metabolic cost of generating muscular force in human walking: insights from load-carrying and speed experiments. J Appl Physiol. 2003;95(1):172–83.
47. Blazevich AJ, Cannavan D, Coleman DR, Horne S. Influence of concentric and eccentric resistance training on architectural adaptation in human quadriceps muscles. J Appl Physiol. 2007;103(5):1565–75.
48. Elmer SJ, Martin JC. Construction of an isokinetic eccentric cycle ergometer for research and training. J Appl Biomech. 2013:29(4):490–5.
49. LaStayo PC, Marcus RL, Dibble LE, Smith SB, Beck SL. Eccentric exercise versus usual-care with older cancer survivors: the impact on muscle and mobility—an exploratory pilot study. BMC Geriatr. 2011;11:5.
50. LaStayo PC, Meier W, Marcus RL, Mizner R, Dibble L, Peters C. Reversing muscle and mobility deficits 1 to 4 tears after TKA: a pilot study. Clin Orthop Relat Res. 2009;467(6): 1493–500.