HHS Public Access

Author manuscript

Spinal Cord. Author manuscript; available in PMC 2017 March 01.

Published in final edited form as:

Spinal Cord. 2016 September ; 54(9): 675–681. doi:10.1038/sc.2015.212.

Effects of Aerobic Exercise Training on Fitness and Walking Related Outcomes in Ambulatory Individuals with Chronic Incomplete Spinal Cord Injury

Nicole D. DiPiro, PhD[1], **Aaron E. Embry, PT, DPT, MSCR**[1,2,3], **Stacy L. Fritz, PhD, PT**[4], **Addie Middleton, PhD, DPT**[4], **James S. Krause, PhD**[1], and **Chris M. Gregory, PhD, PT**[1,2,3]

[1]Department of Health Sciences & Research, Medical University of South Carolina

[2]Division of Physical Therapy, Medical University of South Carolina

[3]Ralph H. Johnson VAMC, Charleston, SC

[4]Department of Exercise Science, Physical Therapy Program, University of South Carolina, Columbia, South Carolina

Abstract

Study Design—Single group, pretest-posttest study.

Objectives—To determine the effects of a non-task-specific, voluntary, progressive aerobic exercise training (AET) intervention on fitness and walking-related outcomes in ambulatory adults with chronic motor-incomplete SCI.

Setting—Rehabilitation research center.

Methods—Ten ambulatory individuals (50% female; 57.94 ± 9.33 years old; 11.11 ± 9.66 years post injury) completed voluntary, progressive moderate-to-vigorous intensity AET on a recumbent stepper three days per week for six weeks. The primary outcome measures were aerobic capacity (VO_{2peak}) and self-selected overground walking speed (OGWS). Secondary outcome measures included: walking economy, six-minute walk test (6MWT), daily step counts, Walking Index for Spinal Cord Injury (WISCI-II), Dynamic Gait Index (DGI), and Berg Balance Scale (BBS).

Results—Nine participants completed all testing and training. Significant improvements in aerobic capacity (P=0.011), OGWS (P=0.023), the percentage of VO_{2peak} utilized while walking at self-selected speed (P=0.03), and daily step counts (P=0.025) resulted following training.

Conclusions—The results indicate that total-body, voluntary, progressive AET is safe, feasible, and effective for improving aerobic capacity, walking speed, and select walking-related outcomes in an exclusively ambulatory SCI sample. This study suggests the potential for non-task-specific

Corresponding Author: Nicole D. DiPiro, PhD, Department of Health Sciences & Research, Medical University of South Carolina, 77 President St., MSC 700, Charleston, SC 29425-7000, Phone: 843-792-9894, Fax.: 843-792-1358, nicole.dipiro@gmail.com.

Conflict of Interest Statement: The authors declare no conflicts of interest.

Adherence to ethics and reporting requirements: We certify that all applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during the course of this research.

aerobic exercise to improve walking following incomplete SCI and builds a foundation for further investigation aimed at the development of exercise based rehabilitation strategies to target functionally limiting impairments in ambulatory individuals with chronic SCI.

Keywords

exercise; recumbent stepping; spinal cord injury; walking

Introduction

Aerobic capacity is a health-related component of physical fitness and an indicator of health, morbidity, and mortality.(1) Following spinal cord injury (SCI), aerobic capacity is significantly diminished, so much so that individuals with SCI are believed to live at the lowest end of the human fitness spectrum.(2) The decline in aerobic capacity after SCI is related to a number of factors, including motor level of injury, functional classification, BMI, age, and activity level.(3, 4) There is sufficient evidence to show that aerobic exercise training (AET) improves aerobic capacity and mitigates the adverse effects of low fitness after SCI.(5-8) However, aerobic capacity and the effects of AET have not been thoroughly studied in ambulatory adults with incomplete SCI, a large and growing segment of the SCI population.

Aerobic capacity is a known determinant of normal walking(9) and has been suggested as a factor that may influence walking ability in individuals with neurological diseases or disorders (e.g. stroke, multiple sclerosis).(10-13) There is ample evidence supporting the beneficial effects of AET on both aerobic capacity and walking outcomes after stroke(14-16) and multiple sclerosis.(17-19) To date however, the relationship between aerobic capacity and walking after SCI is not fully understood, and data regarding the effects of AET on these outcomes in ambulatory adults with SCI is lacking. It is reasonable to believe that diminished aerobic capacity may be a factor limiting walking ability after SCI, and similar to observations from other populations, voluntary (i.e. manual, not assisted or electrically stimulated) AET may result in beneficial effects on fitness and walking outcomes.

The majority of studies aimed at improving walking ability in ambulatory adults with SCI have focused on task-specific (i.e. walking based) strategies, and only a few have assessed changes in fitness following training.(20-22) There is little evidence available regarding the effects of non-task specific exercise on walking outcomes and fitness in ambulatory adults with SCI. Functional electrical stimulation (FES) cycling is one non-task specific AET strategy that has been shown to improve fitness after SCI(23, 24) as well as walking outcomes in ambulatory adults with SCI(25, 26). To date, the impact of voluntary, non-task specific AET has yet to be investigated in this population.

Recumbent stepping is a non-task-specific total-body aerobic exercise that produces reciprocal movements similar to, but simpler than walking, and relies on similar neural control.(27) This exercise modality may target ambulatory deficits via multiple mechanisms, including increased aerobic capacity and muscle strength.(10, 28) Recumbent stepping has been shown to increase aerobic capacity and improve walking outcomes in adults with

neurologic diseases, and is a recommended exercise strategy for rehabilitation of ambulatory impairments, as it is widely accessible, easy to perform, and cost-effective.(10, 29)

Purpose

The purpose of this study was to determine the effects of a six-week non-task specific, progressive AET intervention on fitness and walking-related outcomes in ambulatory adults with chronic motor-incomplete SCI. We hypothesized that a voluntary recumbent stepping exercise program, with sufficient focus on aerobic capacity, would result in significant improvements in the primary outcome measures, aerobic capacity (VO_{2peak}) and self-selected overground walking speed (OGWS). We further hypothesized there would be improvements in secondary walking-related outcome measures including walking economy, six minute walk test (6MWT), daily step counts, Walking Index for Spinal Cord Injury (WISCI-II), Dynamic Gait Index (DGI), and Berg Balance Scale (BBS).

Methods

Participants

Participants were recruited from a pool of individuals who had previously completed studies at the rehabilitation research center, and also from area clinics, support-groups, and by word-of mouth. Twenty-five individuals were screened for eligibility. Ten participants with chronic (>6-months post-injury) motor-incomplete SCI (AIS C, D; C4-T12) volunteered to participate in this single group, pretest-posttest study. Participants received remuneration for their time. Inclusion criteria were (1) Age 18-75 years; (2) A diagnosis of first time SCI including etiology from traumatic or vascular origin; (3) The ability to walk independently for a minimum of 10 meters with or without an assistive device; (4) Self-selected walking speed greater than 0.1 m/s and less than 1.15 m/s; (5) A medically stable condition allowing for testing of walking function and aerobic exercise training. Prior to participation, all participants provided a signed informed consent. We certify that all applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during the course of this research.

Aerobic Exercise Training Intervention

Participants completed a six-week (3 sessions/week; 20 minutes/session) non-task specific, progressive AET program. All training was performed on a NuStep® T5xr recumbent cross-trainer (NuStep Inc., Ann Arbor, MI). The selected exercise modality required bilateral reciprocal stepping against resistive forces and synchronized upper extremity movement, thus a total-body workout was achieved. No assistance in performing the exercise was provided by either personnel or electrical stimulation, thus all AET was voluntary.

The AET intervention was developed to meet the SCI guidelines for aerobic activity (30) (20 minutes, 2 days/week of moderate-to-vigorous exercise) and prepare participants to reach levels of aerobic exercise recommended by the ACSM and 2008 Physical Activity Guidelines for Americans.(1, 31) The primary parameter for progression during the AET was intensity of exercise, expressed as a percentage of VO_2 reserve (VO_2R), where Target VO_2R = % intensity * (VO_{2peak} - VO_{2rest}) + VO_{2rest}. Over the course of the training period,

the exercise dose was progressed from a starting intensity of 40% VO_2R, and increased by at least 5% per week, to a final target exercise intensity of 60% to 70% VO_2R in the final week. Each participant followed an individualized training program, generated based on his or her baseline VO_2 values, the identified target intensity, and the corresponding metabolic equivalent (MET) levels (1 MET = 3.5 mLO_2/kg/min). MET levels were displayed on the NuStep® and were used to track intensity and progression of the exercise sessions.

The weekly sessions included two steady state exercise sessions at the target intensity and one high-intensity interval training session. Two built-in programs were selected for the exercise sessions. The *constant power* program was used for the steady state sessions. In this program, the participants exercised at a constant effort; the program adjusted the workload based on the stepping speed and step length to maintain a constant target MET level. The NuStep® *profiles* program provides five options for different levels of interval training. The built-in interval training program, *profile 5*, was chosen to allow for 1:1 interval training (one minute of high-intensity exercise and one minute of active recovery). The interval training intensities were set based on the *net target workload* for the week (i.e. 40% to 65% VO_2R). During the interval training sessions, the active recovery remained at 20% VO_2R, thus the high-intensity intervals increased from 60% to 110% of pre-training VO_2R over the course of the six weeks. During all exercise sessions, MET level, HR, BP, and RPE levels were monitored for safety and to ensure the participants were exercising at the appropriate intensity.

Outcome Measures

All outcome measures were collected prior to and following the AET intervention. OGWS was assessed weekly. In order to prevent fatigue, the pre and post-test assessments were spread out over two visits, and participants were given rest periods of five to ten minutes between testing at each visit.

Aerobic Capacity—Graded exercise tests were completed on the NuStep® to assess changes in VO_{2peak} presented as milliliters of oxygen per kilogram body mass per minute (mL O_2/kg/min). Following the protocols previously described by Billinger et al.,(33) participants completed the modified total-body recumbent stepper exercise test (mTBRS-XT). This device and protocol have been validated for use in healthy, sedentary, and post-stroke individuals, (33, 34) but have yet to be evaluated in individuals with incomplete SCI. Despite this limitation, the decision was made to use the NuStep® in order to maintain consistency between the testing and training of VO_{2peak}. Our decision was further influenced by safety and feasibility concerns to using other common modalities (e.g. treadmill, arm-crank, or cycle ergometer). For example, walking impairments may affect the amount of time a participant could spend of a treadmill, thus limiting attainment of VO_{2peak}. Additionally, aerobic capacity is often underestimated on arm-crank and cycle ergometer exercise tests, due to the limited muscle mass activated. We believed the participants would more fully tax their cardiorespiratory system by completing a total-body graded exercise test on the NuStep®, which requires active recruitment of a larger muscle mass. Additionally, utilization of both upper and lower extremities was expected to reduce the risk of local fatigue commonly observed in cycle ergometry exercise tests. We acknowledge that further

research is necessary to validate the use of recumbent stepping protocols for assessment of aerobic capacity in individuals with SCI.

Prior to exercise testing, instructions were given to the participants to refrain from consuming caffeine, food or drink (water was permitted) for at least 3 hours, and to avoid significant exertion or exercise on the day of the assessment. The protocol and assessments required during the test were described, and participants were given a few minutes to acclimate to the required step rate (80 steps/minute) prior to starting. Once seated, adjustments were made to the seat and arm positions; if needed, hand and leg stabilizers were used. Participants were then fitted with a facemask that allowed for the collection of respiratory gasses. Oxygen uptake was measured using a Quark CPET metabolic cart (COSMED, Rome, Italy). Breath-by-breath cardiorespiratory data was collected and then averaged every 15 seconds to determine the highest VO_2 (VO_{2peak}) achieved during the test.

The mTBRS-xt consisted of 8 consecutive 2-minute stages, where resistance increased at each stage. Each test was supervised by an exercise physiologist, cardiologist, and trained personnel to ensure participant safety. A 12-lead electrocardiogram was monitored throughout the test. Vitals (HR and BP) and ratings of perceived exertion (RPE; Borg RPE scale 6-20) were recorded at the end of each 2-minute stage. The participants were instructed to discontinue the test if at any point they felt the need to stop. Otherwise, the exercise test was terminated by the cardiologist or exercise physiologist based on the ACSM's general indications(1) and/or the inability of the participant to maintain stepping cadence of 80 steps/minute with verbal cues and encouragement. Peak oxygen consumption was assessed by the attainment of 1) a plateau in VO_2 despite increase in exercise load, 2) RPE >17, and/or 3) respiratory exchange ratio ≥ 1.15.

Walking Speed—Self-selected OGWS was assessed using a GAITRite® portable gait analysis system (CIR Systems Inc. / GAITRite, Sparta, NJ). Participants were fitted with a support vest connected to a passive overhead harness as a safety precaution and were instructed to walk at their comfortable walking speed across the walkway. The use of assistive devices and bracing was only permitted as absolutely necessary (i.e. participants were unable to safely walk without them), and maintained for each test for the duration of the study. Trained personnel walked beside the participants if requested or needed to maintain safety. Four trials were completed at each testing point and the average OGWS recorded.

Walking Related Outcomes—Guided by published recommendations,(35) a number of outcomes were selected to complete a comprehensive assessment of ambulation. The selected outcomes included: walking economy, 6MWT, daily step counts, WISCI-II, DGI, and BBS.

Participants completed a five-minute walking assessment at self-selected speed on a treadmill to assess walking economy. To determine self-selected speed, the treadmill speed was incrementally increased until the participant indicated their comfortable, usual walking speed. Participants completed the post-testing assessment at matched pre-speed. While walking on the treadmill, participants were connected to a passive overhead harness, in place

as a safety precaution only; no body weight support was provided. Oxygen uptake was measured using a metabolic cart. The VO_2 (mL O_2/kg/min) data collected during the last minute of walking test was averaged and normalized by self-selected walking speed to determine walking economy (mL O_2/kg/m). The percentage of VO_{2peak} utilized while walking at self-selected speed (i.e. the relative cost of walking) was also calculated from the VO_2 values obtained.

All participants completed a self-paced six-minute walking assessment (6MWT) in a hallway to assess submaximal levels of functional capacity (i.e. walking endurance). Total distance walked (meters, m) was recorded. The 6MWT is a valid and reliable test commonly used to test walking ability in the incomplete SCI population.(36, 37)

As a participation-level measure, individuals that reported walking as their primary mode of locomotion wore a StepWatch™ 3.0 Step Activity Monitor (SAM), (Orthocare Innovations, Mountlake Terrace, WA) on their dominant, or less affected, ankle to record daily step counts outside of the intervention. Previous studies have shown the SAM accurately and reliably captures walking activity in individuals with incomplete SCI.(38, 39) Following procedures described by Bowden et al.,(39) the settings of each device were manually specified to customize the SAM for each participant at each time point. Participants wore the SAM for four days and step counts were averaged and presented as steps per day.

Lastly, three standardized clinical rehabilitation assessments were completed by a licensed physical therapist. The WISCI-II, a 21-level ordinal scale that assesses degrees of assistance used to walk, is a valid and reliable measure of walking function in individuals with incomplete SCI.(40) The DGI is an 8-item measure that evaluates an individual's capacity to modify walking under different situations and dual tasks that are commonly encountered in daily life. Although commonly used in clinical rehabilitation and research settings to examine gait and balance, the psychometric properties of this measure have not been thoroughly examined after SCI. The BBS is a 14-item instrument that assesses static and dynamic balance abilities as well as fall risk; it is a valid and reliable measure for assessing balance after SCI.(41, 42)

Statistical Analysis

Tests for normality (Shapiro-Wilk test) were completed prior to performing the analyses. Paired-sample t-tests or the non-parametric equivalent, Wilcoxon matched-pairs signed ranks test, were used to assess pre to post-test changes in the outcomes. A significance level of alpha=0.05 was used for all analyses. Effect sizes from the paired-samples t-tests are reported as Cohen's d, $d = M_1 - M_2 / SD_{pooled}$. Effect sizes for the outcomes requiring nonparametric statistics are reported as r, $r = z/\sqrt{N}$. An intention to treat analysis was performed to include all data from the participants who began the AET. Data were analyzed using IBM® SPSS® Statistics Version 22 (IBM Corporation).

Results

Ten adults ages 42 to 72 years old with chronic (10 months to 33 years post injury) motor-incomplete SCI (AIS C, D) participated in the AET intervention. All of the individuals were

ambulatory, however two participants were not primary ambulators and predominantly used a manual wheelchair for daily mobility. Demographic characteristics are presented in Table 1. Baseline participant characteristics and changes in the primary outcomes are presented in Table 2. Of the ten participants who enrolled, nine completed all training visits. One participant withdrew from the study after three weeks of training due to issues related to transportation and chronic pain; the last observation was carried forward. All testing and exercise training was safely completed, and the AET intervention (intensity, progression, duration) was feasible.

Primary and secondary outcomes are described below, with summary results presented in Table 3.

Primary Outcome Measures

Aerobic Capacity—Baseline VO_{2peak} values were 20.90 ± 5.54 mL O_2/kg/min. As hypothesized, following the AET VO_{2peak} significantly increased to 23.86 ± 4.49 mL O_2/kg/min (p=0.01), indicating a large effect (d=1.01). The individual changes in VO_{2peak} ranged from −6.2% to 54.6%, with an average of 17% (Table 2). One participant requested early termination of the post-testing VO_{2peak} assessment due to a flare-up in chronic shoulder pain, thus a negative change was recorded. The mean change in aerobic capacity following AET represents a 14% increase (Table 3).

OGWS—Statistically and clinically significant improvements were found in self-selected OGWS. After AET, participants walked an average 0.06 ± 0.07 m/s faster than at baseline (p=0.02; d=0.86). The individual improvements in self-selected OGWS ranged from −5.5% to 33.3%, with an average of 13% (Table 2). The change in mean OGWS represents a 9% increase in self-selected walking speed (Table 3).

Secondary Outcome Measures

Walking Related Outcomes—Changes in two of the secondary outcomes, percentage of VO_{2peak} at which participants were walking and daily step counts, were statistically significant (Table 3).

Nine participants completed the assessments to determine oxygen consumption at self-selected walking speeds; one participant was unable to walk comfortably on the treadmill and therefore did not complete the test. At pre-testing, average walking economy was 0.75 ± 0.31 mL O_2/kg/m (range: 0.47 to 1.45 mL O_2/kg/m). There was no significant change following training (post = 0.73 ± 0.34 mL O_2/kg/m; range: 0.32 to 1.44 mL O_2/kg/m). However, there was a significant change in the relative cost of walking. At pre-testing, participants walked at an average 62% of VO_{2peak} (range: 51% to 87%). Following training, participants walked at 54% of VO_{2peak} (range: 38% to 65%), which represents a significant reduction (p=0.03. d=0.87) in the percentage of aerobic capacity utilized while walking at self-selected walking speeds.

There was no significant change in the distance walked during the 6MWT, nor did the change meet the previously reported minimal detectable change (45.8 meters or a 22% change).(43) Only one participant was able to exceed the MDC for the 6MWT. Additionally,

although trends towards improvement were seen in the BBS and DGI, there were no statistically significant changes in the walking-related clinical rehabilitation tests. WISCI-II scores did not change.

Following training, there was a significant increase in daily step counts for the eight primary ambulators (916 ± 1410 steps/day; p=0.025, r=*0.56*). Data from the two participants who were primary wheelchair users is not available. One participant did not adhere to wearing the SAM as instructed at baseline and later withdrew from the study. The other participant only walked under supervision with an assistive device in our lab; they elected not to wear the SAM. At baseline, participants walked 5050 ± 1247 steps per day outside of the lab (range: 2612 to 6573 steps/day). After the intervention, the total number of steps taken increased (5967 ± 2174 steps/day; range: 2812 to 10281 steps/day), indicating an average 23% increase in walking activity in the free-living environment.

Discussion

As hypothesized, the results of this study indicate that AET was effective for improving both aerobic capacity and walking outcomes in a sample of ambulatory adults with incomplete SCI. The findings add to the limited body of evidence supporting exercise training in this subpopulation of SCI.

The present findings indicate that aerobic capacity is reduced in these individuals, though not as drastically as previously reported in other SCI subpopulations. Examining aerobic capacity according to recently published reference values for untrained individuals with SCI,(4) on average participants fell within the “excellent” fitness category (>15.2 mL O_2/kg/min). It is important to point out that the SCI reference values were developed based on data obtained from a sample of primary wheelchair users with primarily complete injuries while performing upper extremity exercise. Thus, it is likely that these reference values are not appropriate for classifying fitness levels in the current sample. Conversely, compared to gender and age specific normative percentile rankings, our participants fell in the “well below average” (10^{th} percentile) fitness category, except for one participant who was “below average” (20^{th} percentile).(1) This finding calls into question the applicability of either of these reference values for interpreting fitness in the ambulatory SCI population and highlights a need to extend previous research and develop stratified reference values of fitness for men and women with incomplete injuries who are ambulatory.

Exercise training has long been recommended to improve aerobic capacity in individuals with SCI, but this was the first investigation to demonstrate improvements in fitness levels in ambulatory adults with incomplete SCI following a voluntary, total-body recumbent stepping AET program. Despite the relatively short (six-week) duration, VO_{2peak} significantly increased 14%, which is within the generally expected range of training-induced increase (5%-30%),(1) and slightly lower than that recently reported following a 16-week guideline driven exercise intervention in the SCI population (17% increase).(44) It is reasonable to believe that extending the duration of AET may result in greater improvements in aerobic capacity. Additionally, increasing the training stimulus either by total minutes/day or days/week, would likely result in an increased training effect. Future research should

explore exercise dosage and further evaluate the effectiveness of voluntary, guideline driven AET in the ambulatory SCI population.

Following the AET, both statistically and clinically significant improvements were observed in OGWS. Self-selected speeds increased by an average of 0.06 m/s (9%) after the six-week intervention, meeting the estimated minimally clinically important difference (MCID) for walking speed after incomplete SCI (0.05 m/s).(45) Five of the ten participants met or exceeded the MCID for OGWS. Further investigation is necessary to identify participant characteristics (eg initial walking function, age, fitness level) that may influence changes in walking outcomes following AET. Although larger changes in walking speed have been reported following non-task specific exercise interventions of longer duration, including FES leg cycling(25, 26) and lower extremity resistance training,(46, 47) statistically significant findings are limited. Following a 10-week progressive FES cycling case study, an improvement of 0.33 m/s was reported.(25) In a more recent study, Yasar et al. documented a 0.13m/s increase in walking speed following a 16-week FES cycling intervention, but the results were not significant.(26) Although there are number of benefits associated with FES exercise, we believe voluntary exercise may hold more promise for individuals with SCI who are able to walk. Voluntary, non-task specific exercise in the form of lower extremity resistance training has been shown to improve walking outcomes in ambulatory adults with SCI. Gregory et al. reported dramatic improvements in self-selected (0.26m/s) and fastest-comfortable (0.39m/s) walking speed following 12 weeks of lower extremity resistance training.(46) Recently, more modest changes in preferred and maximal walking speed were reported following 4 weeks of resistance training (0.06 and 0.14m/s, respectively).(47) Importantly, the benefits of non-task specific training were supported, as the study found that maximal walking speed improved significantly more following non-task specific lower extremity resistance training compared to task-specific robot assisted gait training.(47) The findings from these studies, in conjunction with the significant findings from our study, support the benefits of voluntary, non-task specific exercise training for rehabilitation of walking outcomes in ambulatory adults with SCI.

Early studies of the energy cost of locomotion indicate that walking after SCI is a physiologically demanding task, which is supported in our sample. The average walking economy of the participants was within the range previously reported after SCI (0.26 to 1.02 $mLO_2/kg/m$) and was roughly 4 to 5 times greater than that reported in the general population (0.15 to 0.17 $mLO_2/kg/m$).(48-50) Elevated walking economy may be due to increased oxygen consumption or slow walking speed.(50) In the case of our participants, the poor walking economy is likely attributed primarily to slow self-selected walking speeds (0.60 m/s) compared to normal (1.0-1.67 m/s), as oxygen consumption was only slightly elevated (13.1 mL $O_2/kg/min$) compared to that reported in the general population (12.0 mL $O_2/kg/min$).(50) Further evaluation of oxygen consumption during the walking trial indicated that walking at self-selected speed requires a substantial percentage of peak aerobic capacity and is more physically demanding than in the able-bodied population. In the neurologically healthy population, walking is not a significantly taxing activity; reports suggest that while walking at a usual pace, oxygen consumption is generally around 30-40% of maximal VO_2 values.(51-53) At baseline, the participants in our study walked at 62% (range: 50% to 87%) of their VO_{2peak}. The high relative cost results from a combination of

low VO_{2peak} and elevated oxygen consumption during walking. With training, the average percentage of VO_{2peak} at which the participants were walking was significantly reduced to 54%. It is reasonable to believe that the high relative cost of walking may play a role in limiting walking outcomes after SCI. Therefore, increasing aerobic capacity with AET may compensate for the increased cost of walking and improve functional capacity in ambulatory individuals with SCI.

The AET intervention also resulted in a significant improvement in daily step counts, indicative of increased daily activity and participation in the free-living environment. Despite the high relative cost of walking and slow walking speeds, the participants maintained a higher than average activity level. On average, the participants who were primary ambulators far exceeded the step counts previously reported in the incomplete SCI population.(38) Averaging 5,050 steps/day at baseline and 5,967 steps/day at post-testing, the primary ambulators in this sample fell within the normative step ranges for special populations (1,200-8,800 steps/day),(54) and were above the generally accepted threshold for sedentary lifestyles (<5,000 steps).(55) It is important to note that 40% of the participants did not use any assistive devices to walk, and only 20% used a bilateral assistive device, thus the step counts of our sample may not be representative of the population of ambulatory individuals with incomplete SCI. We acknowledge that the use of assistive devices may have influenced step counts, and that the lack of additional data surrounding the daily step activity (i.e. reports on special events, pain, fatigue, or sickness that may have influenced step counts) limits our understanding of this outcome.

At baseline the majority of participants did not engage in any exercise, and most reported a sedentary lifestyle despite the relatively high number of steps taken. After the intervention, in addition to meeting the aerobic exercise guidelines, participants also increased their daily step counts. It is reasonable to hypothesize that the increase in physical activity in addition to increased walking activity in the free-living environment will result in a compounding of health benefits extending beyond the outcomes measured. In the least, changes in free-living physical activity may initiate a perpetual positive cycle whereby increasing fitness decreases the relative cost of walking, resulting in increased activity, thus leading to improved walking function, and may result in greater participation in the community.

Taken together, these results suggest the potential for an non-task specific, voluntary, total-body AET approach to improve fitness and walking related outcomes in ambulatory individuals with chronic incomplete SCI. Based on the findings, we recommend AET on a recumbent stepper as a feasible alternative or adjuvant to current interventions aimed at improving walking outcomes in ambulatory individuals with incomplete SCI. Compared to other modalities such as locomotor training and robotic-assisted gait training, AET on a recumbent stepper requires fewer personnel, utilizes less expensive equipment, and may be more time efficient, thus increasing the benefits of this option. Further, aerobic exercise is widely accessible and may be more easily translated from the lab to community recreation centers, fitness facilities, or home gyms. Most importantly, aerobic exercise can be successfully completed through all stages of one's life, and is known to elicit more than just beneficial changes in fitness and walking outcomes, making AET an attractive option to recommend following SCI.

Limitations

The results of the present study are promising, but several limitations must be addressed when interpreting the findings from this small sample size, non-randomized study. Importantly, the participants were self-selected volunteers, who may be more functional and more motivated to exercise than the general incomplete SCI population. The inclusion criteria for our study limit the interpretation of findings to individuals with chronic incomplete SCI who are able to walk. The lack of an adequate control group is also a limitation. The primary outcome, change in aerobic capacity, was assessed on the NuStep® using a protocol that has not yet been validated for use in SCI. Although this protocol appears to be feasible and well tolerated by the participants, the nature of the total-body graded exercise test makes it difficult to compare the aerobic capacity results to previous results. Future research is necessary to validate the use of this exercise protocol for use in individuals with SCI. We do not have adequate follow-up data to determine if an exercise regimen was maintained following the AET, nor can we determine if the gains observed following AET were maintained.

Conclusions

The AET intervention was safe, feasible and effective. Following six weeks of voluntary, total-body aerobic exercise performed at a moderate-vigorous intensity, meaningful functional improvements in fitness and walking related outcomes were observed. The major finding of the study is that both aerobic capacity and OGWS significantly increased. Further study with a larger sample is necessary to examine correlations between fitness and walking speed and determine if aerobic capacity is a determinant of walking after SCI. Statistical improvements were also observed in outcomes relating to walking function, including the percentage of VO_{2peak} at which participants walk and daily step counts. Although no significant improvements were observed in the remaining walking related outcomes, the results indicate moderate to large effects for these outcomes. Overall, the findings warrant future investigation in a larger cohort, with an adequate control group as well as comparisons to other established exercise interventions (eg resistance training, FES cycling). There is a need for further research into the role of non-task specific AET for improving fitness and walking outcomes in individuals with varying degrees of ambulatory impairment. In addition, there is a need to study the effects of implementing voluntary AET earlier after injury, in attempts to attenuate the effects of physical inactivity on deconditioning and functional limitations. Such investigations could shed light on individual characteristics that influence changes in fitness and walking outcomes to better inform rehabilitation researchers and practitioners.

Acknowledgements

This work was supported by the South Carolina Clinical & Translational Research (SCTR) Institute, with an academic home at the Medical University of South Carolina, through NIH Grant Number UL1 TR000062 and TL1 TR000061. Additional support was provided by the South Carolina Spinal Cord Injury Research Fund (Grant # 13-003) and the South Carolina Spinal Cord Injury Association.

We would like to thank the staff Physical Therapist, Dr. Lindsay Perry, and the project coordinators, Patrick Morgan and Katy Holthaus for their assistance with study management and data collection.

References

1. ACSM. ACSM's Guidelines for Exercise Testing and Prescription. 9ed. Wolters Kluwer / Lippincott Williams & Wilkins; 2013. p. 480
2. Dearwater SR, LaPorte RE, Robertson RJ, Brenes G, Adams LL, Becker D. Activity in the spinal cord-injured patient: an epidemiologic analysis of metabolic parameters. Medicine and science in sports and exercise. 1986; 18(5):541–4. [PubMed: 3534508]
3. Janssen TW, Dallmeijer AJ, Veeger DJ, van der Woude LH. Normative values and determinants of physical capacity in individuals with spinal cord injury. J Rehabil Res Dev. 2002; 39(1):29–39. [PubMed: 11930906]
4. Simmons OL, Kressler J, Nash MS. Reference Fitness Values in the Untrained Spinal Cord Injury Population. Archives of physical medicine and rehabilitation. 2014
5. Ginis KAM, Jorgensen S, Stapleton J. Exercise and sport for persons with spinal cord injury. PM & R : the journal of injury, function, and rehabilitation. 2012; 4(11):894–900.
6. Hicks AL, Martin Ginis KA, Pelletier CA, Ditor DS, Foulon B, Wolfe DL. The effects of exercise training on physical capacity, strength, body composition and functional performance among adults with spinal cord injury: a systematic review. Spinal Cord. 2011; 49(11):1103–27. [PubMed: 21647163]
7. Jacobs PL, Nash MS. Exercise recommendations for individuals with spinal cord injury. Sports medicine. 2004; 34(11):727–51. [PubMed: 15456347]
8. Warburton DE, Eng JJ, Krassioukov A, Sproule S, the SRT. Cardiovascular Health and Exercise Rehabilitation in Spinal Cord Injury. Topics in spinal cord injury rehabilitation. 2007; 13(1):98–122. [PubMed: 22719205]
9. Barbeau H, Nadeau S, Garneau C. Physical determinants, emerging concepts, and training approaches in gait of individuals with spinal cord injury. J Neurotrauma. 2006; 23(3-4):571–85. [PubMed: 16629638]
10. Pilutti LA, Hicks AL. Rehabilitation of ambulatory limitations. Physical medicine and rehabilitation clinics of North America. 2013; 24(2):277–90. [PubMed: 23598263]
11. Michael KM, Allen JK, Macko RF. Reduced ambulatory activity after stroke: the role of balance, gait, and cardiovascular fitness. Archives of physical medicine and rehabilitation. 2005; 86(8): 1552–6. [PubMed: 16084807]
12. Patterson SL, Forrester LW, Rodgers MM, Ryan AS, Ivey FM, Sorkin JD, et al. Determinants of walking function after stroke: differences by deficit severity. Archives of physical medicine and rehabilitation. 2007; 88(1):115–9. [PubMed: 17207686]
13. Courbon A, Calmels P, Roche F, Ramas J, Rimaud D, Fayolle-Minon I. Relationship between maximal exercise capacity and walking capacity in adult hemiplegic stroke patients. Am J Phys Med Rehabil. 2006; 85(5):436–42. [PubMed: 16628151]
14. Severinsen K, Jakobsen JK, Overgaard K, Andersen H. Normalized muscle strength, aerobic capacity, and walking performance in chronic stroke: a population-based study on the potential for endurance and resistance training. Archives of physical medicine and rehabilitation. 2011; 92(10): 1663–8. [PubMed: 21872846]
15. Stoller O, de Bruin ED, Knols RH, Hunt KJ. Effects of cardiovascular exercise early after stroke: systematic review and meta-analysis. BMC Neurol. 2012; 12:45. [PubMed: 22727172]
16. Saunders DH, Sanderson M, Brazzelli M, Greig CA, Mead GE. Physical fitness training for stroke patients. Cochrane Database Syst Rev. 2013; 10:CD003316. [PubMed: 24142492]
17. Snook EM, Motl RW. Effect of exercise training on walking mobility in multiple sclerosis: a meta-analysis. Neurorehabil Neural Repair. 2009; 23(2):108–16. [PubMed: 18948413]
18. Pearson M, Dieberg G, Smart N. Exercise as a Therapy for Improvement of Walking Ability in Adults With Multiple Sclerosis: A Meta-Analysis. Archives of physical medicine and rehabilitation. 2015
19. Latimer-Cheung AE, Pilutti LA, Hicks AL, Martin Ginis KA, Fenuta AM, MacKibbon KA, et al. Effects of exercise training on fitness, mobility, fatigue, and health-related quality of life among adults with multiple sclerosis: a systematic review to inform guideline development. Archives of physical medicine and rehabilitation. 2013; 94(9):1800–28. e3. [PubMed: 23669008]

20. Kressler J, Nash MS, Burns PA, Field-Fote EC. Metabolic responses to 4 different body weight-supported locomotor training approaches in persons with incomplete spinal cord injury. Archives of physical medicine and rehabilitation. 2013; 94(8):1436–42. [PubMed: 23473703]
21. Alexeeva N, Sames C, Jacobs PL, Hobday L, Distasio MM, Mitchell SA, et al. Comparison of training methods to improve walking in persons with chronic spinal cord injury: a randomized clinical trial. J Spinal Cord Med. 2011; 34(4):362–79. [PubMed: 21903010]
22. Hoekstra F, van Nunen MP, Gerrits KH, Stolwijk-Swuste JM, Crins MH, Janssen TW. Effect of robotic gait training on cardiorespiratory system in incomplete spinal cord injury. J Rehabil Res Dev. 2013; 50(10):1411–22. [PubMed: 24699976]
23. Hettinga DM, Andrews BJ. Oxygen consumption during functional electrical stimulation-assisted exercise in persons with spinal cord injury: implications for fitness and health. Sports Med. 2008; 38(10):825–38. [PubMed: 18803435]
24. Davis GM, Hamzaid NA, Fornusek C. Cardiorespiratory, metabolic, and biomechanical responses during functional electrical stimulation leg exercise: health and fitness benefits. Artif Organs. 2008; 32(8):625–9. [PubMed: 18782133]
25. Page SJ, Levine P, Strayer J. An electric stimulation cycling protocol for gait in incomplete spinal cord injury. Archives of physical medicine and rehabilitation. 2007; 88(6):798–800. [PubMed: 17532906]
26. Yasar E, Yilmaz B, Goktepe S, Kesikburun S. The effect of functional electrical stimulation cycling on late functional improvement in patients with chronic incomplete spinal cord injury. Spinal Cord. 2015
27. Stoloff RH, Zehr EP, Ferris DP. Recumbent stepping has similar but simpler neural control compared to walking. Experimental brain research Experimentelle Hirnforschung Experimentation cerebrale. 2007; 178(4):427–38. [PubMed: 17072607]
28. Hass CJ, Garzarella L, de Hoyos DV, Connaughton DP, Pollock ML. Concurrent improvements in cardiorespiratory and muscle fitness in response to total body recumbent stepping in humans. European journal of applied physiology. 2001; 85(1-2):157–63. [PubMed: 11513310]
29. Billinger SA, Mattlage AE, Ashenden AL, Lentz AA, Harter G, Rippee MA. Aerobic exercise in subacute stroke improves cardiovascular health and physical performance. J Neurol Phys Ther. 2012; 36(4):159–65. [PubMed: 23111686]
30. Ginis KA, Hicks AL, Latimer AE, Warburton DE, Bourne C, Ditor DS, et al. The development of evidence-informed physical activity guidelines for adults with spinal cord injury. Spinal Cord. 2011; 49(11):1088–96. [PubMed: 21647164]
31. US Department of Health and Human Services. Physical Activity Guidelines for Americans. 2008. p. 2008http://www.health.gov/PAGuidelines
32. WHO. Towards a Common Language for Functioning, Disability, and Health: ICF. World Health Organization; Geneva, Switzerland: 2002.
33. Billinger SA, Tseng BY, Kluding PM. Modified total-body recumbent stepper exercise test for assessing peak oxygen consumption in people with chronic stroke. Physical therapy. 2008; 88(10): 1188–95. [PubMed: 18772275]
34. Billinger SA, Loudon JK, Gajewski BJ. Validity of a total body recumbent stepper exercise test to assess cardiorespiratory fitness. Journal of strength and conditioning research / National Strength & Conditioning Association. 2008; 22(5):1556–62. [PubMed: 18714232]
35. Alexander MS, Anderson KD, Biering-Sorensen F, Blight AR, Brannon R, Bryce TN, et al. Outcome measures in spinal cord injury: recent assessments and recommendations for future directions. Spinal Cord. 2009; 47(8):582–91. [PubMed: 19381157]
36. Scivoletto G, Tamburella F, Laurenza L, Foti C, Ditunno JF, Molinari M. Validity and reliability of the 10-m walk test and the 6-min walk test in spinal cord injury patients. Spinal Cord. 2011; 49(6): 736–40. [PubMed: 21221120]
37. van Hedel HJ, Wirz M, Dietz V. Assessing walking ability in subjects with spinal cord injury: validity and reliability of 3 walking tests. Archives of physical medicine and rehabilitation. 2005; 86(2):190–6. [PubMed: 15706542]

38. Ishikawa S, Stevens SL, Kang M, Morgan DW. Reliability of daily step activity monitoring in adults with incomplete spinal cord injury. J Rehabil Res Dev. 2011; 48(10):1187–94. [PubMed: 22234663]
39. Bowden MG, Behrman AL. Step Activity Monitor: accuracy and test-retest reliability in persons with incomplete spinal cord injury. J Rehabil Res Dev. 2007; 44(3):355–62. [PubMed: 18247232]
40. Ditunno JF Jr. Ditunno PL, Scivoletto G, Patrick M, Dijkers M, Barbeau H, et al. The Walking Index for Spinal Cord Injury (WISCI/WISCI II): nature, metric properties, use and misuse. Spinal Cord. 2013; 51(5):346–55. [PubMed: 23459122]
41. Wirz M, Muller R, Bastiaenen C. Falls in persons with spinal cord injury: validity and reliability of the Berg Balance Scale. Neurorehabil Neural Repair. 2010; 24(1):70–7. [PubMed: 19675123]
42. Lemay JF, Nadeau S. Standing balance assessment in ASIA D paraplegic and tetraplegic participants: concurrent validity of the Berg Balance Scale. Spinal Cord. 2010; 48(3):245–50. [PubMed: 19773797]
43. Lam T, Noonan VK, Eng JJ, Team SR. A systematic review of functional ambulation outcome measures in spinal cord injury. Spinal Cord. 2008; 46(4):246–54. [PubMed: 17923844]
44. Pelletier CA, Totosy de Zepetnek JO, MacDonald MJ, Hicks AL. A 16-week randomized controlled trial evaluating the physical activity guidelines for adults with spinal cord injury. Spinal Cord. 2014
45. Musselman K. Clinical significance testing in rehabilitation research: what, why, and how? . Physical Therapy Reviews. 2007; 12(4):287–96.
46. Gregory CM, Bowden MG, Jayaraman A, Shah P, Behrman A, Kautz SA, et al. Resistance training and locomotor recovery after incomplete spinal cord injury: a case series. Spinal Cord. 2007; 45(7):522–30. [PubMed: 17228358]
47. Labruyere R, van Hedel HJ. Strength training versus robot-assisted gait training after incomplete spinal cord injury: a randomized pilot study in patients depending on walking assistance. J Neuroeng Rehabil. 2014; 11:4. [PubMed: 24401143]
48. Waters RL, Lunsford BR. Energy cost of paraplegic locomotion. The Journal of bone and joint surgery American volume. 1985; 67(8):1245–50. [PubMed: 4055849]
49. Waters RL, Yakura JS, Adkins RH. Gait performance after spinal cord injury. Clin Orthop Relat Res. 1993; (288):87–96. [PubMed: 8458158]
50. Waters RL, Mulroy S. The energy expenditure of normal and pathologic gait. Gait & posture. 1999; 9(3):207–31. [PubMed: 10575082]
51. Blessey RL, Hislop HJ, Waters RL, Antonelli D. Metabolic energy cost of unrestrained walking. Physical therapy. 1976; 56(9):1019–24. [PubMed: 959328]
52. Waters RL, Hislop HJ, Perry J, Thomas L, Campbell J. Comparative cost of walking in young and old adults. Journal of orthopaedic research : official publication of the Orthopaedic Research Society. 1983; 1(1):73–6. [PubMed: 6679578]
53. Waters RL, Lunsford BR, Perry J, Byrd R. Energy-speed relationship of walking: standard tables. Journal of orthopaedic research : official publication of the Orthopaedic Research Society. 1988; 6(2):215–22. [PubMed: 3343627]
54. Tudor-Locke C, Craig CL, Aoyagi Y, Bell RC, Croteau KA, De Bourdeaudhuij I, et al. How many steps/day are enough? For older adults and special populations. The international journal of behavioral nutrition and physical activity. 2011; 8:80. [PubMed: 21798044]
55. Tudor-Locke C, Craig CL, Brown WJ, Clemes SA, De Cocker K, Giles-Corti B, et al. How many steps/day are enough? For adults. The international journal of behavioral nutrition and physical activity. 2011; 8:79. [PubMed: 21798015]

Table 1

Sample Characteristics (N=10).

	N or Mean (SD) **N=10**
Demographics	
Gender	
Male	5
Female	5
Age (years)	57.9 (9.3)
Race/Ethnicity	
White	6
Black/African American	3
Hispanic/Latino	1
Injury Related Characteristics	
Etiology of Injury	
Fall	5
Motor vehicle accident	1
Vascular	1
Gun shot wound	1
Construction related	2
Time since injury (years)	11.1 (9.6)
AIS	
C	1
D	9
ASIA Motor Score	85.9 (8.4)
LEMS	42.1 (4.9)
Injury Level	
Cervical	9
Thoracic	1
Ambulatory Characteristics	
Mobility Aids Used for Walking	
None	4
Walker (two wheeled, rolling)	1
Cane	4
Crutches (bilateral axillary)	1
Orthotic Use	
None	8
Ankle-foot orthosis	1
Knee brace	1

AIS= American Spinal Injury Association Impairment Scale; ASIA= American Spinal Injury Association; LEMS= Lower extremity motor score

Table 2

Baseline Participant Characteristics and Change in Primary Outcomes following AET.

Participant	Age	TSI (years)	Level of Injury	AIS	LEMS	Primary Ambulator	Mobility Aid/Orthotic Device	Walking Speed (m/s)			VO_{2peak} (mLO2/kg/min)		
								PRE	POST	% Change	PRE	POST	% Change
1	55	5	C2	D	46	Yes	None	0.99	1.01	2	18.8	23.07	23
2	67	16	C4	D	46	Yes	None	0.96	1.03*	7	20.16	24.24	20
3	54	3	C4	C	43	Yes	None	0.44	0.49*	11	26.16	32.52	24
4	62	6	C2	D	46	Yes	None	0.82	0.84	2	17.58	19.85	13
5	72	33	C3	D	47	Yes	SPC, AFO	0.54	0.51	−6	23.5	24.03	2
6	49	18	C3	D	36	Yes	BAC	0.37	0.46*	24	28.84	27.04	−6
7	42	6	C8	D	37	No	MW, SPC, Brace	0.55	0.65*	18	28.33	28.33	0
8	55	0.9	T9	D	33	No	MW, Walker	0.06	0.08	33	13.56	17.23	27
9	52	11	C7	D	44	Yes	SPC	0.98	1.01	3	14.23	22	55
10	67	8	C5	D	43	Yes	SPC	0.66	0.88*	33	17.86	20.33	14

TSI= Time since injury; AIS= ASIA Impairment Scale; LEMS= Lower extremity motor score; AFO= ankle foot orthotic; SPC= single point cane; MW=manual wheelchair; BAC= bilateral axillary crutches.

* Meets or exceeds MCID (0.05m/s) for overground walking speed

Table 3

Effects of AET on fitness and walking related outcomes.

	Pre Mean (SD)	Post Mean (SD)	% change	*P*	Effect Size (*d* or r)
	(N=10, unless otherwise noted)				
VO_{2peak} (mL O_2/kg/min)	20.90 (5.54)	23.86 (4.49)	14	0.01	1.01
OGWS (m/s)	0.64 (0.31)	0.70 (0.31)	9	0.02	0.86
Economy (mL O_2/kg/m)[a]	0.75 (0.31)	0.73 (0.34)	−3	0.39	0.3
Walking at % VO_{2peak} [a]	62.03 (11.87)	54.10 (7.80)	−13	0.03	0.87
6MWT (m)[b]	259 (114)	273 (117)	5	0.37	0.2
Daily Step Count [b, c]	5051 (1248)	5967 (2174)	18	0.03	0.56
WISCI (0-20)	17.70 (2.67)	17.70 (2.67)		no change	
DGI (0-24)[b]	14.6 (4.55)	15.20 (5.05)	4	0.73	0.08
BBS (0-56)	41.3 (13.42)	43.00 (14.88)	4	0.15	0.5

[a] n=9; One subject did not complete walking test on treadmill.

[b] Non-parametric analyses: Wilcoxon Matched-Pairs Signed Ranks Test; effect size=r

[c] n=8; Two subjects were not primary ambulators and did not wear a SAM.