Strength and Step Activity After Eccentric Resistance Training in Those With Incomplete Spinal Cord Injuries

Whitley J. Stone, PhD,[1] *Sandra L. Stevens, PhD,*[2] *Dana K. Fuller, PhD,*[3] *and Jennifer L. Caputo, PhD*[2]

[1]*School of Nutrition, Kinesiology, and Psychological Science, University of Central Missouri, Warrensburg, Missouri;* [2]*Department of Health and Human Performance,* [3]*Department of Psychology, Middle Tennessee State University, Murfreesboro, Tennessee*

Background: Individuals with spinal cord injuries (SCIs) often experience general weakness in the lower extremities that undermines daily step activity. **Objective:** To investigate the efficacy of eccentrically biased resistance training on lower extremity strength and physical activity of individuals with spinal injuries. **Methods:** Individuals with long-standing incomplete SCIs (N = 11) capable of completing a 10-meter walk assessment were included. All participants who completed the familiarization period finished the training. Individuals trained two times per week for 12 weeks on a lower body eccentric resistance training machine. It was hypothesized that the outcome variables (eccentric strength, isometric strength, and daily step physical activity) would improve as a result of the training intervention. **Results**: Eccentric strength [F(1.27, 12.71) = 8.42, MSE = 1738.35, H-F p = .009] and isometric strength [F(1.97, 19.77) = 7.10, MSE = 11.29, H-F p = .005] improved as a result of the training while daily step activity remained unchanged [F(2.00, 18.00) = 2.73, MSE = 216,836.78, H-F p = .092]. **Conclusions:** Eccentric resistance training improves eccentric and isometric strength. These physiological adaptations may translate to improved gait mechanics, but further study is required to identify this potential crossover effect. **Key words**: *exercise, lower limbs, paraplegia, spinal, weight lifting*

Incomplete spinal cord injury (iSCI) can interrupt communication between higher level brain centers and sensory-motor neurons and skeletal muscle.[1] Individuals with an iSCI experience diminished neurological and muscle function below the lesion.[2] Following denervation, skeletal muscle transitions to a predominantly anaerobic fiber arrangement, further degrading oxidative function.[3] With aerobic capacity averaging below the fifth percentile of individuals without SCI,[4] focused efforts are necessary to offset the spiraling effects of the often-sedentary lifestyle following iSCI. Much like in the able-bodied population, it is recommended that individuals with iSCI participate in regular physical activity (PA) throughout the week, including activities that develop cardiorespiratory and musculoskeletal health.[5] Contemporary physical activity recommendations advise individuals post iSCI to partake in a minimum of three sets of strengthening activities in working muscle groups.[5] Although these new recommendations are advantageous for those post iSCI, impaired neuromuscular function may limit the loading capacity and active range of motion of the affected limbs when performing a traditional eccentric and concentric repetition.

Focus should be given to improving muscle strength after iSCI based on the strong positive correlation between walking performance and strength of hip flexors, extensors, and abductors, respectively.[6] Eccentric resistance training (ERT) involves muscle actions only during the lowering, or eccentric, portion of a repetition. When compared to concentric muscle work, eccentric muscle actions have a lower metabolic demand, allow for greater force production, and lead to greater improvements in neural activation and strength.[7] There are four known modalities for ERT: (1) the participant eccentrically lowers a weight and a bystander performs the concentric portion of the repetition by returning the load

Corresponding author: Whitley J. Stone, PhD, Assistant Professor, School of Nutrition, Kinesiology, and Psychological Science, University of Central Missouri, Morrow 146, Warrensburg, MO 54093; phone: 660-543-4148; email: whstone@ucmo.edu

Top Spinal Cord Inj Rehabil 2018;24(4):343–352

www.thomasland.com
Published online ahead of print August 7, 2018
doi: 10.1310/sci17-00052

back to position, (2) the participant eccentrically resists the pedals spinning backwards of motor-driven cycle ergometers, (3) the participant performs unilateral training on an isokinetic dynamometer, or (4) the participant eccentrically resists the upward motion of the pedals on motor driven, recumbent stair steppers. The use of isokinetic stair steppers has improved balance, neurological function, coordination, and muscle architecture in older adults,[8-10] a population with similar muscle strength characteristics as those with iSCI (sarcopenia,[11] denervation, and decline in aerobic enzymes[12]). Further, training on a recumbent stair stepper may increase neurological adaptations because of the alternating neural activation necessary to perform ERT. Beyond this, eccentrically biased strengthening repetitions can be performed at greater volumes (sets, repetitions, resistances) than could be completed if the repetition also included a concentric phase. As such, individuals with impaired functional capacity (strength, coordination, range of motion) may benefit from an isokinetic device that requires eccentric neuromuscular coordination, delivers high volumes of work, and allows the individual to work autonomously.

Given the lack of information detailing the efficacy and safety of implementing lower body ERT after iSCI, the purpose of this study was to quantify changes in lower body eccentric and isometric strength following a 12-week ERT program on a recumbent stair stepping device. It was hypothesized that ERT for individuals with iSCI would increase eccentric strength, isometric strength, and step PA.

Methods

Participants

Apparently healthy males and females ($N = 11$) completed the ERT program. These individuals had cervical ($n = 6$), thoracic ($n = 4$), or lumbar ($n = 1$) iSCI for an average of 9.5 ± 4.7 years and were an average age of 39.1 ± 15.9 years. Exclusion criteria included musculoskeletal injury during or within 1 year of training and participation in other structured resistance training for the lower extremities. Participant characteristics are presented in **Tables 1** and **2**. This study was approved by the university Institutional Review Board, and participants signed a written consent form prior to the pretesting days.

Instrumentation

Anthropometric measurement and pain

Body mass was measured in gym clothing with shoes removed to the nearest tenth of a kilogram (Health o meter 753KL, McCook IL, or Seca 674,

Table 1. Participant descriptive statistics ($N = 11$)

Variable	*M*	*SD*
Height, cm	166.6	122.4
Weight, kg	76.0	21.9
Baseline walking speed, m/s	0.34	0.42
Baseline WISCI	8	7

Note: Walking speed assessed at baseline with a 10-meter walk test. WISCI = Walking Index for Spinal Cord Injury.

Table 2. Individual descriptive characteristics of study participants

Participant	Level of lesion	Years post injury	Mode of locomotion	WISCI
1	C5-6	10.3	Ambulation	9
2	T12-L1	8.6	Wheelchair	6
3	C3-7 & L4-5	5.2	Ambulation	19
4	T9-10	8.3	Wheelchair	6
5	T5-6	4.9	Wheelchair	2
6	T6	9.1	Wheelchair	9
7	C1-L5	4.9	Ambulation	10
8	C6-7	8.8	Wheelchair	2
9	C4-T3	8.9	Wheelchair	2
10	C5-6	20.5	Ambulation	20
11	L2	15.0	Wheelchair	2

Note: C = cervical; L = lumbar; T = thoracic; WISCI = score on baseline Walking Index for Spinal Cord Injury.

Hamburg, Germany). General lower extremity pain or soreness was assessed at the beginning of each day. Individuals marked a vertical line representing lower extremity pain or soreness on a 10-cm visual analog scale (VAS) where the left end of the scale equaled zero (*no pain*) and the right end of the scale equaled 10 (*pain as bad as it could possibly be*).[13] Initial pain measures on days 1 and 2 were averaged to establish a baseline for future comparisons. In the instance that pain or soreness increased more than 3 cm from baseline, training was postponed or any increase in training load was delayed until the next session.

Isometric strength

Isometric strength was assessed using a hand-held, digital dynamometer (JTech Commander PowerTrack II, Midvale, UT). The validity ($R^2 = .66$ to .76) and reliability ($r = .81$ to .93) of this dynamometer have been confirmed,[14] and the use of hand-held dynamometry is highly correlated with the gold standard isokinetic testing in those with neurological impairments.[15,16] Isometric strength was measured on both pretesting days, midway through the ERT, and after the ERT. The flexors and extensors of the knees and hip and plantar- and dorsiflexors were assessed based on their positive relationship with ambulation in individuals with frailty or neurological disorders.[17-20]

For hip extensor strength, the participant was supine on a cushioned table with one leg fully extended and the other flexed to 90° at the hip and knee joints. The investigators assisted the participant in holding this leg position to prevent muscular fatigue. Once hip and knee angles were established based on goniometry validation, the investigator placed the dynamometer's sensor immediately proximal to the knee. When ready, the participant used his or her hamstrings and gluteal muscles to press against the sensor in the investigator's hand for approximately 4 seconds, establishing a maximal voluntary contraction (MVC) for hip extension. After resting, the participant repeated this procedure until there was no improvement. The testing procedure was then repeated on the other limb. While in this position, the investigator moved the sensor to the anterior portion of the thigh, proximal to the knee to capture forces exerted during hip flexion. Next, the participant sat upright with both legs off the table, again, with the hips and knees at 90°. One at a time, the participant attempted to extend the shank with the quadriceps to obtain a knee extension MVC. The sensor was located directly above the ankle on the anterior portion of the shin. Testing was repeated on the contralateral leg. To assess knee flexion, the sensor was moved to the posterior portion of the shank directly above the calcaneus tendon. The sensor was then moved to the bottom of the foot and the participant was asked to plantarflex. For comparison, a single, summed isometric strength score (in newtons and relative to the participant's mass = N/kg) was created using the best recordings on day 2.

Eccentric strength

Eccentric strength testing was completed on a recumbent, motor-driven stepper (Eccentron, BTETech, Hanover, MD). The participant was seated in a chair that was adjusted so that when both feet were on the pedals one leg was extended (knee flexion between 45° and 55°) and the other was flexed (knee at approximately 90°). After familiarization and a 1-minute warm-up, participants were asked to allow the pedals to move through several repetitions without exerting force, allowing the investigators to determine resting tone (or involuntary resting muscular tension). After familiarization with the function of the machine and an eccentric warm-up, the participant completed two bilateral, three repetition maximum (RM) attempts (left leg, then the right leg, and so on[21]) at 12 revolutions per minute (rpm). A 1RM for eccentric strength was calculated from the peak force of the more impaired limb for subsequent exercise prescription[22] (see **Table 3**). Although readily used as a training tool, the Eccentron has yet to be evaluated against other criterion, isokinetic dynamometers (likely due to its unique movement and muscle recruitment pattern).

Daily step physical activity

Daily step PA was captured by the validated and reliable[23] Step Activity Monitor (SAM). Validity and reliability for the SAM was established in a sample of individuals with iSCI with similar

Table 3. Eccentric resistance training program

Week	Day	Resistance	Sets	Reps	RPM	Rest (min)
1	1	Familiarization			12	
	2	Familiarization			12	
2	1	Familiarization			12	
	2	**3RM assessment for workload 2				
3	1	≥85	2-6	≤6	12	3.0
	2	67-75	3-6	6-10	12	1.5
4	1	≥85	3-6	≤6	12	3.0
	2	67-75	3-6	6 -10	12	1.5
5	1	≥85	4-6	≤6	12	3.0
	2	70-80	4-6	8-12	12	1.5
6	1	≥85	5-6	≤6	12	3 - 5
	2	**3RM assessment for workload 3 and mid-test outcome				
7	1	≥85	2-6	≤6	12	3-5
	2	67-75	3-6	6-10	12	1.5
8	1	≥85	3-6	< 6	12	3.0
	2	67-75	3-6	6-10	12	1.5
9	1	≥85	4-6	≤6	12	3.0
	2	67-75	4-6	8-12	12	1.5
10	1	≥85	5-6	≤6	12	3.0
	2	70-80	5-6	8-12	12	1.5
11	1	≥85	5-6	≤6	12	3-5
	2	70-80	5-6	10 -12	12	1.5
12	1	≥85	5-6	≤6	12	3-5
	2	75-85	5-6	10-12	12	1.5

Note: Day 1 = muscular strength; Day 2 = muscular hypertrophy; familiarization = self-selected training duration and intensity, approximately 2 x 8 at 50% of Workload 1 at 12 rpm; min = minutes; reps = repetitions; rest = time between sets; RPM = repetitions per minute; resistance = percent of peak mean force of the weaker leg during respective three repetition maximum (3RM).

gait capacity as the current sample (intraclass correlation [ICC] comparing a 10-meter walk test and SAM was 0.97).[23] Calibration for expected gait characteristics followed procedures outlined by previously published reports.[24] The participant affixed the SAM with a Velcro strap around the less-impaired leg.[23] Daily step counts began the day after the participant received the SAM and continued for three consecutive weekdays and one weekend day (excluding bathing activities). Data were collected in 1-minute epochs.

Procedures

Participants were instructed not to engage in strenuous exercise for 2 days prior to pre-, mid-, and posttesting. When entering the laboratory on day 1, participants completed the VAS, isometric strength, and eccentric strength testing protocols for familiarization. On day 2, the participants repeated the procedures to establish baseline. On the third visit, participants began training on the eccentric stepping ergometer. Participants trained two times a week for 12 weeks with a minimum of 48 hours between training sessions. Exercise prescription progression is presented in **Table 3**. Muscle strength measures and step PA were repeated at the end of weeks 6 and 12. The ERT was designed to target muscular strength and hypertrophy according to guidelines presented by the National Strength and Conditioning Association.[25] If, however, the calculated training workload outlined in **Table 3** was less than the previously evaluated tone, the same intensity progression was followed wherein the investigator added to the tone value serving as the training workload (eg, tone + 35% and tone + 17%). When participants could complete two additional repetitions in the last two sets of a training day, exercise intensity was increased in accordance to the training guidelines presented in **Table 3**. However, if participants were unable to reach target workloads for more than 30% of repetitions, the intensity was reduced. Efforts were made to ensure that mid and post assessments and training occurred at approximately the same time of day.

Statistical analyses

An a priori power computation indicated that the analyses would be powered at 80% when 10 participants completed the ERT (G*Power, Version 3.1) based on measured effect sizes reported previously in a similar participant pool.[26] IBM Statistics for Windows, Version 23.0 (IBM Corp., Armonk, NY) was used to analyze data. Three one-way repeated measures analyses of variance (ANOVAs) were used to evaluate the impact of ERT (baseline, midtraining, and posttraining) on isometric strength, eccentric strength, and average daily step PA. An a priori familywise alpha of $p < .05$ was used.

Results

Statistics characterizing the participants are provided in **Tables 1** and **2**. The study included 14 individuals, however 3 discontinued participation for personal reasons prior to completing the familiarization period. Analyses included the 11 individuals who finished the ERT, completing an average of 98% of training sessions (see **Table 2**). Step PA data were lost for one participant due to a monitor clearing error. As such, all analyses involving step PA included 10 individuals. Average step PA did not differ following ERT [$F(2.00, 18.00) = 2.73$, $MSE = 216{,}836.78$, H-F $p = .092$]. Significant improvements were documented for eccentric strength [$F(1.27, 12.71) = 8.42$, $MSE = 1738.35$, H-F $p = .009$] and isometric strength [$F(1.97, 19.77) = 7.10$, $MSE = 11.29$, H-F $p = .005$]. Post hoc comparisons with Sidak corrections indicated that eccentric strength improved from pretest to midtest ($p = .034$) and from pretest to posttest ($p = .038$). No change was noted between midtest and posttest ($p = .15$). Differences in isometric strength occurred from pretest to posttest data ($p = .031$). See **Figure 1** for means, standard deviations, and individual participant responses on study variables.

Discussion

The current investigation was designed to determine how ERT affected eccentric strength, isometric strength, and daily step PA for those with chronic iSCI. Eccentric strength improved as a result of the ERT (~38%), with most improvements occurring during the initial 6 weeks of training (~23%). Isometric strength improved an average of 65%. While not statistically significant, step PA, on average, increased 32% across the ERT.

In support of previous work,[26] data from the current study support the contention that individuals with iSCI have the capacity to improve neuromuscular function of the affected limbs similarly to unimpaired individuals. Our participants with iSCI showed similar improvements as young, healthy men who completed 35 ERT training sessions on a knee extension machine (~39%)[27] and neurologically intact men who completed 8 weeks of unilateral knee extensors (~29%) ERT.[28] These investigations varied in ERT design in regard to training intensity, sets, repetitions, and total volume. Seynnes et al[27] designed the ERT so that participants completed four sets of seven maximal eccentric muscle actions.

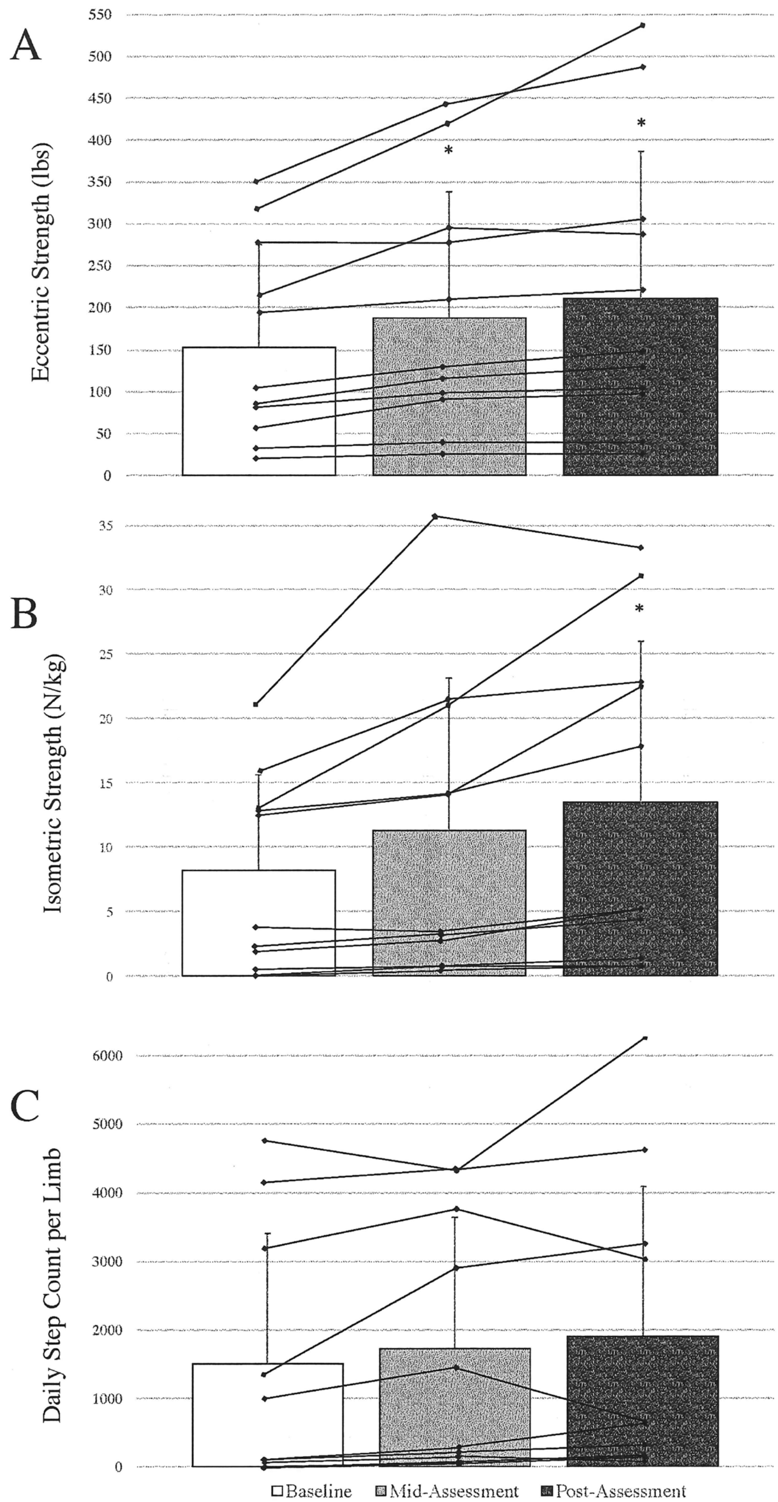

Figure 1. Strength and step activity resulting from ERT. (A) Eccentric strength is sum of the right and left legs during dosing procedure (in pounds). (B) Isometric strength is sum of the highest trial for the right and left legs from each assessment (in newtons per kilogram). (C) Average daily step activity is step activity of less impaired limb during 3 week days and 1 weekend day. * = Significantly different from pretest ($p < .05$).

Weir and colleagues[28] allowed for a familiarization period, wherein participants increased from three to five sets across the first 3 weeks with the final 5 weeks consisting of six sets of six repetitions at 80% 1RM. While the current investigation also measured eccentric strength, it should be noted that the assessment devices differed. Investigators are cautioned against making direct comparisons between eccentric strength typically assessed via criterion measures (Cybex II or Biodex System 3) and the Eccentron as the validity is still being juried.[29,30]

A sample of individuals with Parkinson's disease showed improvements ranging from 13% to 29% after 12 weeks of ERT on a recumbent, eccentrically driven cycle ergometer.[31] These individuals progressed from 3 to 5 minutes per session to 15 to 20 minutes per session while mediating intensity through ratings of perceived exertion.[31] The more dramatic improvements observed in the current study may be due to the higher intensities and the overall program design.

Previously, Stone et al[26] utilized the same training ergometer in a sample of individuals with iSCI who would be described as daily ambulators (one cervical and two thoracic iSCIs). Here, improvements in eccentric strength averaged 79% following an 8-week ERT. These participants completed three training sessions per week where the first 4 weeks emphasized muscular endurance and the second 4 weeks targeted muscular strength and hypertrophy. The eccentric strength improvements might be higher than in the current study because of the variability in iSCI severity (ie, the inclusion of wheelchair users) and differences in overall training volume. Data are not available to determine whether the variance between these two ERT protocols derives from neurological or architectural origins. Future investigations may consider directly comparing the available ERT programs to determine the value of each design relative to local muscular adaptations.

Summed isometric strength improved from pre-ERT to post-ERT. It is likely that the nearly 72% improvement from pretest to midtest and 29% change from mid- to posttesting failed to reach statistical significance because of the variance in interparticipant performance. For example, if one participant improved from 100 N/kg to 150 N/kg, this individual response would equate to a 50% improvement. Similarly, another participant who improved from 1 N/kg to 3 N/kg would improve by 300%. Future investigations may consider separating samples into groups of those who are primarily wheelchair users and community ambulators to achieve a more refined statistic. Despite this, the effect of the ERT was large enough to detect improvement in isometric strength from pre-ERT to post-ERT.

The improvements in bilateral leg strength in participants with iSCI following the ERT are like those shown following gait training modalities. Stevens et al[24] noted a 57% improvement in isometric leg strength following 8 weeks of underwater treadmill training in individuals with chronic iSCI. These individuals were older (average of 47.7 years) and closer in duration to their iSCI (average of 4.8 years) compared to the current sample (average of 9.5 years post-iSCI and 39.1 years old). Weir and colleagues[28] noted a 13.5% improvement in isometric strength in healthy men following an 8-week ERT program. The current ERT program may have elicited a greater percent change than previously reported protocols for various reasons: (1) The ERT was performed by individuals with lower levels of baseline function allowing for a greater ability to respond to the training, and (2) the current study had an additional 4 weeks of training than these comparison studies. Knowing that eccentric strength training can translate to isometric strength has clinical implications. Eccentric training may allow improvements in gait mechanics such as stride length and stance support time with lower metabolic demand for patients.

While speculative, the improvements observed for eccentric and isometric strength in participants with iSCI may be derivative of both neural and architectural adaptations. Short duration, high-intensity ERT has resulted in increased cross-sectional area, fascicular length, pennation angle, and muscular activity in healthy adults.[27,32] Additionally, evidence is available to support that sarcomeres are added longitudinally to myofibrils in as few as 10 days following repeated exposure to ERT.[32] Others have shown that short-term (approximately 1 month) ERT is sufficient to increase agonist activation and attenuate antagonist coactivation.[33,34]

Eccentric and isometric strength are valuable musculoskeletal fitness components of gait training after neurological disorders. The potential for neurogenesis and regeneration of muscle microarchitecture following ERT sets the stage for individuals with iSCI to regain neuromotor control and strengthen muscles below the iSCI. Focused training of the muscles involved with standing and ambulation on the recumbent stepper may serve as a starting point for those with iSCI seeking to regain ambulatory capacity. In a different sample, it was shown that in people with cerebral palsy, strengthening of the knee flexors ($r = .60$) and extensors ($r = .68$) highly correlated with walking skills.[35] Damiano et al[35] identified weakness in the quadriceps and lower muscle activity tied to depreciated walking function in cerebral palsy. Specific to the ankle, gait parameters such as speed ($r = .58$) and single leg support time ($r = -.25$) are correlated with plantar flexor strength.[36] In the current study, plantar flexor strength improved by 124% across the 12-week ERT. Although not specifically defined in a population with iSCI, it is postulated that lower extremity strength is highly correlated with physical function. Future investigations are needed to solidify this theory and to identify the relationship between hip strength and walking function after iSCI.

There were no significant changes in step activity as a result of the ERT. On average, daily step PA improved by 32%. This improvement and effect are smaller than that seen with iSCI after aquatic gait training (120%).[2] Unsolicited participant remarks indicated that perceived walking self-efficacy improved following the ERT. However, if there were not sufficient means for the participant to walk at home (walker, braces, physical assistance, etc), the individual may have been limited in translating the improvements in leg strength to home or community walking activity. As such, future investigations seeking to identify the relationship between ERT and daily step PA should limit participation to individuals with the means to perform gait activities at home. The documented change in step activity should be valued because any improvement in PA in a population as sedentary as those with iSCI is worthwhile. However, this method of exercise training is likely not the most effective in eliciting the greatest ambulatory PA changes.

This study was an initial attempt to increase strength and step activity using a novel training modality with individuals with iSCI. Many opportunities for future research can be derived from this investigation. Investigations may consider evaluating applied outcomes such as balance, gait mechanics, and coordination when descending stairs or sitting. Further, due to the documented relationship between isometric and concentric strength and ambulation, respectively, future research aimed at determining how eccentric strength is related to walking speed is warranted.

Study limitations

Although all participants who completed the study met the inclusion criteria, there was a large range of daily step PA among participants (4.5-4,900 steps). This variability may have undermined the power to detect change in step activity resulting from the ERT. Post hoc analyses were conducted to determine whether a minimum WISCI (Walking Index for Spinal Cord Injury) score or level of strength could be identified that would be indicative of thresholds necessary to elicit improvements from the ERT. However, no threshold values were apparent. It would be valuable for forthcoming studies to include nonexercising control groups, larger sample sizes, and/or crossover designs. These additions would allow for smaller changes in outcome variables to be identified, allow greater generalization of findings, and allow for analyses of detraining. Moreover, future investigators may consider dividing the sample between those who primarily ambulate versus wheelchair users or recruiting a more homogenous sample. Lastly, empirical evidence is needed to determine the validity and reliability of the Eccentron as a muscle strength assessment tool.

Conclusion

ERT can serve as a potent stimulus in the development of eccentric and isometric strength in persons with iSCI. Although not studied in the current investigation, it may be speculated that the attained isometric and eccentric strength could translate to specific gait mechanics and walking function and is a valuable avenue for future research.

Conflicts of Interest

The authors declare no conflicts of interest.

REFERENCES

1. Kirshblum S, Burns S, Biering-Sorensen F, et al. International standards for neurological classification of spinal cord injury. *J Spinal Cord Med.* 2011;34(6):535-546.
2. Riley DA, Burns AS, Carrion-Jones M, Dillingham TR. Electrophysiological dysfunction in the peripheral nervous system following spinal cord injury. *Am Acad Phys Med Rehabil.* 2011;3:419-425.
3. Round JM, Barr FMD, Moffat B, Jones DA. Fibre areas and histochemical fibre types in the quadriceps muscle of paraplegic subjects. *J Neuro Sci.* 1993;116(2):207-211.
4. Janssen TWJ, Dallmeijer AJ, Veeger D, van der Woude LHV. Normative values and determinants of physical capacity in individuals with spinal cord injury. *J Rehabil Res Dev.* 2002;39(1):29-40.
5. Martin Ginis KA, van der Scheer JW, Latimer-Cheung A, et al. Evidence-based scientific exercise guidelines for adults with spinal cord injury: An update and a new guideline [published online ahead of print October 25, 2017]. *Spinal Cord.* doi:10.1038/s41393-017-0017-3.
6. Kim CM, Eng JJ, Whittaker MW. Level walking and ambulatory capacity in persons with incomplete spinal cord injury: Relationship with muscle strength. *Spinal Cord.* 2004;42:156-162.
7. Hortobagyi T, Barrier J, Beard D, et al. Greater initial adaptations to submaximal muscle lengthening than maximal shortening. *J Appl Phys.* 1996;81(4):1677-1682.
8. LaStayo P, Ewy GA, Peirotti DD, Johns RK, Lindstedt S. The positive effects of negative work: Increased muscle strength and decreased fall risk in a frail elderly population. *J Gerontology.* 2003;58A(5):419-424.
9. Mueller M, Brell F, Vogt M, et al. Different response to eccentric and concentric training in older men and women. *Eur J Appl Physiol.* 2009;107:145-153.
10. Reeves ND, Maganaris CN, Longo S, Narici MV. Differential adaptations to eccentric versus conventional resistance training in older humans. *Exp Physiol.* 2009;94(7):825-833.
11. Janssen I, Heymsfield SB, Ross R. Low relative skeletal muscle mass (sarcopenia) in older persons is associated with functional impairment and physical disability. *J Am Geriatr Soc.* 2002;50:889-896.
12. Kirkendall DT, Garrett WE. The effects of aging and training on skeletal muscle. *Am J Sports Med.* 1998;26(4):598-602.
13. Flann K, LaStayo P, McClain D, Hazel M, Lindstedt S. Muscle damage and muscle remodeling: No pain, no gain? *J Exp Biol.* 2011;214:674-679.
14. Roy JS, MacDermid JC, Orton B, et al. The concurrent validity of a hand-held versus a stationary dynamometer in testing isometric shoulder strength. *J Hand Ther.* 2009;22(4):320-326.
15. Berry ET, Giuliani CA, Damiano DL. Intrasession and intersession reliability of handheld dynamometry in children with cerebral palsy. *Pediatr Phys Ther.* 2004;16:191-198.
16. Riddle DL, Finucane SD, Rothstein JM, Walker ML. Intrasession and intersession reliability of hand-held dynamometer measurements taken on brain-damaged patients. *Phys Ther.* 1989;69:182-194.
17. Damiano DL, Kelly LE, Vaughn CL. Effects of quadriceps femoris muscle strengthening on crouch gait in children with spastic diplegia. *Phys Ther.* 1995;75:658-667.
18. Eagleton M, Iams A, McDowell J, Morrison R, Evans C. The effects of strength training on gait in adolescents with cerebral palsy. *Pediatr Phys Ther.* 2004;16:22-30
19. McMeekan J, Stillman B, Story I, Kent P. The effects of knee extensor and flexor muscle training in individuals with rheumatoid arthritis. *Physiother Res Int.* 1999;4:55-67.
20. Rasch A, Dalen N, Berg HE. Muscle strength, gait, and balance in 20 patients with hip osteoarthritis followed for 2 years after THA. *Acta Orthop.* 2020;81:183-188.
21. Jacobs P. Effects of resistance and endurance training in persons with paraplegia. *Med Sci Sports Exerc.* 2009;41(5):992-997.
22. Brzycki M. Strength testing-- predicting a one-rep max from reps-to-fatigue. *J Phys Educ Rec Dance.* 1993;64(1):88-90.
23. 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):355-362.
24. Stevens SL, Caputo JL, Fuller DK, Morgan DW. Effects of underwater treadmill training on leg strength, balance, and walking performance in adults with incomplete spinal cord injury. *J Spinal Cord Med.* 2015;38(1):91-101.
25. Haff GG, Triplett NT. *Essentials of Strength Training and Conditioning.* 4th ed. Champaign, IL: Human Kinetics; 2016.
26. Stone W, Stevens S, Fuller D, Caputo J. Eccentric resistance training in adults with and without spinal cord injuries. *Int J Exerc Sci.* 2017;10(1):154-165.
27. Seynnes OR, de Boer M, Narici MV. Early skeletal muscle hypertrophy and architectural changes in

response to high-intensity resistance training. *J Appl Physiol.* 2007;102:368-373.
28. Weir JP, Housh DJ, Housh TJ, Weir LL. The effect of unilateral eccentric weight training and detraining on joint angle specificity, cross-training, and the bilateral deficit. *J Sport Phys Ther.* 1995;22(5):207-215.
29. Dolny DG, Collins MG, Wilson T, Germann ML, Davis HP. Validity of lower extremity strength and power utilizing a new closed chain dynamometer. *Med Sci Sports Exerc.* 2001;33:171-175.
30. Arnold CM, Warkentin KD, Chilibeck PD, Magnus CRA. The reliability and validity of handheld dynamometry for the measurement of lower-extremity muscle strength in older adults. *J Strength Cond Res.* 2010;24(3):815-824.
31. Dibble LE, Hale TF, Marcus RL, Droge J, Gerber JP, LaStayo PC. High-intensity resistance training amplifies muscle hypertrophy and functional gains in persons with Parkinson's disease. *Mov Disord.* 2006;21(9):1444-1452.
32. McHugh P, Tetro D. Changes in the relationship between joint angle and torque production associated with the repeated bout effect. *J Sports Sci.* 2003;21(11):927-932.
33. Krentz JR, Farthing JP. Neural and morphological changes in response to a 20-day intense eccentric training protocol. *Eur J Appl Physiol.* 2010;110: 333-340.
34. Pensini M, Martin A, Maffiuletti NA. Central versus peripheral adaptations following eccentric resistance training. *Int J Sports Med.* 2001;2:567-574.
35. Damiano DL, Martellotta TL, Sullivan DJ, Granata KP, Abel MF. Muscle force production and functional performance in spastic cerebral palsy: Relationship of cocontraction. *Arch Phys Med Rehabil.* 2000;81: 895-900.
36. Lin P, Yang Y, Cheng S, Wang R. The relation between ankle impairments and gait velocity and symmetry in people with stroke. *Arch Phys Med Rehabil.* 2006;87:562-568.