Locomotor Training and Muscle Function After Incomplete Spinal Cord Injury: Case Series

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Abstract

Background/Objective: To determine whether 9 weeks of locomotor training (LT) results in changes in muscle strength and alterations in muscle size and activation after chronic incomplete spinal cord injury (SCI).

Study Design: Longitudinal prospective case series.

Methods: Five individuals with chronic incomplete SCI completed 9 weeks of LT. Peak isometric torque, torque developed within the initial 200 milliseconds of contraction ($Torque_{200}$), average rate of torque development (ARTD), and voluntary activation deficits were determined using isokinetic dynamometry for the knee-extensor (KE) and plantar-flexor (PF) muscle groups before and after LT. Maximum muscle cross-sectional area (CSA) was measured prior to and after LT.

Results: Locomotor training resulted in improved peak torque production in all participants, with the largest increases in the more-involved PF ($43.9\% \pm 20.0\%$), followed by the more-involved KE ($21.1\% \pm 12.3\%$). Even larger improvements were realized in $Torque_{200}$ and ARTD (indices of explosive torque), after LT. In particular, the largest improvements were realized in the $Torque_{200}$ measures of the PF muscle group. Improvements in torque production were associated with enhanced voluntary activation in both the KE and ankle PF muscles and an increase in the maximal CSA of the ankle PF muscles.

Conclusion: Nine weeks of LT resulted in positive alterations in the KE and PF muscle groups that included an increase in muscle size, improved voluntary activation, and an improved ability to generate both peak and explosive torque about the knee and ankle joints.

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Key Words: Spinal cord injuries, incomplete; Paraplegia; Tetraplegia; Skeletal muscle; Dynamometry; Magnetic resonance imaging; Locomotion; Locomotor training; Body weight support; Muscle strength, activation

INTRODUCTION

Traumatic spinal cord injury (SCI) is a potentially disabling condition that is associated with a variety of functional deficits (1). Muscle atrophy and a reduced ability to generate torque may contribute to the development of disability after SCI (2–5). Individuals with complete SCI have 32% to 46% smaller muscle

cross-sectional area (CSA) in the calf and thigh muscles, relative to matched control study participants, within 6 months after injury, while study participants with incomplete SCI demonstrate a 25% to 30% reduction in lower extremity muscle CSA (2,3). Few studies have quantitatively analyzed skeletal muscle strength after incomplete SCI (4,5). However, we recently demonstrated in persons with chronic upper motor lesions and incomplete SCI that both knee extensor (KE) and plantar flexor (PF) skeletal muscles generate ~70% less peak torque, with even larger reductions in measures of instantaneous or explosive peak torque (4).

Repetitive locomotor training (LT) with body weight support has emerged as a promising therapeutic intervention aimed at promoting motor recovery and ambulation following incomplete SCI (6–8) and has been suggested to have a positive impact on walking ability

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(8,9), functional independence, and subjective well being (10). In addition, Giangregorio et al (11,12) and Stewart et al (13) have shown that LT involves sufficient mechanical loading to induce muscle plasticity, increasing muscle size and altering the muscle phenotype both after acute and chronic incomplete SCI. Interestingly, studies involving animal models of incomplete SCI have shown that LT also has the potential to augment the force-generating capabilities of affected lower hind limb muscles (14,15). To our knowledge, no study has investigated the effect of LT on lower extremity muscle-force production and instantaneous power in persons with incomplete SCI. Previous studies have relied on manual muscle tests and American Spinal Injury Association (ASIA) motor scores (via manual muscle tests) to assess voluntary strength in persons with incomplete SCI. However, ASIA scores have been criticized for lacking sensitivity and having a limited ability as indicators of neuromuscular recovery in chronic SCI (8,9,16–18).

Therefore, the purpose of this study was to determine the effect of 9 weeks of LT on lower extremity muscle strength, size, and voluntary activation in persons with chronic incomplete SCI. Specifically, we measured peak isometric torque, torque developed within the initial 200 milliseconds of contraction ($Torque_{200}$), and the average rate of torque development (ARTD) in the KE and ankle PF muscle groups. In addition, we quantified voluntary activation deficits and alterations in maximal muscle CSA using superimposed electrical stimulation and magnetic resonance imaging. The KE and PF muscle groups were

selected for study because of their purported role during human locomotion.

METHODS

Subjects

Five persons (1 woman, 4 men) with chronic motor incomplete SCI underwent 9 weeks (45 sessions, 5 times/wk) of LT. A summary of the participants’ demographics is provided in Table 1. Criteria for inclusion included: (a) age 18 to 70 years; (b) history of SCI as defined by the (ASIA) Impairment Scale categories C or D; (c) initial traumatic SCI at cervical or thoracic levels (C4-T12), resulting in upper motor neuron lesions in the lower extremity; (d) medically stable and asymptomatic for bladder infection, decubitus ulcers, cardiopulmonary disease, or other significant medical complications prohibiting testing and/or training; and (e) if using antispasticity medication, agreement to maintain current levels throughout the study. Exclusion criteria were as follows: (a) participation in a rehabilitation or research protocol that could influence the outcome of this study; (b) magnetic resonance imaging–incompatible implants or devices, pregnancy, or severe claustrophobia. Prior to participating in the study, written informed consent was obtained from all participants, as approved by the Institutional Review Board.

Locomotor Training Protocol

Each participant completed 45 training sessions (5 per week) of a LT intervention (Table 2) spread over 9 to 11

Table 1. Characteristics of Participants With Incomplete SCI

Study Participant	Age (y)	Height (cm)	Body Mass (kg)	ASIA Impairment Classification	Level of Injury	Duration of Injury (mo)	Mobility Status	LEMS (pre-LT)	LEMS (post-LT)	WISCI-II (pre-LT)	WISCI-II (post-LT)
S1	44	154.9	74.8	C	C6	20	Power wheelchair	33/50	34/50	6	13
S2	21	185.4	68.0	D	T4	8	Bilateral canes	44/50	44/50	19	19
S3	48	198.6	77.0	D	C6	39	Bilateral crutches	35/50	38/50	12	19
S4	58	183.0	90.7	D	C4	14	Wheelchair	45/50	45/50	13	13
S5	36	176.9	83.9	C	C6	16	Wheelchair	17/50	17/50	6	8

*SCI indicates spinal cord injury; LEMS, lower extremity motor score; WISCI-II, walking index for spinal cord injury; and LT, locomotor training.

Table 2. Locomotor Training Demographics for Participantss With Incomplete SCI*

Study Participant	Starting BWS (%)	Ending BWS (%)	Start Speed (mph)	End Speed (mph)
S1	40	15	0.7	2.4
S2	40	5†	2.4	2.7
S3	40	5†	1.7	2.7
S4	30	15	1.9	2.0
S5	40	10	0.8	2.6

*SCI indicates spinal cord injury; BWS, body-weight support.
†No one trained less than 5% due to physical limitations of the BWS system.

weeks (1 participant required a 2-week break in the middle of the training program for non-intervention-related personal reasons). Each session consisted of 30 minutes of stepping on a treadmill with body-weight support (BWS). Speed of treadmill stepping was kept in a range consistent with normal walking (2.0–2.8 mi/h). The BWS was initially set at 40% and was reduced per previously reported guidelines (8).

Progression of training was achieved by decreasing BWS, altering speed, increasing trunk control, decreasing manual assistance for limb control, and increasing the time spent walking on the treadmill per bout (8). All participants received the same number of sessions and spent approximately the same amount of time involved in training, although progression of training parameters was individualized. Individual demographics of LT are summarized in Table 3.

During each rest break, the participant stood with the minimal BWS required to maintain balance with minimal assistance from the trainers. Initially, treadmill

sessions required up to 60 minutes to achieve 30 minutes of stepping, but the amount decreased with improved walking ability and endurance such that stepping could be completed in 45 minutes or less. Immediately following step training on the treadmill, each participant engaged in 20 minutes of overground training. Overground training incorporated use of assistive devices, but participants were otherwise bearing full weight on the lower extremities. A more detailed description of the training principles and parameters has been provided by Behrman and Harkema (19).

Experimental Protocol

Experimental measures were performed on the day prior to the start of training (pre-LT) as well as the day following cessation of training (post-LT).

Strength Assessment. Voluntary contractile measurements were determined in the self-reported more-involved and less-involved limbs for the KE and PF muscle groups before and after LT, using a Biodex System

Table 3. Isometric Peak Torque and Average Rate of Force Development

	Isometric Peak Torque (Nm)				
	S1	S2	S3	S4	S5
Knee extensors					
More involved					
Pre-LT*	35.8	95.8	26.8	176.5	10.8
Post-LT	42.6	84.6	39.0	181.8	15.7
Less involved					
Pre-LT	65.0	136.5	62.6	179.0	15.7
Post-LT	70.3	190.5	78.0	199.9	18.0
Plantar flexors					
More involved					
Pre-LT	11.7	45.5	19.4	65.2	12.5
Post-LT	23.3	51.9	29.1	63.3	20.0
Less involved					
Pre-LT	24.8	52.3	42.7	90.2	21.9
Post-LT	35.5	60.7	51.7	82.5	21.0
Average Rate of Torque Development (Nm/s)					
	S1	S2	S3	S4	S5
Knee extensors					
More involved					
Pre-LT	92.6	281.5	62.3	572.1	30.8
Post-LT	182.5	337.1	81.8	613.3	46.0
Less involved					
Pre-LT	270.4	338.0	233.1	727.1	58.1
Post-LT	325.9	588.1	239.2	746.8	63.3
Plantar flexors					
More involved					
Pre-LT	17.8	27.4	20.0	94.7	21.2
Post-LT	30.8	44.4	45.9	91.2	22.2
Less involved					
Pre-LT	36.5	47.0	103.8	130.3	22.9
Post-LT	101.0	82.7	105.0	203.5	21.9

*LT indicates locomotor training.

3 Dynamometer (Biodex Medical Systems, Inc, Shirley, NY). Testing was performed with participants seated with hips flexed to $\sim 85^\circ$, as previously described (3). For KE testing, the knees were flexed to $\sim 90^\circ$, and the axis of rotation of the dynamometer was aligned with the axis of the knee joint and the lever arm secured against the anterior aspect of the leg, proximal to the lateral malleolus. Testing of PF was performed with the knee flexed at $\sim 30^\circ$ and the ankle at $\sim 0^\circ$ plantar flexion. The anatomical axis of the ankle was aligned with the axis of the dynamometer, while the foot was secured to the footplate with straps placed at the forefoot and ankle. Proximal stabilization for all testing was achieved with straps across the chest, hips, and thigh.

Voluntary Contractile Measurements. Prior to testing, subjects performed 3 warm-up contractions to become familiar with the testing procedures. Subjects then performed 3 maximal voluntary isometric contractions (~ 5 seconds each with 1-minute rest intervals) while receiving verbal encouragement. Peak torque was defined as the highest value obtained during the 3 maximal contractions. In the event that the peak torque values differed by more than 10%, additional contractions were performed. In addition to peak torque, we also determined the absolute torque generated during the initial 200 milliseconds of contraction (Torque_{200}) as well as the average rate of torque development (ARTD) during the contractile effort, as indices of explosive muscle strength (4). The ARTD was defined as the average increase in torque generated in unit time, and was calculated in the time interval corresponding to 20% to 80% of peak amplitude, starting from muscle perturbation. This time interval was selected to reduce the effect of errors in calculating peak amplitude. Hence, ARTD was calculated through numerical differentiation as:

$$\text{ARTD} = \frac{1}{N} \sum_{i=1}^N \frac{\delta f_i}{\delta t}$$

Where N is the total number of time slots for numerical differentiation, δf_i is the change in torque in the time slot i , and δt is the unit time duration for a slot. Torque_{200} was defined as the absolute torque reached at 200 milliseconds during a maximal voluntary contraction (Nm).

Voluntary Activation Deficits. Voluntary activation deficits were determined using the twitch interpolation method (20). Briefly, a single biphasic, supramaximal electrical pulse (600 microsecond pulse duration) was delivered at rest and during maximal voluntary isometric contraction. Supramaximal intensity was determined by increasing the current voltage until twitch-torque production plateaued. Voluntary activation deficit was calculated using the ratio between the torques produced by the superimposition of a supramaximal twitch on a peak isometric contraction (a) and the torque produced by the same stimulus in the potentiated, resting muscle (b).

$$\text{Voluntary activation deficit (\%)} = (a/b) \times 100$$

Electrical stimulation was elicited using a Grass S8800 stimulator with a Grass Model SIU8T stimulus isolation unit (Grass Instruments, Quincy, MA). Electrically induced contractions were delivered through two 3.0×5.0 inch self-adhesive neuromuscular stimulation electrodes placed over the proximal and distal portions of the muscle group being tested. The stimulator and the dynamometer were interfaced with a personal computer through a commercially available hardware system (Biopac MP150 system, BIOPAC Systems Inc, Goleta, CA) sampling at 400 Hz, and data were analyzed with commercially available software (AcqKnowledge 3.7.1).

Magnetic Resonance Imaging. Magnetic resonance imaging was performed prior to and after 9 weeks of LT (pre-LT and post-LT) to determine the maximal fat-free muscle CSA of the PF and KE muscle groups in the self-reported more-involved limb. All magnetic resonance data were acquired in a 1.5 Tesla scanner (Signa; General Electric, GE Medical Systems, Waukesha, WI), as previously described (3). After obtaining a scout image, 3-dimensional transaxial images were collected using a standard (20 cm long) extremity quadrature coil (PF) or a body coil (KE). The extremity coil covered the length of the leg starting from above the lateral ankle malleolus and extending a few centimeters above the knee joint. Each sequence employed an encoding matrix of 256×256 , a field of view that ranged from 16 to 18 cm (PF) or 22 to 28 cm (KE), a pulse repetition time of 300 milliseconds, an echo time of 10 milliseconds, and a slice thickness of 7 mm with a 0 mm gap. Data were analyzed using a custom-designed interactive computer program as previously described (21). Maximal fat-free CSA of the KE muscles was defined as the maximum CSA of the 4 quadriceps femoris muscles combined, whereas maximal fat-free CSA of the PF muscle group was defined as the sum of the maximal CSAs of the soleus, medial gastrocnemius, and lateral gastrocnemius muscles.

Statistical Analyses

A longitudinal, prospective case series in which participants completed 9 weeks of LT was used. Individual data have been summarized in the tables and as plots. Descriptive statistics of all the participants have also been presented as ranges and means.

RESULTS

The results presented are descriptive statistics for 5 participants and are presented in Table 2 and Figure 1a through d and Figure 2a and b.

Voluntary Contractile Measurements

All individuals with chronic incomplete SCI demonstrated improvements in their ability to generate peak isometric torque following LT. The most robust increase in isometric peak torque production was observed in the ankle PF muscles (average increase $43.9\% \pm 20.0\%$) of

Figure 1. $Torque_{200}$ (Nm) measured in the knee extensor muscle group of the more-involved (a) and less-involved (b) limbs as well as in the plantar flexor muscle group of the more-involved (c) and less-involved limbs (d) of individuals with incomplete spinal cord injury before (pre-LT) and after (post-LT) locomotor training.

the self-reported more-involved limb, followed by the KE muscles of both the more-involved ($21.1\% \pm 24.7\%$) and less-involved ($19.8\% \pm 12.7\%$) limbs. Individual gains in peak torque ranged from 8% to 45% in the KE and 14% to 98% in the PF muscle groups. Note that 4 out of 5 subjects showed an increase in isometric peak torque in at least 3 of the 4 tested muscle groups. Individual torque data prior to and after 9 weeks of LT are summarized in Table 3.

Both indices of explosive muscle torque generation, ARTD and $Torque_{200}$, showed large improvements in the ankle PF and KE muscles' LT. In particular, large bilateral improvements in PF $Torque_{200}$ measures were realized, with average improvements of $587\% \pm 247\%$ and $219\% \pm 126\%$ in the more-involved and less-involved limbs, respectively. However, individual increases in ankle PF $Torque_{200}$ ranged from 8% to 835%. Specifically, in the more-involved limb participant S3 showed only an 8% increase, while participant S1 showed an 835% increase. In the less-involved limb participant S5 showed a 20% decrease while participant S4 showed a 640% increase, indicating variable responses to the training intervention.

A varied response was also noted in the KE, with some participants showing an enhancement in the more-involved limb (participants S2, S3, and S5) and others in the less-involved limb (participants S1 and S4). $Torque_{200}$ data for both the KE and ankle PF are presented in Figure 1a through d. The ARTD values showed a similar pattern with relatively larger improvements in the ankle PF muscles compared to the KE (Table 3). Mean ARTD in the ankle PF muscles improved from 36.3 ± 16.5 Nm/s to 46.9 ± 13.3 Nm/s in the more involved limb and from 68.2 ± 23.2 Nm/s to 102.8 ± 32.7 Nm/s in the less involved limb. The mean ARTD in the KE muscles increased from 207.9 ± 112.9 Nm/s to 252.1 ± 115.7 Nm/s and from 325.5 ± 132.6 Nm/s to 392.7 ± 137.0 Nm/s.

Voluntary Activation Deficits

An impaired ability to voluntarily activate the muscles following SCI is known as a voluntary activation deficit. Participants with incomplete SCI have a $\sim 55\%$ activation deficit in both the KE and ankle PF compared to a $\sim 5\%$ activation deficit (ability to voluntarily activate 95%) in

Figure 2. Voluntary activation deficits (%) measured in the knee extensor (a) and plantar flexor (b) muscle groups of the more-involved and less-involved limbs of individuals with incomplete spinal cord injury before (pre-LT) and after (post-LT) locomotor training.

noninjured controls (4). All subjects showed voluntary activation deficits in both the KE and ankle PF muscles prior to LT. Interestingly, LT improved the ability to voluntarily activate the bilateral KE muscle groups as well as the more-involved PF muscles. Mean activation deficits in the KE improved from $63\% \pm 15\%$ to $43\% \pm 10\%$ and from $41\% \pm 16\%$ to $31\% \pm 16\%$ in the more-involved and less-involved sides, respectively, reflecting an improved ability to voluntarily activate these muscle groups. Only one participant (S4), the individual with the highest pre-LT KE strength, did not show any improvement in KE activation deficit after LT. Similar to the KE, activation deficits in the more-involved PF improved from $61\% \pm 10\%$ to $41\% \pm 11\%$ after 9 weeks of LT. Individual data are summarized in Figure 2a and b.

Maximal Muscle CSA

The KE and PF max-CSAs prior to LT were $55.8 \pm 6.5 \text{ cm}^2$ and $38.3 \pm 1.2 \text{ cm}^2$, respectively. All participants demonstrated an increase in PF max-CSA with values ranging from 6.8% to 21.8% (Figure 3). On average, LT resulted in a $15.1\% \pm 4.5\%$ increase in PF max-CSA, but no meaningful increase in KE maximal CSA was noted, except in 1 participant (S1; data not shown). As a consequence, post-LT the KE and PF max-CSAs were $57.1 \pm 5.6 \text{ cm}^2$ and $44.0 \pm 1.4 \text{ cm}^2$, respectively.

DISCUSSION

The results of this case series suggest that 9 weeks of LT in persons with chronic motor incomplete SCI results in positive alterations in lower extremity skeletal muscles that include an increase in maximal muscle CSA as well as an improved ability to generate isometric torque about both the knee and ankle joints. Interestingly, increases in

torque production and muscle size were more pronounced in the ankle PF muscles rather than the KE muscles, consistent with previous literature suggesting that the ankle PFs are critical for propulsive force generation during locomotion and experience high loads (22,23). Superimposed electrical stimulation further showed that improvements in muscle strength with LT are accompanied by improved voluntary activation.

A myriad of physiological changes occur as a result of traumatic SCI. Many of these changes are due to direct effects of the injury (ie, neural circuitry disruptions), while others may result from decreased neuromuscular activity and muscle unloading (ie, atrophy and activation deficits) (3,4). Among the physiological changes is a dramatic loss in the ability to voluntarily produce muscle force, leading to impaired motor function and disability. We previously demonstrated that isometric peak torque generation in the KE and PF muscle groups is reduced $\sim 70\%$ in individuals with chronic incomplete SCI (>1 year), compared to age-, gender-, and body weight-matched control participants (4). Individuals in the present study demonstrated similar reduced PF and KE peak torque values prior to LT. Forty-five sessions of LT resulted in a robust increase in isometric peak torque production in the ankle PF muscles (average increase $43.9\% \pm 20.0\%$) of the self-reported more-involved limb and the KE muscles of both the more-involved ($21.1\% \pm 12.3\%$) and less-involved ($19.8\% \pm 6.3\%$) limbs. The ability to improve peripheral muscle strength in persons with incomplete SCI seemingly adds to the positive attributes previously assigned to this therapeutic intervention.

In addition to peak torque generation, we suggest that the functionally more relevant characteristics of muscle torque production in a person with incomplete

Figure 3. Maximal cross-sectional area (cm²) of the ankle plantar flexor muscle group of individuals with incomplete spinal cord injury, pre-locomotor training (pre-LT) and post-locomotor training (post-LT).

SCI are represented by the indices of explosive or instantaneous strength, ARTD and Torque₂₀₀. The ARTD represents the average rate of contractile torque development during maximum voluntary contraction, while Torque₂₀₀ measures the absolute torque generated within the initial 200 milliseconds of contraction. We previously showed that both ARTD and Torque₂₀₀ are significantly reduced in persons with incomplete SCI, with more pronounced deficits in the ankle PF muscles compared to the KE muscles (4). In particular, large deficits were noted in the Torque₂₀₀ of the ankle PF muscles, with a 11.7-fold difference between the Torque₂₀₀ measured in the self-reported more-involved limb and a fivefold difference in the less-involved limb compared to control muscles.

With 9 weeks of LT, improvements in both measures of explosive muscle strength (Torque₂₀₀ and ARTD) were noted. In particular, the largest bilateral individual improvements were seen in the ankle PF Torque₂₀₀ measures. Smaller and less consistent relative gains were realized in the KE muscle group. The large increase in the Torque₂₀₀ of both ankle PF muscle groups with LT deserves special attention, given these muscles' importance during bipedal walking. For example, at a speed commonly deemed necessary for persons to safely ambulate in the community (1.2 m/s) (24), a time window of only about 200 milliseconds is available to generate the necessary concentric torque in the PF muscle group to produce forward propulsion (23). Data from our previous and current study combined indicate that the torque produced by the ankle PF in this time window is significantly reduced in persons with incomplete SCI and can be considerably improved with intense LT (4). An improved ability to generate instantaneous torque may be critical to facilitating functional recovery and ambulation in patients with incomplete SCI. The suggested importance of PF muscle torque generation for improving ambulation in persons with central nervous system injuries is not new and has previously been reported in persons poststroke (22,23).

Improvements in skeletal muscle force-generating capacity can be accomplished by alterations in muscle size (hypertrophy) and/or improvements in muscle activation. Loss of skeletal muscle mass below the level of the spinal cord lesion is a widely recognized consequence of SCI (25,26). Skeletal muscle atrophy following SCI is a result of primary injury to the spinal cord and concurrent inactivation of affected skeletal muscles along with subsequent changes in mechanical loading conditions (27). Even though LT is not considered a therapeutic intervention designed to induce muscle hypertrophy, previous studies have shown that in the incomplete SCI population the training stimulus and loading can be of sufficient magnitude to induce muscle plasticity. Specifically, Stewart et al reported a 25% increase in the mean muscle fiber area of type I and IIa fibers in the vastus lateralis following 6 months of BWS treadmill training in individuals with chronic incomplete SCI (13). Giangregorio et al, using computed tomography, found increases in thigh and calf muscle CSA ranging from 3.8% to 56.9% in an acute (2–6 months postinjury) incomplete SCI population after 48 sessions of LT (11). A follow-up study in individuals with chronic incomplete SCI showed 4.9% and 8.2% increases in the thigh and calf muscle CSAs, respectively, following 144 sessions of treadmill training (12). Using 3-dimensional magnetic resonance imaging, a noninvasive imaging technique well-suited for morphometric measures of skeletal muscle, we found 15.1% and 3.4% increases in the mean fat-free maximal CSA of the ankle PF and KE muscles of the involved limb, respectively. Interestingly, all participants showed an increase in PF max-CSA, with values ranging from 6.8% to 21.8%, while only 1 participant showed an increase in KE muscle max-CSA. The seemingly larger increases in muscle CSA in the ankle PF relative to KE during 9 weeks of LT may suggest a hierarchy of loading and functional importance in these key lower extremity muscle groups during locomotion.

The ability to drive α -motoneurons to elicit maximal muscle recruitment is often referred to as maximal voluntary activation and can be estimated using superimposed electrical stimulation, a method commonly implemented in a variety of populations (5,28,29). In a previous study, we measured voluntary activation deficits ranging between 42% and 66% in the lower extremity muscles of individuals with incomplete SCI, whereas control participants in the study showed a ~5% voluntary activation deficit (4). Similar voluntary activation deficits were found in this study prior to LT. Interestingly, voluntary activation deficits were partially attenuated after 45 sessions of LT (30–40% posttraining), even though they did not return to values typical for able-bodied individuals. In particular, in the KE muscles, bilateral improvements in voluntary muscle activation were associated with gains in muscle torque production, while muscle CSA was relatively unchanged. Improvements in muscle activation in persons with incomplete

SCI with LT have also been reported using iEMG (integrated electromyography) (6). Of interest is that voluntary activation deficits can also be observed following disuse or immobilization. However, in these models the phenomenon is transient and normalization in muscle activation is typically observed after 3 to 4 weeks of rehabilitation (30).

Despite the measured increases in muscle CSA, instantaneous and peak force production, and improvements in voluntary activation, only 1 of the 5 participants in this study showed a significant change in lower extremity motor scores (LEMS) assessed via multiple lower extremity manual muscle tests, following LT. Specifically, LT improved LEMS of participant S3 from 35 to 38. In all other participants no substantial change in LEMS could be detected. These data are consistent with other LT studies, which often fail to demonstrate a change in ASIA scores with training in persons with chronic injuries (8,9,18). We believe that the lack of change in ASIA motor scores in the present study reflects a limitation in the measurement tool. Compared to isokinetic dynamometry, manual muscle tests have a limited interrater reliability and have been criticized as lacking sensitivity, especially at scores above 3 (out of 5) (16,17). Others have argued that while ASIA scores are valuable in predicting motor recovery in acute patients, they may be less powerful as measures of neuromuscular recovery in chronic SCI (11,31–33).

Lastly, there are some shortcomings in our study. This study comprises a 5-subject case series with data presented in the form of descriptive statistics using ranges and means $\pm$ standard deviations. A randomized, controlled design was not employed due to the small sample size and ethical implications concerned with assignment of participants to a control group (no intervention). The chances of a placebo effect have also been considered, but we think this is extremely minimal since the participants in this study were not involved in any other rehabilitation intervention during that time. In addition, we did not directly relate the changes in strength to improvements in ambulation. Despite these limitations, this case series provides unique findings regarding the muscular adaptations following LT in individuals with incomplete SCI.

CONCLUSION

Nine weeks of LT resulted in improved lower extremity skeletal muscle function and muscle size in individuals after incomplete SCI. Specifically, extensor muscles about the ankle and knee joint demonstrated an improved ability to generate both peak and instantaneous torque. Relative gains in muscle function were greatest in the ankle PF muscles, consistent with their critical role for propulsive force generation and high loading during locomotion. Ankle PF muscles also showed a significant increase in maximal CSA, while increases in KE force

production were mainly linked to improvements in voluntary muscle activation.

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