Research Article

Multi-muscle electrical stimulation and stand training: Effects on standing

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Objective: To examine the biomechanical and neuromuscular effects of a longitudinal multi-muscle electrical stimulation (submaximal intensities) training of the lower limbs combined with/without activity-based stand training, on the recovery of stability and function for one individual with spinal cord injury (SCI).

Design: Single-subject, longitudinal study.

Setting: Neuroplasticity laboratory.

Participant: A 34-year-old male, with sensory- and motor-complete SCI (C5/C6).

Interventions: Two consecutive interventions: 61 hours of supine, lower-limb ES (ES-alone) and 51 hours of ES combined with stand training using an overhead body-weight support system (ST + ES).

Outcome Measures: Clinical measures, trunk stability, and muscle activity were assessed and compared across time points. Trunk Stability Limit (TSL) determined improvements in trunk independence.

Results: Functional clinical values increased after both interventions, with further increases post ST + ES. Post ES-alone, trunk stability was maintained at 81% body-weight (BW) loading before failure; post ST + ES, BW loading increased to 95%. TSL values decreased post ST + ES (TSL_{A/P}=54.0 kg.cm, TSL_{M/L}=14.5 kg.cm), compared to ES-alone (TSL_{A/P}=8.5 kg.cm, TSL_{M/L}=3.9 kg.cm). Trunk muscle activity decreased post ST + ES training, compared to ES-alone.

Conclusion: Neuromuscular and postural trunk control dramatically improved following the multi-muscle ES of the lower limbs with stand training. Multi-muscle ES training paradigm of the lower limb, using traditional parameters, may contribute to the functional recovery of the trunk.

Keywords: Spinal cord injury, Multi-muscle electrical stimulation, Stand training, Locomotor training, Body weight supported training

Introduction

Acute spinal cord injury (SCI) can lead to a complete or partial loss of ability to sense and move below the level of injury, resulting in skeletal unloading and rapid muscle atrophy.¹ The early musculoskeletal deterioration while affecting both acute and chronic health conditions after a spinal cord injury can also directly impact future functional mobility, trunk independence, and independent standing or walking.²

Studies involving longitudinal applications of neuromuscular electrical stimulation-elicited contraction for a single muscle (i.e. evoked isometric muscle contraction) or multiple muscles (i.e. functional electrical stimulation, FES) have shown a direct improvement in skeletal muscle size, skeletal muscle atrophy, skeletal muscle strength,

body composition, metabolic profile, function, and reduction of fatigue of the muscles being stimulated.^{3–7} Additionally, studies for both chronic incomplete and acute SCI using multi-muscle functional electrical stimulation of the lower and upper extremity, respectively, have determined an improvement in muscle function during activities of daily living (ADLs);^{8,9} however, few studies^{10,11} have quantified the systemic effect of multi-muscle stimulation for motor complete SCI during stand protocols on the biomechanical, neuromuscular, and clinical outcome variables.

Stand training (ST), a component of locomotor training, is an activity-based therapy for the improvement of standing for individuals with SCI.^{10,11} Step and stand training protocols combined (i.e. locomotor training) or stand protocols alone have been extensively published to show improvements in independent standing and seated balance, stepping, and walking measures for individuals with a motor incomplete or complete SCI.^{12–16}

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Table 1 Demographics of the participant with spinal cord injury (SCI) and the able-body control (AB).

Participant	Age (y)	Height (cm)	Weight (kg)	TSI ^a (months)	AIS ^b	Intervention (hours)
SCI	34	180.3	66.4	19	A	ES-alone: 61 ST + ES: 51
AB	25	185.0	76.4	—	—	—

^aTime since injury.^bAmerican Spinal Injury Association Impairment Scale from The International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI).^{19,20}

The primary purpose of this paper was to present longitudinal training data evaluating the effect of multi-muscle electrical stimulation (ES) of the lower limbs combined with and without activity-based stand training, for the improvement of independent standing for one individual with SCI. The secondary purpose of the paper was to understand the biomechanical and neuromuscular effect of this training paradigm on trunk stability, trunk function, and trunk neuromuscular activity during independent standing, as well as to highlight the clinical relevance of these changes.

Methods

This is a single-subject, longitudinal study. All procedures performed in this study were approved by the Institutional Review Board and informed consent was obtained prior to participation.

Participant

The participant with SCI was 34 years old, with a neurological level of injury at C5/C6 (Table 1). Clinical, biomechanical, and neuromuscular assessments were conducted on the participant with SCI: 1) prior to any ES interventions, 2) after 61 sessions of bilateral ES of the lower limbs while supine (ES-alone), and 3) after 51 sessions of intense active stand training using an overhead body weight support with bilateral ES of the lower limbs (ST + ES).

Training protocol

All training sessions were 1 hour in duration, 3-4 times a week in each intervention. For the safety of the participant, blood pressure and heart rate were monitored every 10 minutes throughout training. The two interventions occurred in consecutive order, without overlap or delay in between, and the details of each are explained below:

Supine electrical stimulation (ES-alone)

Stimulation was applied in the supine position via bifurcated leads and self-adhesive reusable surface electrodes. Electrodes were placed over the motor points of both legs on the following muscles: rectus femoris (RF),

biceps femoris (BF), gastrocnemius (GN), and tibialis anterior (TA). Two electrodes were used for each muscle (5 × 10 cm oval electrodes on the RF and BF with an active area of 40.5 cm² and 5 × 5 cm square electrodes on the GN and TA with an active area of 23.4 cm²). The stimulation unit was the Rehabicare IF 3WAVE System (Compex Technologies Inc., New Brighton, MN) with a DC 3.6 V rechargeable Lithium-ion battery that powered the device. In the neuromuscular electrical stimulation mode, the Rehabicare IF 3WAVE unit delivered a biphasic square wave pulse. For our protocol, symmetrical 300 μs biphasic pulses at 35 Hz were delivered (over a duty cycle of 11 seconds on, 60 seconds off), with a 7-second stimulation overlap between the upper and lower leg in each cycle. In other words, GN and TA muscles were stimulated first for 4 seconds; then, RF and BF were stimulated for the remaining 7 seconds while the GN and TA stimulation continued (total stimulation cycle of 11 seconds). A rest period followed with 60 seconds of no stimulation. Timing and phasing of contractions were selected to promote muscle groups to contract and relax alternately.¹⁷ The participant was acclimated to ES prior to training in order to determine the maximum tolerable level of neuromuscular stimulation that could be applied during training. The subject was stimulated to a predetermined ES intensity during pretesting evaluation to produce both visible and palpable muscle contractions in all of the muscles during supine and standing.

Stand training and electrical stimulation (ST + ES)

ST + ES is the combination of *Stand Training* (ST) protocol combined with the multi-muscle ES protocol (described above). Stand Training is a protocol during which the participant completes a series of dynamic training tasks while standing on a treadmill using an overhead body-weight support system (Robomedica®, Irvine, CA). Tasks were divided into two phases of adaptability and retraining.¹⁸ Adaptability occurred at higher body-weight support (BWS), with the BWS raised as needed to maximize the participant's ability

to perform a given task as independently as possible while promoting trunk and pelvis control and overall standing balance. Retraining was achieved with the BWS as low as possible, with the trainers providing as much assistance as needed for the task to be performed successfully while promoting weight-bearing during standing.

Data collection

Data collection and testing sessions occurred at baseline and after ES-alone and ST + ES interventions.

Clinical testing session

The International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI)^{19,20} evaluation was completed to assess neurologic function using the combined scores from upper and lower extremity motor and sensory scores. The participant completed the Modified Functional Reach Test (mFRT), Activity-based Balance Level Evaluation (ABLE) scale, and Modified Ashworth scale.²¹ The mFRT (i.e. seated reach)^{22,23} was used to examine the changes in the participant's ability to maintain control over his upright posture during forward reach, without any assistance. The ABLE scale is developed and validated to assess balance abilities specifically in the SCI population across the full spectrum of functional recovery.²⁴ In the current study, only the sitting balance subscale (i.e. first eight items on the test) was used.

Trunk independence test

Trunk independence is defined as the ability to maintain upright trunk position for a minimum of 60 seconds, without manual assistance to the trunk. The test was performed during standing on a treadmill using an overhead BWS with a harness. BWS was lowered gradually from 75% to a minimum percentage BWS where the participant was able to independently stabilize his trunk. Throughout the test, trainers provided manual assistance for knee extension. *Trunk Stability Limit* (TSL), a measure of trunk stability and independence, was calculated to quantify trunk independence.^{25,26} Note at baseline, the participant was not able to complete the test to show any trunk independence; baseline data presented for standing at 50% BWS with manual assistance at trunk and knees. Data are also presented for one able-body control (AB) during quiet standing (on the treadmill, without BWS and harness).

Neuromuscular testing

Surface electromyography (sEMG) data were collected using the tethered MA-100 and MA-300 EMG systems (Motion Lab Systems Inc., Baton Rouge, LA).

Pairs of stainless-steel, high-gain, differential input design, surface electrodes (Motion Lab Systems Inc., Baton Rouge, LA), with an inter-electrode distance of 18 mm, were utilized. Electrodes were placed on the following muscles, bilaterally: erector spinae T5 (SES), erector spinae T12 (IES), external obliques (EO) just below the ribcage along a line connecting the most inferior point of the costal margin and the contralateral pubic tubercle, internal obliques (IO) 1 cm medial to anterior-superior iliac spine, gluteus maximus (GM), rectus femoris (RF), vastus lateralis (VL), biceps femoris (BF), tibialis anterior (TA), gastrocnemius (GN), and soleus (S).²⁷ Location of the electrode placement has been explained elsewhere.²⁸ Ground electrodes were placed on the clavicles for providing a common reference. Surface EMG data were acquired at 2520 Hz. Prior to electrode placement, the skin was prepared by shaving all hair, lightly abrading the skin, and cleansing with alcohol.^{14,15}

Biomechanical/kinematics testing

Kinematic data were collected using Vicon motion capture system (Vicon Motion Systems Ltd., Oxford Metrics, UK). Reflective markers were placed on specific anatomical landmarks using adhesive Velcro tape, according to the Plug-In Gait (Vicon) marker set. Motion capture data were collected at 60 Hz.

Data analysis

Quantification of sEMG was completed through custom-written programs, developed in MATLAB (MathWorks™, Natick, MA). Raw sEMG data were modulated by individual channel gains, filtered by using 4th-order, band-pass (20-150 Hz) and band-stop (60 ± 3 Hz) Butterworth filters, full-wave rectified, and the onset and cessation of sEMG bursts were identified.¹⁰ Mean amplitude (EMG_{mean} , μV), peak amplitude (EMG_{peak} , μV), burst duration (BD, %), and integrated EMG (iEMG, mV.s) were derived from the sEMG signals for further analysis.

Kinematics data were filtered using a 4th-order, zero-lag, low-pass Butterworth filter with a cut-off frequency of 6 Hz. The bilateral heel markers' 3-D coordinates were used to determine the base of support (BoS). Trunk model,²⁹ using acromion and anterior superior iliac spine (ASIS) markers, determined the excursion ($C_{T, BoS}$) and velocity ($\dot{C}_{T, BoS}$) for trunk center-of-mass (CoM) in the Anterior/Posterior (A/P) and Medial/Lateral (M/L) directions (on the transverse plane) relative to the centroid of the BoS for all trials.

$C_{T, BoS}$ curve was extracted from the onset time (t_1) to point of failure (t_n). Onset time refers to the start time

for decrease in BWS. Failure refers to the time point at which the loss in independent trunk stability occurred and manual assistance was required. Failure (t_n) was established through a custom-written algorithm in MATLAB (MathWorks™, Natick, MA) that utilizes a 3-second (i.e. 180 frames) sliding window over the CoM velocity signal ($\dot{C}_{T,BoS}$), one frame at a time, to identify a window with the maximum mean velocity. Next, the $C_{T,BoS}$ values within this window were examined and the time point of the largest $C_{T,BoS}$ excursion was extracted as the point of failure (t_n).

To quantify improvements in participant's trunk independence post-intervention, we calculated bidirectional *Trunk Stability Limit* (TSL) for A/P and M/L directions, separately. First, the time-normalized $C_{T,BoS}$ function, $g(t)$, was centered by removing its overall mean (Eq. 1).

$$f(t) = g(t) - \left(\frac{1}{t_n - t_1} \right) \cdot \int_{t_1}^{t_n} g(t) dt \quad (1)$$

where t_1 is the onset time segment, and t_n is the point of failure segment.

Then, the integral of $f(t)$, the centered $C_{T,BoS}$ function, was calculated for each segment in time (i) (Eq. 2).

$$A_{t_i} = m_i \cdot \int_{t_i}^{t_{i+1}} |f(t)dt|, \quad i = 1, 2, \dots, n-1 \quad (2)$$

where m_i is the percentage body-weight support provided by the overhead BWS system, in kilograms. The sum of all calculated A_{t_i} integrals represents the total TSL value over time (Eq. 3).

$$TSL_t = \sum_{i=1}^{n-1} A_{t_i} = \sum_{i=1}^{n-1} \left(m_i \cdot \int_{t_i}^{t_{i+1}} |f(t)dt| \right) \quad (3)$$

Next, the TSL_t value was averaged over time to enable within-subject comparison across trials, in either A/P ($TSL_{A/P}$) or M/L ($TSL_{M/L}$) directions (Eq. 4).

$$TSL = \frac{TSL_t}{t_n - t_1}, [kg \cdot m] \quad (4)$$

Note: Smaller TSL values demonstrate a lower level of effort required by the participant to maintain their trunk stability and independence at minimal %BWS, with smaller excursions from the midpoint, and for the whole duration of the assessment.

Table 2 Clinical assessments at baseline and post ES-alone and ST + ES interventions.

Assessment		Side	Baseline	ES-alone	ST + ES
Motor Score	Upper-Extremity	–	27	28	28
	Lower-Extremity	–	0	0	0
mFRT (seated reach)	Anterior (Δ , cm)	Left	0	6.4	7.6
		Right	0	0	11.4
	Lateral (Δ , cm)	Left	0	5.1	6.4
		Right	0	3.8	3.8
ABLE Scale (subscale)	Item 1	–	0	2	2
	Item 2	–	1	1	1
	Item 3a	Left	0	0	0
	Item 3b	Right	0	0	0
	Item 4	–	1	1	1
	Item 5	–	3	3	3
	Item 6	–	1	1	1
	Item 7	–	0	0	1
	Item 8	–	0	0	1
	SCORE (out of 36)	–	6	8	10
Modified Ashworth Scale	Hip Flexors	Left	1	1	1
		Right	0	0	0
	Hip Extensors	Left	1	2	2
		Right	1	1	1
	Hip Adductors	Left	3	3	3
		Right	3	3	3
	Knee Flexors	Left	2	3	1+
		Right	1	1+	1+
	Knee Extensors	Left	1+	0	0
		Right	1	1	0
	Ankle Plantarflexors	Left	3	3	3
		Right	3	3	3
	Ankle Invertors	Left	0	0	0
		Right	0	0	0
	Ankle Evertors	Left	1	0	0
		Right	1+	0	0

Table 3 Trunk Stability Limit (TSL) and lowest percentage of body-weight support (%BWS) measures at baseline and post ES-alone and ST + ES interventions for the participant with SCI.

Time Point	Direction	TSL (kg.cm)	Lowest %BWS
Baseline	A/P	— *	50
	M/L	— *	With Trunk Assistance
ES-alone	A/P	54.0	19
	M/L	14.5	No Trunk Assistance
ST + ES	A/P	8.5	5
	M/L	3.9	No Trunk Assistance

*Participant was unable to perform the assessment without upper limb assistance.

Results

Clinical measures

Upper and lower extremity Motor Scores for ISNCSCI remained unchanged throughout the study. Total ABLE score improved from 6 at baseline to 8 and 10 post ES-alone and ST + ES interventions, respectively (Table 2). Main improvements occurred post ES-alone on item 1, sitting with back unsupported, and post ST + ES on items 7 and 8, wheelchair to chair transfers and support surface displacement while seated in a wheelchair. Modified Functional Reach test (mFRT) values improved by $\Delta 1.2$ cm (16%) on the left and $\Delta 11.4$ cm on the right side post ST + ES, compared to ES-alone. Participant's scores on the ABLE scale, mFRT, and Modified Ashworth Scale are reported in Table 2.

Trunk stability measure

Bidirectional TSL values (A/P and M/L directions) for post interventions are presented in Table 3. At baseline, participant's stability was maintained using upper limb manual assistance with over 50% BWS. Post ES-alone, trunk stability was maintained up to 19% BWS and the participant sustained stability at this BWS for ~ 3 seconds whereas post ST + ES intervention, trunk stability was maintained until 5% and sustained for ~ 60 seconds before failure. Post ST + ES bidirectional TSL values were lower compared to post ES-alone intervention. Note, for the able-body individual during a quiet-standing assessment without using the harness, the TSL values are calculated as zero. In addition, the integral of the CoM excursion curves for A/P or M/L directions result in values less than 0.06 kg.cm. Figure 1 illustrates the excursion of trunk Center of Mass (CoM) at each time point.

Muscle activation

No substantial change in EMG activity (EMG_{mean} and iEMG) of lower limb muscles among all testing sessions was observed (Figure 2). EMG outcome variables for the trunk muscles are reported in Table 4. At baseline, minimal activity in trunk muscles ($EMG_{mean} <$

$4.14 \pm 2 \mu V$ and iEMG < 0.01 mV.s) were observed, albeit, SES_R showed activation (EMG_{mean} : $10.29 \pm 7 \mu V$ and iEMG: 0.05 mV.s). After ES-alone, all trunk muscles (SES , IES , IO , EO) increased level of EMG activity, bilaterally, with higher amplitudes on the right. Post ST + ES intervention compared to ES-alone, all trunk muscles decreased EMG amplitudes and BD, except for left IO and bilateral SES muscles. Highest iEMG values were recorded for the left IES muscle post ES-alone (2.79 mV.s) as well as the SES muscles post ST + ES (left: 1.14 mV.s, right: 1.46 mV.s).

Discussion

In the current study, we evaluated the effects of longitudinal, multi-muscle electrical stimulation using traditional parameters of stimulation during unloaded (ES-alone) and loaded (ST + ES) conditions on postural stability for an individual with a cervical sensory- and motor-complete SCI. Regardless of condition, the participant required assistance at the knees during the stand assessment after each intervention phase.

At baseline, the participant was unable to stand independently and required manual assistance at the trunk and knees with 50% overhead body weight support. Following the 61 hours of multi-muscle stimulation of the lower limbs alone (ES-alone), standing ability and trunk independence dramatically improved. The participant could stand, while loading increased up to 81% bodyweight (i.e. 19% overhead body weight support) without trunk assistance, for a total period of around 2 minutes. Bilateral trunk muscle activation amplitudes markedly increased for the inferior and superior trunk muscles with little neuromuscular changes recorded in the lower limbs (Figure 2). The clinical values reflected gains in the recovery of the trunk and seated postural control. Post ST + ES training, the participant was able to stand with 95% bodyweight (i.e. 5% overhead body weight support) for a minute, with no trunk assistance. In addition, he could sit for greater than 30 seconds, without using any form of compensation, in a standard height chair without armrests, with the trunk

Figure 1 Excursion (on the transverse plane, horizontal axis: M/L, vertical axis: A/P) of the trunk center-of-mass (CoM) at baseline and post ES-alone and ST + ES interventions for the SCI participant. Light to dark colors indicate the progression of time, during the assessment period. At baseline, body-weight support (BWS) was set at 50% throughout the assessment. Post ES-alone and ST + ES interventions, BWS was lowered from 75% to the identified failure: 19% and 5%, respectively. The trunk CoM excursion for able-body control (AB) is superimposed on all plots, as a point of reference.

Figure 2 EMG activity of muscles (root-mean-square) during the assessment periods, at baseline and post ES-alone and ST + ES interventions.

Table 4 Measures of sEMG during the assessment period, at baseline, post ES-alone, and post ST + ES interventions.

Time Point	Muscle		EMG _{mean} (μ V)	EMG _{peak} (μ V)	BD (%)	iEMG (mV.s)
Baseline	IES	Left	— *	— *	— *	— *
		Right	— *	— *	— *	— *
	SES	Left	— *	— *	— *	— *
		Right	10.29 $\pm$ 7	41.57	13.87	0.05
	EO	Left	— *	— *	— *	— *
		Right	4.14 $\pm$ 2	8.72	0.18	— *
ES-alone	IO	Left	1.00 $\pm$ 1	2.58	0.36	— *
		Right	3.73 $\pm$ 3	16.84	6.08	0.01
	IES	Left	88.37 $\pm$ 59	475.09	14.30	2.79
		Right	3.82 $\pm$ 2	9.19	0.11	— *
	SES	Left	3.06 $\pm$ 3	37.61	1.74	0.01
		Right	49.37 $\pm$ 35	225.55	3.50	0.38
	EO	Left	8.17 $\pm$ 5	22.45	0.40	0.01
		Right	24.34 $\pm$ 17	135.34	0.62	0.03
	IO	Left	5.27 $\pm$ 5	40.30	0.20	— *
		Right	24.89 $\pm$ 18	139.40	0.68	0.04
ST + ES	IES	Left	— *	— *	— *	— *
		Right	— *	— *	— *	— *
	SES	Left	80.13 $\pm$ 55	358.48	16.61	1.14
		Right	66.47 $\pm$ 49	392.25	25.63	1.46
	EO	Left	6.39 $\pm$ 4	19.41	0.32	— *
		Right	5.01 $\pm$ 3	18.79	1.66	0.01
	IO	Left	22.11 $\pm$ 15	123.59	16.91	0.32
		Right	3.52 $\pm$ 2	12.09	0.26	— *

*No or minimal activity was detected from the corresponding muscle.

not touching the back of the chair and arms folded or rested in his lap.

The longitudinal training bouts of multi-muscle stimulation of the lower limbs alone (ES-alone, unloaded) potentially precipitated a change in central neural drive that cannot be explained by the supine training position. The systemic effect of single-muscle or multi-muscle electrical stimulation on functional, neuromuscular, or clinical gains has not been studied extensively, although there is now emerging work focusing on the parameters of stimulation and the potential effect of pulse width, frequency, and intensity of stimulation^{30,31} on the central contribution to muscle contraction. Frequently, peripheral or transcutaneous electrical stimulation involves parameters that are more traditional for recruiting motor units and depolarizing motor axons under the site of the surface electrodes; thus, promoting contraction through the summation of successive motor units or M-waves.³² More recently, authors have alluded to the electrical stimulation depolarizing sensory axons for generating “sensory or afferent volleys” that can recruit motor units in a more reflexive fashion to induce a contraction.^{30,31} A series of experiments involving electrical stimulation induced contractions of the triceps surae using pulse widths of 200, 500, and 1000 μ s and different frequency ranges (20-100 Hz) at submaximal intensities were all capable of generating contractions with a central contribution or a central torque.³¹ Therefore, we

propose the lower limb, multi-muscle stimulation paradigm, using traditional parameters of 300 μ s and 35 Hz, at the submaximal intensities may have generated some contractions with contributions from the central nervous system, albeit this proposition needs to be explored and evaluated much further.

Following 51 hours of stand training and multi-muscle stimulation of the lower limbs (ST + ES), the participant stood close to full bodyweight (95%) for one minute before failure, without manual assistance at the trunk. Compared to post ES-alone, the deviation of trunk CoM from mid base of support (Figure 1) and the TSL values (Table 3) decreased indicating an improvement in trunk independence. Additionally, the muscle activation in the superior trunk muscles increased, concomitant with a decrease in muscle activity of all other trunk muscles (Figure 2). In summary, post ST + ES training, the participant gained greater improvement in neuromuscular (Figure 2) and postural trunk control (Figure 1) during standing with a lower level of effort (i.e. decreased TSL value), compared to post ES-alone, similar to the able-body control during quiet standing using no harness (i.e. no BWS). Clinical values illustrated functional recovery gains for i) wheelchair transfers requiring less assistance, ii) improved seated balance as shown by improved bilateral mFRT values,³³ and iii) independent seated trunk rotation without assistance or without using any compensation techniques (e.g. use of arms).

These gains in functional recovery translated into gains in community ADLs where the participant reported only one individual's assistance is required for bed transfers instead of two individuals.

There have been animal and human studies to show that specificity of repetitive bouts of stand training directed towards sensorimotor pathways and central pathways can promote the recovery of full weight bearing for extended periods.^{34–36} Harkema *et al.*³⁶ have established that epidural stimulation combined with over 80 bouts of stand training can improve postural trunk stability during independent standing (without hip and knee assistance). Prior to stand training, independent trunk and posture during standing were not present. Interestingly, we have recently shown that the combination of repeated bouts of multi-muscle stimulation and standing has a greater effect on the amplitude of lower extremity muscle activation as well as trunk neuromuscular control during a 10-minute stepping trial compared to stand training alone and multi-muscle stimulation alone for individuals with motor complete SCI.^{10,11} The multi-muscle stimulation combined with the stand training for 51 sessions did not improve the reciprocal firing of the lower limbs during the 10-minute stepping trial, highlighting the lack of sensory input to neural drive or neural priming required for stepping as shown previously.¹⁵ In addition, Breuhner *et al.*¹³ and Forrest *et al.*¹⁶ have shown that after longitudinal training bouts of locomotor training for individuals with incomplete lesions, there were gains in upper extremity strength scores and gains in seated postural balance or trunk control. Cumulatively, these studies reinforce the potential systemic effect of sensory input to central neural drive from repeated bouts of step training and or stand training (with and without multi-muscle stimulation) for gains in neuromuscular and postural control. The limitation of the above results for the present study is the insufficient sample size to show a more generalized effect for SCI in stand training only (loaded), multi-muscle ES-alone (unloaded), and the combination (ST + ES) groups. Future studies should also investigate potential improvements in muscle mass and musculoskeletal adaptations (e.g. muscle force, tendon stiffness, etc.) that could lead to enhanced physical health and function.

Conclusions

In the current study, postural control and trunk independence dramatically improved following the multi-muscle stimulation of the lower limbs, combined with and without stand training. Therefore, we postulate that the lower limb, multi-muscle stimulation training

paradigm, using traditional parameters at submaximal intensities, may contribute to the functional recovery of the trunk. These improvements were observed to be greater while electrical stimulation was combined with stand training. Further studies, with a larger sample size, are required to examine the generalizability of the present findings, as well as to assess the motor patterns during assisted stepping following the multi-muscle electrical stimulation and stand training paradigms.

Disclaimer statements

Contributors None.

Declaration of interest None.

Conflicts of interest None.

Ethics approval Kessler Foundation Institutional Review Board.

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