Research Article

Effects of body weight-support treadmill training on postural sway and gait independence in patients with chronic spinal cord injury

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Objective: To examine the effects of a six-week body weight-support treadmill training (BWSTT) program on center-of-mass control and gait independence in chronic, incomplete spinal cord injury (iSCI) patients.
Design: Descriptive.
Setting: Clinica Los Coihues. Neurorehabilitation center in Santiago, Chile.
Participants: 17 chronic iSCI patients and 17 healthy subjects.
Outcome Measures: An instrumented sway (ISway) test was performed before and after the implementation of a six-week BWSTT program. The standing balance of participants was measured by Normalized jerk (NJ) and root mean square (RMS). These values were used to assess the standing balance of participants, and were correlated with the scores obtained on the Walking Index Spinal Cord Injury (WISCI) II test.
Results: Significant differences were found in standing balance (i.e., through NJ) after the BWSTT program ($P = 0.016$), but no significant differences were found in RMS values for postural sway ($P = 0.693$). None of the patients obtained improved WISCI II scores pre- vs. post-intervention.
Conclusion: While a BWSTT program can improve center-of-mass control in iSCI patients, no effects were recorded for gait independence.
Trial Registration: National Clinical Trials, registry number NCT02703883.

Keywords: Spinal cord injury, Body weight-support treadmill, Locomotor training, Jerk, Center of mass

Introduction

Spinal cord injury (SCI) is a devastating event, the degree and severity of which determines impacts to sensorimotor and autonomous functions.[1] The global yearly incidence of SCI is an estimated 83 cases per million persons, with 12,000 new cases reported in the United States each year.[2] Epidemiological studies report that approximately 50% of traumatic SCI patients suffer incomplete lesions.[3,4] The International Standards for Neurological Classification of SCI, as developed by the American Spinal Injury Association (ASIA), further defines approximately 40% of these patients as either motor non-functional (ASIA Impairment Scale (AIS) C) or motor functional (AIS D).[3] This population can usually execute many functional activities, such as standing balance and gait.[5] In fact, 80–100% of AIS D patients at least partially recover walking functions within a year after injury.[6]

Recovering locomotor function is a high priority for SCI patients, independent of injury severity and the time elapsed.[7] Specifically for incomplete SCI (iSCI) patients, the ability to walk can be limited by lower limb paresis, increased spasticity, poor coordination, and impaired postural control, all clinical factors that contribute to low walking speed and biomechanical gait inefficiencies.[8,9] Locomotor training promotes the plasticity of neural spinal circuits, which can induce

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functional recovery in iSCI patients.[1,10] Body weight-support treadmill training (BWSTT), in particular, is positively associated with increased muscle strength, kinematics, and spatiotemporal gait parameters, thereby promoting locomotor function recovery of the central nervous system in iSCI patients.[11–13] However, the contribution of BWSTT towards the recovery of walking independence in chronic iSCI patients is unclear.[13–15]

Reduced balance during walking is associated with a high risk of falls.[16] This risk is up 75% after iSCI,[17] which directly impacts on autonomy and functional independence. Currently, clinical rating scales such as the Berg Balance Scale (BBS) are regularly used to assess balance in SCI patients, and several studies using this scale have shown that BWSTT improves balance.[4,5,18] However, while clinical rating scales assess general functional aspects of balance and transitions,[19] analytical components of postural control are not evaluated, including center-of-mass (COM) displacement and associated derivatives. These postural-control components are directly related to proper body stability and reflect how the nervous system controls the complex sensorimotor task of maintaining bipedal equilibrium.[20] No clinical rating scale has, as yet, proven to accurately measure postural stability in iSCI patients.

Force plates that analyze center-of-pressure displacement in a quiet stance are the gold standard for balance assessments in patients with musculoskeletal and neurological injuries.[21] However, force plates are expensive, not easy to move, and infrequently available in rehabilitation centers.[22] Inertial sensors are a possible valid and reliable alternative for assessing postural control in people with disabilities.[23,24] More specifically, body-worn accelerometers show promise as a practical and low-cost option for measuring instrumented postural sway (ISway) and, consequently, replacing force-plate posturography.[25]

The ISway test establishes sway through time-domain, frequency-domain, and JERK measures. These data respectively characterize the amplitude, frequency, and smoothness of body sway.[23] JERK, a time derivative of acceleration, is used as an empirical measure of sway smoothness,[26] and, together with time-domain parameters, is more reliable than frequency-domain parameters.[23] Evaluating the basic accelerometric parameters associated with JERK analysis might permit discriminating between postural control strategies in different neurological diseases.[26,27] These data might also be applicable in obtaining objective parameters of sensory-motor abilities and establishing the efficacy of therapeutic tools.[27]

The implementation of BWSTT during early rehabilitation seems to help restore walking functions in iSCI patients, as widely associated with improvements in balance and muscle strength.[11,13] However, the effectiveness of BWSTT in improving analytical measures of postural control and functional independence during locomotion has not been determined for long-term rehabilitation of chronic injuries.[19,27] Therefore, the aim of this study was to assess if a six-week BWSTT program improved COM control in chronic iSCI patients during a standing balance task. This was measured using the ISway test, which included an inertial sensor positioned at L5. Additionally, evaluations were conducted to determine if changes in COM control were correlated with the achievement of independent walking, where the degree of gait independence was measured by the Walking Index Spinal Cord Injury (WISCI) II scale.[4] The WISCI II scale is more sensitive than other functional scales for assessing balance during gait in SCI patients.[4,9] Overall, the assessed six-week BWSTT program positively impacted COM control, as measured by the normalized JERK (NJ) parameter. However, this improvement in standing balance did not correlate with improvements in gait independence.

Methods

Design

Patients were recruited from Clínica Los Coihues (Santiago, Chile), which provides outpatient and hospital care. Consolidated Standards of Reporting Trials (CONSORT) recommendations for nonpharmacological studies were followed. This study was approved by the Ethics Committee of the Universidad de Chile (Santiago, Chile), and is registered in the National Clinical Trials database under registry number NCT02703883. Written informed consent was obtained from all subjects prior to participation.

Participants

The study included 17 iSCI patients and 17 healthy subjects. The degree of SCI was determined through a physical examination by a rehabilitation physician. The physician evaluated the presence of dermatomes and myotomes, as established by ASIA, for each patient (Table 1).[28] The healthy control group was statistically similar in age and sex to the patient group (Table 2).

Inclusion criteria were as follows: individuals ≥ 18 years-old; neurological level of C5 or below; AIS C or D classifications; traumatic and non-traumatic injury; non-progressive lesions; onset > 12 months; ability to ambulate with or without assistive devices; ability to

Table 1 Demographic traits of the assessed spinal cord injury patients.

Patient	Sex	Age (years)	Height (cm)	Level of injury	Time elapsed since injury (months)	AIS classification
1	M	65	167	T10	33	C
2	F	51	163	C7	18	D
3	M	64	167	L2	29	C
4	M	58	170	C6	31	C
5	F	28	157	C5	14	C
6	M	45	178	C5	14	C
7	M	33	170	T12	17	D
8	M	25	168	C6	15	D
9	M	19	167	T9	18	D
10	M	26	177	T6	27	D
11	M	30	175	C6	23	C
12	M	33	170	C7	31	C
13	M	45	173	T10	28	C
14	M	48	165	C7	13	C
15	F	59	161	C6	17	D
16	M	47	170	C7	19	D
17	M	63	173	C6	48	C

M, male; F, female; AIS, American Spinal Cord Injury Association impairment scale.

maintain a standing position for 30 s without assistance; and ability to follow verbal or visual commands.[29]

Exclusion criteria were as follows: unstable orthopedic injuries; osteoporosis with a high risk for pathological fracturing; cutaneous lesions and/or pressure ulcers; pregnancy; body weight >150 kg.[29]

Training protocol

The BWSTT program was distributed across 18 sessions over a six-week period (i.e., three sessions per week). Each session consisted of three 6-minute series of locomotor treadmill training, with 2 minute breaks between each series. In the first training session, a trained therapist selected the appropriate amount of body weight support for each participant. This weight was determined according to motor commitment and exercise tolerance. For safety, initial treadmill speed was 0.5 km/h. Furthermore, two physical therapist sat on either side of the treadmill and assisted participants in the gait cycle when it was necessary.[29]

Table 2 Statistical comparisons between the control and iSCI groups.

	Control Group	iSCI Group	P
	(n = 17)	(n = 17)	value
Age (years)	37.5 ± 8.9	43.5 ± 3.7	0.181 (ns)
Sex			
Male, n (%)	13(76.5%)	14 (82.4%)	
Female, n (%)	4 (23.5%)	3 (17.6%)	
Height (cm)	171.6± 6.6	168 ± 1.3	0.208 (ns)
NJ	4.055± 0.8	5.803± 1.7	0.009
RMS	0.041±0.008	0.115±0.05	0.0001
WISCI-II	-	18 (13 – 20)	
AIS Classification			
AIS C, n (%)	-	10 (58.8%)	
AIS D, n (%)	-	7 (41.2%)	
Level of injury			
Cervical, n (%)	-	11 (64.7%)	
Thoracic, n (%)	-	5 (29.4%)	
Lumbar, n (%)	-	1 (5.9%)	
Time elapsed since injury, months	-	19 (16 – 30)	

iSCI, incomplete spinal cord injury; NJ, normalized jerk; RMS, root mean square, ns = non-significant. Values are expressed as the mean ± SD if data is normally distributed or as the median (P25-P75) if data distribution is skewed.

Training sessions were conducted on an h/p/cosmos® treadmill system, which included a specialized built-in weight support device, namely, the h/p/cosmos® airwalk ap (HP Cosmos sports & medical GmbH, Nussdorf-Traunstein, Germany). A pulley system was used to hoist participants into a standing position over the treadmill. Once upright, a second set of cables was used to connect participants to weight stacks located at the front of the treadmill. Weight stacks were set at a predetermined percentage of each participant's body weight. The speed of the h/p/cosmos® treadmill system ranges between 0.1 and 22 km/h, and speed can be adjusted in 0.1 km/h increments.[29]

Prior to and after the six-week BWSTT program, participants were assessed i) by a physical therapist; ii) through a standing balance test (i.e., ISway); and iii) using WISCI II to determine walking independence. Standing balance was measured via an ISway test that employed the APDM Mobility Lab™ (APDM Inc., Portland, OR, USA).[23] Briefly, a wireless Opal™ inertial sensor with a docking station was attached with Velcro straps to the waist of each participant at level L5. The sensor recorded 2D linear accelerations and angular velocity, which were transmitted to a wireless receiver that streamed data to a laptop. Outcome measures were recorded and automatically generated using the Mobility Lab™ software (APDM Inc.).[23] For the ISway test, participants were instructed to maintain an upright standing position, with the arms crossed over the chest, and a fixed heel-to-heel distance of 10 cm.[23] Data were recorded for three quiet-standing trials (30 s each).

The obtained ISway measures were validated against postural sway values previously determined through center-of-pressure displacement tests with a force plate.[23] The recorded ISway parameters included the root mean square (RMS, m/s^2) of sway trajectory and JERK normalized to the excursion and duration of the sway trajectory. JERK was defined as the third derivative of displacement, and the subsequently NJ was used as the index of trajectory smoothness.[26,28] The NJ was calculated as shown in Eq. (1):[30,31]

$$NJ = \sqrt{1/2} \times \int_{t1}^{t2} (d^3p \div dt^3)^2 \times (t^5 \div (P_{t2} - P_{t1})^2) dt \quad (1)$$

where Pi is the COM position at the ith sample; $t1$ is the onset of movement; $t2$ is the offset of movement; $d3p/dt3$ is the third derivative of displacement (i.e., JERK); t is movement time; and $Pt2 - Pt1$ is movement range.

Statistical analysis

Statistical analyses were performed using the SPSS v.22 software (IBM Corp., Armonk, NY, USA). All data were analyzed for normal distribution with the Shapiro-Wilk test. Continuous variables were presented, where appropriate, as means ± standard deviation (S.D.) or as medians and 25th-75th percentiles. Data were analyzed using one-way ANOVA with repeated measures in each group. Differences were considered statistically significant at $P < 0.05$. Since the WISCI II test data had a non-parametric distribution, Spearman's rank correlation coefficient was used to analyze relationships between basal NJ and basal performance in the WISCI II test. A *post-hoc* power analysis was conducted using the G*Power v.3.1.8.2 statistical software (Dusseldorf, Germany).

Results

The 17 included iSCI patients presented C7 to T10 injury levels classified as AIS C or D. Participants were allowed to wear their regular ankle-foot orthosis during all training sessions and to use their usual walking devices during assessments. All participants successfully completed the six-week BWSTT program and the ISway test. Traits of the study groups (i.e., patients and healthy subjects) are given in Tables 1 and 2.

Standing balance

Differences in standing balance between iSCI patients and healthy participants were established with the NJ and RMS, both computed during the ISway test. Significant differences in initial NJ measurements existed between groups ($P < 0.001$) (Fig. 1). Furthermore, iSCI patients had an increased initial RMS value as compared to the control group ($P < 0.001$) (Fig. 2).

After the six-week BWSTT program, no significant differences in ISway RMS values were found between groups ($P = 0.693$) (Fig. 2). A noteworthy post-intervention change was found for the NJ of iSCI patients

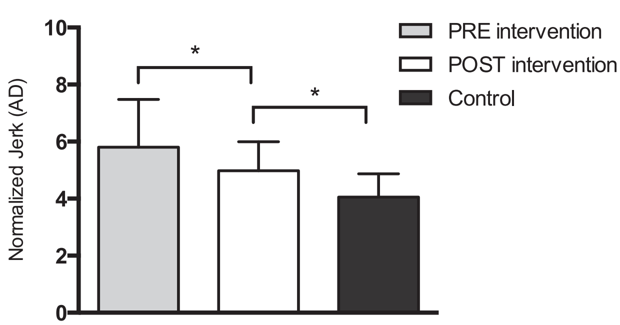

Figure 1 Differences in normalized JERK (NJ) for iSCI patients pre- and post-intervention (P = 0.016), between pre-intervention values for iSCI and control subjects (P < 0.001), and between post-intervention values for iSCI patients and control subjects (P = 0.004). Error bars represent one standard error (SE) of the mean. Significant differences between groups are denoted by an asterisk (*). AD, amplitude duration.

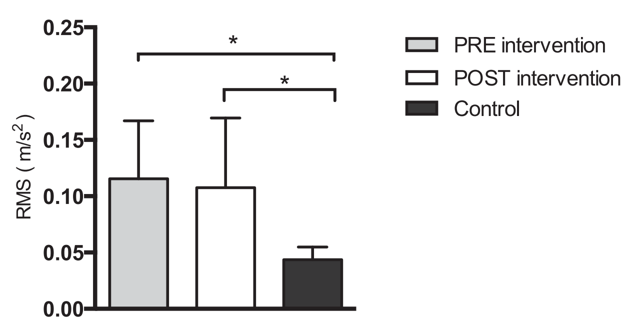

Figure 2 Differences in root mean square (RMS) values for iSCI patients pre- and post-intervention (P = 0.693), between pre-intervention values for iSCI patients and control subjects (P < 0.001), and between post-intervention values for iSCI patients and control subjects (P < 0.001). Error bars represent one standard error (SE) of the mean. Significant differences between groups are denoted by an asterisk (*).

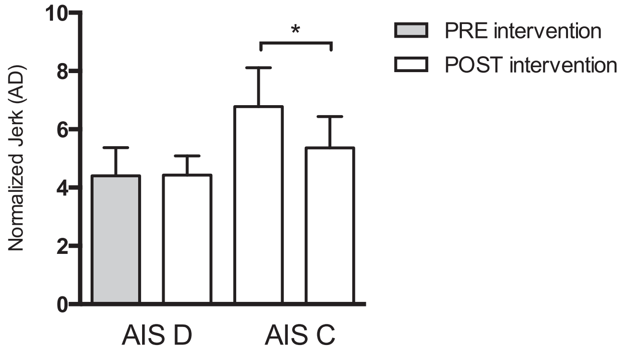

Figure 3 Differences in normalized JERK (NJ) values pre- and post-intervention in AIS D (P = 0.931) and AIS C (P = 0.008) patients. Error bars represent one standard error (SE) of the mean. Significant differences between groups are denoted by an asterisk (*). AD, amplitude duration.

(P = 0.016) (Fig. 1), but this improvement remained poorer than values obtained in control participants.

Initial and post-training NJ (Fig. 3) and RMS (Fig. 4) values were also compared within the AIS C and AIS D patient sub-groups (Table 3). AIS C patients showed a significant decrease in the NJ after training (P = 0.008). In contrast, AIS D patients evidenced no significant changes in this indicator (P = 0.931). No significant differences in RMS were found in either iSCI patient group.

Despite achieving decreased NJ values post-training, no changes in gait independence were found. To determine this, initial and post-training NJ values and WISCI II scores were correlated for all iSCI patients (Fig. 5). An inverse correlation was found between the initial measures (P = 0.020, r = 0.564). However, no statistically significant correlation was observed between post-training NJ values and WISCI II scores (P = 0.526, r = 0.151).

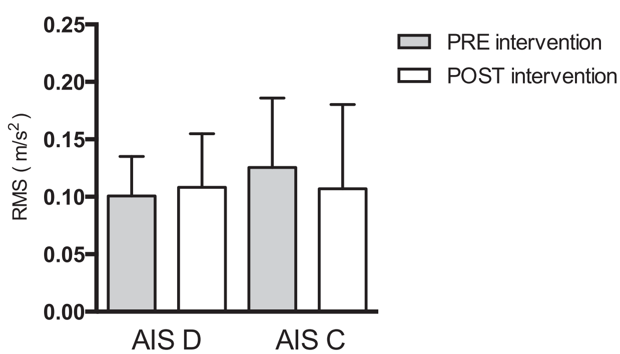

Figure 4 Differences in root mean square (RMS) values pre- and post-intervention in AIS D (P = 0.630) and AIS C (P = 0.244) patients. Error bars represent one standard error (SE) of the mean.

Table 3 Normalized JERK and RMS values pre- and post-BWSTT.

	iSCI Group AIS C (n = 10)			iSCI Group AIS D (n = 7)		
	Initial	Post-BWSTT	*P*-value	Initial	Post-BWSTT	*P*-value
RMS	0.107 ± 0.07	0.126 ± 0.06	0.244 (ns)	0.101 ± 0,03	0.108 ± 0.05	0.630 (ns)
NJ	6.80 ± 1.33	5.37 ± 1.07	0.008	4.41 ± 0.97	4.43 ± 0.67	0.931 (ns)

Abbreviations: iSCI, incomplete spinal cord injury; NJ, normalized jerk; RMS, root mean square, ns = non-significant. Values are expressed as the mean ± SD.

Discussion

To our knowledge, this is the first study to evaluate the impact of a six-week BWSTT program in chronic iSCI patients (AIS C and D) using an ISway test with inertial sensors (i.e., an accelerometer, a magnetometer, and a gyroscope).The main findings were as follows: (1) the NJ of chronic iSCI patients significantly decreased after completion of the BWSTT protocol; (2) no significant pre- vs. post-BWSTT differences in RMS values were recorded; and (3) postural control improvements in the standing balance of iSCI patients, measured by the NJ, had no impact on gait independence.

Since the ISway test provides sensitive measures of the complex sensorimotor control loop responsible for

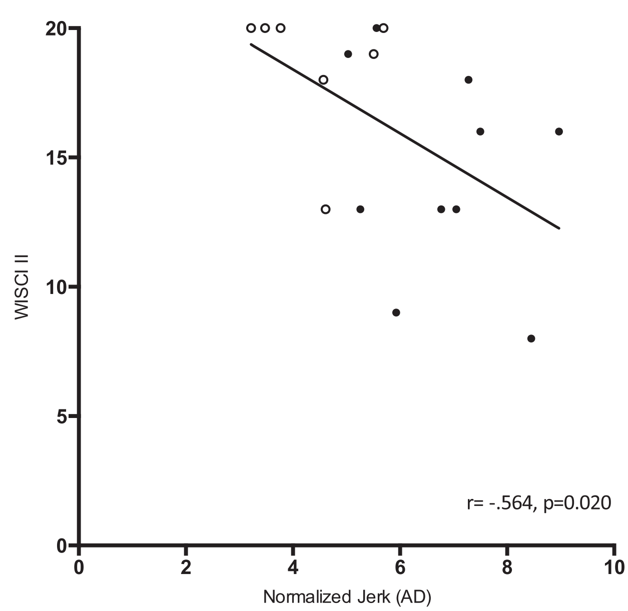

Figure 5 Inverse correlation between initial WISCI II scores and normalized JERK (NJ) values in iSCI patients. Black dots = AIS C patient values; White dots = AIS D patient values. Spearman's correlation coefficients and P values are provided for each association. The solid line indicates the computed linear correlation. r = 0.564; P = 0.020. AD, amplitude duration.

regulating standing balance, it is an excellent method for measuring postural instability.[23] Indeed, the ISway test could be used to initially assess standing balance before implementing interventions. Some research shows that postural sway measurements are more affected by a physical therapy postural training program than clinical rating measurements.[23,32] The ISway test establishes JERK, which is an indicator of sway smoothness for the assessed movement.[20,26] Furthermore, this test is the most sensitive measurement for discriminating postural-control differences in Parkinson's disease.[23,26] Nevertheless, the potential applications of the ISway test are not limited to Parkinson's disease. This method can be used to obtain the amplitude, smoothness, and frequency measures needed to characterize body sway,[33] all parameters that would be useful for testing any individual with postural and motor control deficits.

Effects of the BWSTT program on COM oscillatory dynamics

The assessed iSCI patients presented altered initial values of NJ (Fig. 1) and RMS (Fig. 2). In other words, despite being able to generate postural adaptations to environmental challenges and being able to complete the standing balance task, these patients could not fully compensate for the postural control changes caused by their sensory and motor impairments.

Standing balance requires appropriate sensory inputs, brain integration, and an intact neuromuscular system. iSCI patients may present increased postural sway as a result of deficient motor responses related to timing muscle contractions. This, in turn, would be the consequence of the residual motor pathways left after SCI being insufficient to react and generate appropriate postural adjustments. Increased postural sway can also result from damaged somatosensory pathways.[6] These pathways are often compromised after SCI and subsequently reflect noisy somatosensory feedback from foot pressure, muscle proprioceptors, and joint receptors.[34] Damaged somatosensory pathways can ultimately provide inaccurate information about body position in space and result in an abnormal internal map of stability limits. Altogether, these possible consequences of SCI can generate frequent, abrupt corrections of postural sway direction and may be responsible for higher JERK values as compared to healthy individuals (Fig. 1).

The presently obtained results also show that NJ significantly decreased in iSCI patients after the BWSTT program (Fig. 1). Although the NJ was measured in only 17 iSCI patients, the respective *post hoc* power was 98.8%. In contrast, RMS values did not change significantly (Fig. 2). These results indicate that the BWSTT program helped iSCI patients improve their ability to spontaneously compensate smoothness, the amount of sway trajectory was unaffected. In other words, iSCI patients did not decrease COM oscillation levels after the BWSTT program (Fig. 2). However, their ability to control COM acceleration changes during the ISway test was improved after program completion (Fig. 1).

A more detailed analysis revealed that 8 of the 17 iSCI patients underwent a significant decrease in sway NJ. All eight were classified as AIS C patients and evidenced the worst initial postural control measures (Fig. 3). These results indicate that the primary benefactors of a BWSTT program would be individuals with poor motor performance and static postural control. Regarding RMS measures, no significant differences were found among the AIS C patients following completion of the BWSTT program (Fig. 4).

Correlation between ISway measures and WISCI II scores

An inverse correlation was found between initial JERK values and WISCI II scores for iSCI patients (Fig. 5), i.e., individuals with worse indicators of postural control (increased JERK) presented poorer gait independence. This finding supports the sensitivity of accelerometer-based measures of sway in differentiating degrees of gait functionality, specifically as related to the NJ indicator.

Despite the inverse correlation between accelerometer-based measures of sway and WISCI II scale scores, significant changes in the NJ after the six-week BWSTT program did not correlate with improvements in gait independence. These results indicate that changes in static postural control (measured by the NJ) did not generate functional improvements (measured by the WISCI II scale).

Effects of the BWSTT program on gait independence in chronic iSCI patients

No changes were found in the gait independence of iSCI patients after the six-week BWSTT program. Individuals with neurological disorders that participate in motor learning processes display significant, correlative changes in sensorimotor performance and functional independence. Recent research suggests that after neurological damage there is a short plasticity window (i.e., 3–6 months) during which motor learning can be achieved through physical and pharmacological therapies.[35,36] In turn, improvements achieved in the chronic stages of injury are related to optimization processes of compensatory behaviors, which may be less effective in achieving functional goals. In the present study, all of the participating iSCI patients were in the chronic stage of injury (i.e. > 12 months post-injury). The lack of improvements in gait independence as a result of improvements in postural control indicators (NJ) could be due to an absence of experiencing-learning processes, which likely would have allowed the iSCI patients to significantly improve their motor performance.

Another possible explanation for the obtained results is that various approaches exist for gait training in iSCI patients, and while many show improvement potential, no approach has been decidedly established as superior.[37] The recommended methodology is to use different therapeutic strategies for recovering gait and to combine conventional therapies with conventional over-ground training and BWSTT. In the present study, only one intervention was tested. While this intervention led to significant changes in static postural control, these improvements did not correlate with improvements in gait independence. These results support the notion that the neural controls of balance and gait are relatively independent. That is, measures of postural sway while standing on a firm surface with the eyes open appear insufficient for predicting clinical improvements in gait for individuals with SCI. Although many measures of postural sway and gait were abnormal in the present study, balance control while standing was not related to gait control, suggesting that postural sway in these static conditions could not predict dynamic postural instability while walking. Postural control models further demonstrate that instability of the postural control loop is also reflected by an increased postural sway frequency, as resulting from the nervous system increasing the stiffness and frequency of postural corrections.[38,39]

In summary, no single measure of balance or gait can fully characterize mobility impairments in individuals with SCI, but a small set of relatively independent measures is useful for strategic assessments and targeted rehabilitation. Finally, a significant limitation of this study in correlating NJ improvements and changes in gait independence was that five of the iSCI patients achieved a maximum WISCI II score before beginning the BWSTT program.

Conclusion

Balance is an important ambulation component for those with spinal cord injury. This study evidenced that a six-week body weight-support treadmill training program modified center-of-mass control, as measured by the normalized JERK parameter. Nevertheless, this improvement in static postural control did not correlate with improvements in gait independence. Further research is needed to assess the impact of longer training protocols or of a similar program in acute iSCI patients. Future studies should also to better establish the relationship between postural control and functional independence.

Disclaimer statement

Conflicts of interest The authors declare no conflict of interest.

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