Postural regulatory strategies during quiet sitting are affected in individuals with thoracic spinal cord injury

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Abstract

Thoracic spinal cord injury (SCI) can have significant negative consequences, which can affect the ability to maintain unsupported sitting. The objectives of this study were to compare postural control of individuals with high- and low-thoracic SCI to able-bodied people and evaluate the effects of upper-limb support on postural control during quiet sitting. Twenty-five individuals were recruited into: (a) high-thoracic SCI; (b) low-thoracic SCI; and (c) able-body subgroups. Participants were seated and asked to maintain a steady balance in the following postures: (1) both hands resting on thighs; (2) both arms crossed over the chest; and (3) both arms extended. Center of pressure (COP) fluctuations were evaluated to compare postural performance between groups and different postures. Results showed that individuals with high- and low-thoracic SCI swayed more compared to the able-bodied group regardless of upper-limb support. No differences between the two SCI groups were observed, but the neurological level of injury was correlated to postural performance implying that those with higher injuries swayed more and faster. Unsupported sitting was more unstable in comparison to supported sitting posture, especially in the anterior-posterior direction. The velocity of postural sway was not different between groups, but the results suggest that postural regulation had unique effect during different postures in different groups. These results imply reduced postural stability after thoracic SCI. Overall, the way individuals with high-thoracic SCI achieved stability was different from that of individuals with low-thoracic SCI, suggesting different postural regulation strategies.

Key words: spinal cord injuries; thoracic injuries; posture; sitting position; upper-limb.

Introduction

Postural instability during sitting balance is a significant problem for individuals with spinal cord injury (SCI). Injuries above the mid-thoracic neurological level often result in motor and/or sensory impairment of the trunk muscles [1-3]. As a result, individuals with thoracic SCI compensate for the impairment by using non-postural muscles to maintain sitting, but their balance remains compromised [3]. They often utilize compensatory mechanism, which includes using their arms for support [4-6] and foot support [7].

It has previously been shown that trunk control is mostly responsible for the impaired sitting balance in individuals with SCI, whereas foot support provides passive forces [8]. Upright sitting posture is mostly maintained by modulating the tension of the posterior muscle chain. Grangeon et al. [5] compared sitting balance of individuals with SCI to able-bodied people during quiet sitting in various upper-limb support conditions. They showed that individuals with SCI have reduced stability irrespective of the upper-limb support during quiet sitting compared to able-bodied individuals. Moreover, they showed that upper-limb support can improve seated stability in individuals with SCI, especially in the anterior-posterior direction. Shirado et al. [9] showed that outstretching the arms over the thighs decreased anterior-posterior stability during quiet sitting, compared to sitting with hands supported on the thighs. This is likely because outstretching the arms typically shifts the center of mass superiorly and anteriorly with respect to the hip joint, creating greater postural oscillations [5,9]. Ability to maintain hands-free unsupported sitting is thought to be more difficult for individuals with high-thoracic and low cervical SCI compared to able-bodied people [6]. Paresis or paralysis of back and abdominal muscles minimizes the contribution of these postural muscles to sitting balance. Individuals with SCI often use upper extremities for support and when asked to elevate their arms they often have worse postural control, whereas individuals with low-thoracic SCI often have sufficient postural stability to maintain seated balance with both arms elevated [6].

Chen et al. [1] compared sitting balance performance of individuals with high- and low-thoracic SCI during static balance (i.e., quiet sitting) and dynamic balance (i.e., weight transfer) tasks. Individuals with low-thoracic SCI demonstrated better dynamic stability, compared to high-thoracic SCI. However, there were no differences in static sitting balance between individuals with high- and low-thoracic SCI [1]. Also, neurological injury level did not correlate well with static sitting stability among individuals with thoracic SCI, but it was correlated with dynamic stability performance [1]. However, Chen et al. [1] compared only one measure related to the postural performance (i.e., related to the amount of sway) and did not have sufficient outcome measures to fully characterize postural control mechanisms in the context of static sitting balance [4]. Furthermore, they did not examine the effects of upper-limb support on sitting balance nor compare sitting balance of individuals with thoracic SCI to the able-body control group. Previous investigations [1,9] also did not account for the effects of foot support on postural stability, which has been shown to influence sitting balance [7,8].

To date, there is no clear understanding of how postural control differs in individuals with high- and low-thoracic SCI and how upper-limb support influences sitting balance in these individuals. Therefore, the objectives of this study were to: (1) compare quiet sitting postural control of individuals with high- and low-thoracic SCI as well as able-bodied individuals; and (2) evaluate the effect of upper-limb support on postural control. We hypothesized that postural control will be impaired in individuals with thoracic SCI and that upper-limb support will have different effects on individuals with high- and low-thoracic SCI.

Methods

Participants

A total of twenty-five participants were recruited into: (a) high-thoracic SCI (SCI_H); (b) low-thoracic SCI (SCI_L); and (c) able-body (AB) subgroups (Table 1). Individuals were recruited in the SCI groups if they had a motor and/or sensory incomplete or complete thoracic SCI American Spinal Injury Association (ASIA) Impairment Scale (AIS) A to C, and could independently maintain unsupported sitting. Individuals with SCI were excluded if they had secondary complications, pressure sores, or other impairment, which may limit their ability to perform the experiment. Individuals were recruited in the able-bodied group if they had no history of impairments that could affect their sitting balance or performance of the experiment. All participants gave written informed consent in accordance with the Declaration of Helsinki. The experimental procedures were approved by the local institutional Research Ethics Board.

Experimental protocol

Participants were seated upright such that their thigh-trunk angle was at approximately 90°. They were seated on a height-adjustable chair without back support and with their feet parallel and flat on the ground. The height of the chair was adjusted for each participant such that the knees were flexed at about 75-85^o and were seated centrally with 75% of their thighs supported on the seating surface (Figure 1). Participants were asked to maintain visual contact with a target set at eye level, 2m in front of them [4,5]. Participants were asked to keep a steady sitting balance in the following postures: (1) both hands resting on their thighs (HT); (2) both arms crossed over their chest (AC); and (3) both arms elevated (abduction=45^o and flexion=90^o) (AE) as illustrated in Figure 1. Participants were instructed to refrain from using their hands for support. The position of the arms and feet was verified before each task using a goniometer to ensure consistency. Each posture was recorded over 50 seconds and repeated in two separate trials. All trials were performed in a predetermined random order.

Data acquisition

The seating and foot support surfaces were instrumented with AMTI force platforms (Advanced Mechanical Technology, Inc., Newton, MA, USA, OR6-7-1000) and strain gauge transducers (MC3A-3-250). The obtained forces and moments were used to compute the global center of pressure (COP) underneath both the seat and foot support surfaces [5,10,11]. The x and z denote the respective coordinates of the anterior-posterior (AP) and medial-lateral (ML) directions in the horizontal plane and the radial distance (RD) time series was calculated as $RD = \sqrt{AP^2 + ML^2}$ to represent the combined AP and ML COP [12,13] and evaluate postural control during sitting [4,5,8]. Data were sampled at 600 Hz and stored on a computer using a custom LabVIEW program (National Instruments, Austin, USA). All data was down-sampled to 300Hz and a low-pass filtered using a zero-lag 2nd order Butterworth filter with a cut-off frequency at 5 Hz [5,12,13].

Data analysis

Time and frequency domain parameters that quantified COP fluctuations were calculated during the 30 second steady state period (first and last 10 seconds of each trial from the original 50 second recording were excluded). The results obtained for the two repeated trials were averaged for each subject in each posture. The COP fluctuations were first referenced by subtracting them from their mean [12]. Time-domain measures included: (i) mean distance (MD)

- average distance traveled by the COP; (ii) 95% confidence ellipse (AREA-CE) - estimate of the elliptical area of best fit enclosed by 95% of COP points; (iii) mean velocity (MV) - average velocity of the COP time series; and (iv) mean frequency (MFREQ) - a hybrid measure that represented the rotational frequency of the COP series by the ratio of the mean velocity to the mean distance in revolutions per second (Hz) [12]. Frequency-domain parameters were calculated in the frequency range from 0.15 to 5.0 Hz [5,12] and included: (i) centroidal frequency (CFREQ) - central mass frequency (Hz); and (ii) frequency dispersion (FREQD) - a unit-less measure of the variability of the power spectral density [12].

Statistics

Comparisons were performed using the mixed-design analysis of variance (ANOVA) to evaluate within-subject effects (i.e., differences between HT, AC, and AE postures) and between subject effects (i.e., differences between SCI_H, SCI_L, and AB participant groups), while ensuring all assumptions for the study design were met [14]. Significant results on the ANOVA test were followed up with the Tukey's post-hoc multiple comparisons with a Bonferroni correction. Since the Shapiro-Wilk test showed that all measures were not normally distributed, a logarithmic transformation was performed to normalize the data prior to performing the ANOVA. Spearman correlation coefficients between the COP measures and participants' demographic and clinical assessments were also calculated among individuals with SCI (both SCI_H and SCI_L groups combined). Significance level was set to $p<0.05$.

Results

Participants

The mean age (*F*(2,24)=0.782, p=0.470), weight (*F*(2,23)=0.334, p=0.525), and height (*F*(2,24)=0.664, p=0.720) were similar across participant groups (Table 1).

Postural control measures

Postural control comparison results are summarized in Table 2. The amount of sway (MD and AREA-CE) had a significant posture effect and group effect, with no significant interactions. Post hoc analysis revealed that in unsupported postures (AC and AE), the amount of sway was typically larger compared to the supported posture (HT). Also, both individuals with high- and low-thoracic SCI (SCI_H and SCI_L) swayed more than the able-bodied group (AB) in the RD and ML directions. The postural sway velocity (MV) was significantly affected by the posture during sitting and there was an interaction between the posture and the participant groups. Post hoc analysis revealed that in unsupported postures (AC and AE), the sway velocity was larger compared to the supported posture (HT). The frequency measures (MFREQ and CFREQ) had a significant posture effect in the RD and ML directions and a significant group effect with an interaction between posture and group. Post hoc analysis revealed that when arms were extended (AE posture), the frequency of fluctuations was increased compared to when hands were supported (HT posture). In both individuals with high- and low-thoracic SCI (SCI_H and SCI_L), the frequency of fluctuations were lower compared to the able-bodied individuals (AB). The frequency dispersion (FREQD) had a significant group effect and no interactions. Post hoc analysis revealed that individuals with high-thoracic SCI (SCI_H) have a higher frequency dispersion in comparison to the individuals with low-thoracic SCI (SCI_L) in the RD and AP directions.

Correlations between postural control and clinical measures

Correlation results are summarized in Table 3. The neurological level of injury was positively correlated to the ML direction amount and velocity of sway (MD and MV) and frequency dispersion (FREQD), as well as AP direction frequency measures (MFREQ and CFREQ). The ASIA motor and sensory score was negatively correlated to the amount of sway (MD and AREA-CE) and velocity of sway (MV) when arms were extended (AE posture). The AIS classification and ASIA motor and sensory impairment scores were negatively correlated with the frequency measures (MFREQ and CFREQ) when the arms were crossed on the chest (AC posture). Finally, the ASIA sensory impairment was negatively correlated to frequency dispersion (FREQD) during supported posture (HT posture).

Discussion

Postural stability impairment after SCI

Our results showed that the amount of postural sway (MD and AREA-CE) was larger among both high- and low-thoracic SCI group compared to able-bodied individuals (Table 2), which supports our hypothesis. These results were observed in the anterior-posterior and medial-lateral directions, with more pronounced differences in the later. More sway during sitting balance implies that individuals with SCI are less stable and have impaired posture [4]. Considering that foot support [7,8] and upper-limb support on the thighs [5] provides passive forces via the posterior postural chain during sitting balance, larger instability in the medial-lateral plane is not surprising. The observed medial-lateral instability of the trunk is consistent with findings in individuals with thoracic SCI [9] and cervical SCI [8]. Our present results showed no differences in postural stability between the high and low SCI individuals as previously suggested [1]. Alongside, our results showed weak correlations between neurological level of injury and postural performance, consistent with previous reports [5]. These results suggest that individuals with higher neurological levels of injury typically swayed more and faster during unsupported sitting postures (Table 3), implying that neurological level of injury does affect postural control during quiet sitting. Similarly, ASIA motor and sensory impairment scores were correlated to the amount of postural sway and velocity during unsupported sitting (Table 3). These results also suggest that individuals with higher clinical motor and sensory impairment scores swayed more and faster, implying that they were less stable than those who were less impaired.

Our results also showed that the speed of postural sway (MV) was not different between the participant groups, but the frequency measures (MFREQ and CFREQ) were different in both high- and low-thoracic SCI individuals compared to able-bodied participants (Table 2). Mean velocity describes the control demand that the postural system needed in order to achieve stability [4]. Grangeon et al. [5] have previously shown that individuals with SCI had larger mean velocity, implying increased control demand compared to able-bodied individuals. Similarly, larger mean velocity of trunk fluctuations was shown among individuals with cervical injury [8]. In our current study, there were no differences, which could suggest that individuals with thoracic SCI require less work compared to those with cervical injuries. Furthermore, our results showed that the frequency (CFREQ) among both high- and low-thoracic SCI individuals was smaller compared to able-bodied participants. Individuals with cervical SCI did not have different centroid frequency compared to able-bodied people [8]. However, Grangeon et al. [5] had consistent results to ours in individuals with thoracic and cervical SCI. Smaller centroidal frequency is associated with the larger moment of inertia of a swaying object [5,8]. This implies that the system is more sluggish, requiring more time to return to equilibrium and is, therefore, less stable [13]. Our findings suggest that the effective moment of inertia during postural sway among individuals with thoracic SCI was larger (i.e. smaller centroidal frequency), implying that they used a less effective strategy to adjust posture, which also resulted in less postural stability.

The only postural measure able to distinguish between individuals with high- and low-thoracic SCI in our present study was frequency dispersion (FREQD). Individuals with high-thoracic SCI had higher frequency dispersion compared to the low-thoracic SCI individuals in the anterior-posterior direction (Table 2). It has previously been shown that frequency dispersion was inversely related to the stiffness of the inverted pendulum [15]. Moreover, individuals with high-thoracic SCI used more trunk muscle co-contractions during sitting compared to those with low-thoracic SCI [16]. Therefore, it seems that individuals with high-thoracic SCI utilize a stiffness balance control strategy, which could be related to use of non-postural muscles [4,5] or to the spasticity after SCI [17].

Effects of upper-limb support

Our results showed that the amount of sway (MD and AREA-CE) was larger during unsupported sitting (AC and AE postures) compared to supported sitting (HT posture) (Table 2), implying improved postural performance with upper-limb support. The speed of postural sway (MV) was also affected by upper-limb support, with the higher speed of sway when arms were not supported on the thighs (AC and AE post). These results suggest increased control demand during unsupported sitting [8]. Overall, our results demonstrated improved postural control when upper-limbs were supported on the thighs, which were mostly characterized by anterior-posterior stability [4,5]. This is likely because the passive mechanics of upper-limb support are aligned with anterior-posterior direction. However, sensory information passed through the hands during supported sitting (HT posture) can provide feedback information that could also have contributed to the postural differences. Moreover, in our study, the frequency components (CFREQ and MFREQ) of postural sway overall and in the medial-lateral direction were also affected during unsupported sitting with arms extended (AE posture) (Table 2). It was also previously shown that centroidal frequency and mean frequency of postural sway were larger during upper-limb supported sitting [5]. Frequency of an inverted pendulum is inversely proportional to the moment of inertia [18]. Larger centroidal frequency was related to smaller effective moment of inertia of the trunk [4,8], suggesting a sluggish system and unstable posture [13]. Overall, our findings suggest that the moment of inertia during sitting with upper-limb support was lower compared to unsupported sitting (i.e. larger centroidal frequency), implying more stable posture. However, individuals with SCI often have to extend their arms during performance of functional activities (e.g., reaching for an object). Our results imply that they are less stable during such postures. Poor trunk stability can also lead to reduced ability to extend the upper-limbs [19], which can in turn lead to a decreased functional workspace [20]. Therefore, rehabilitation should focus on training unsupported sitting to potentially improve performance of functional activities.

Interaction between participant groups and upper-limb support postures for the velocity and frequency measures (MV, CFREQ and MFREQ) shown in our study suggests that the control demand during unsupported sitting was uniquely affected in different participant groups, which is consistent with our hypothesis. Individuals with high-thoracic SCI were most affected and had to do most postural control work when sitting unsupported (Table 2). Previously, Minkel [6] reported that individuals with low-thoracic SCI often have sufficient sitting postural stability to maintain unsupported sitting, whereas those with higher thoracic SCI have to rely on upper extremities for support during. Overall, large destabilizing effect during sitting with arms extended in individuals with high-thoracic SCI suggests that clinical assessments of sitting balance should include arms extended posture to gain an understanding of the impairment severity. Moreover, our results imply that individuals with high- and low-thoracic SCI use different postural regulatory strategies during sitting balance, confirming that the trunk neuromuscular impairment in those with high-thoracic SCI [16] results in suboptimal posture during sitting. Therefore, rehabilitation strategies should focus on recovering trunk function to improve sitting balance in individuals with thoracic SCI.

Conclusions

Our study demonstrated that individuals with both high- and low-thoracic SCI were less stable during quiet sitting, suggesting impaired postural control. There was no difference in postural stability between dichotomised groups of individuals with high- and low-thoracic SCI. However the neurological level of injury was correlated to postural performance, suggesting that those with higher injuries have worse postural control. Moreover, individuals with higher thoracic SCI utilized different postural regulatory strategies, especially during unsupported sitting. This could be related to increased stiffness in those with high-thoracic SCI. In conclusion, our study provides evidence to suggest that suboptimal posture during sitting is related to the impairment of the trunk.

Conflict of interest statement

The authors declare that there are no conflicts of interest associated with this publication.

Authors' contributions:

DHG, MM, and KN designed the study. PG and DHG collected the data. PG, MM, and KN analyzed and interpreted the data. MM wrote the article. DHG, PG, and KN revised the article for the intellectual content. All authors have approved the final manuscript.

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Tables

Table 1: Participant age, height, weight, and clinical evaluations for the high-thoracic SCI (SCI$_{H}$), low-thoracic SCI (SCI$_{L}$), and able-body (AB) groups.

Group	**Age (years)**	**Height (m)**	**Weight (kg)**	**Neurological level of injury**	**AIS**	**ASIA Motor (/100)**	**ASIA Sensory (/224)**	**Time since Injury (years)**
SCI$_{H}$	45.8	1.8	80.0	T7	A	50	117	12.1
	55.8	1.8	73.9	T7	A	50	112	0.4
	36.5	1.7	67.9	T6	A	50	53	6.9
	53.2	1.8	84.7	T4	A	50	-	27.9
	50.2	1.7	70.2	T7	C	52	88	5.5
	60.7	1.7	62.3	T5	A	50	92	38.3
	39.4	1.8	84.8	T6	C	50	166	9.0
Mean	**48.8**	**1.8**	**74.8**			**50.3**	**104.7**	**14.3**
SD	**8.8**	**0.1**	**8.7**			**0.8**	**37.6**	**13.7**
SCI$_{L}$	34.6	1.9	-	T12	C	56	162	9.2
	35.4	1.8	101.7	T11	C	54	182	2.8
	29.7	1.9	73.0	T12	A	50	154	11.9
	41.7	1.5	66.5	T8	B	50	134	11.0
	24.1	1.8	54.0	T11	A	66	160	0.1
	53.9	1.8	110.7	T9	A	50	132	20.0
	37.6	1.9	83.5	T10	A	50	138	2.4
	57.1	1.8	85.3	T12	A	55	168	25.0
	61.2	1.9	102.4	T10	A	50	140	6.3
	54.0	1.7	73.6	T12	B	63	172	10.2
Mean	**42.9**	**1.8**	**83.4**			**54.4**	**154.2**	**9.9**
SD	**12.8**	**0.1**	**18.7**			**5.9**	**17.4**	**7.8**
AB	31.9	1.7	57.9					
	43.5	1.7	100.8					
	34.2	1.8	93.6					
	59.8	1.8	68.9					
	42.8	1.8	78.1					
	50.2	1.9	76.2					
	27.8	1.7	54.8					
	54.8	1.9	71.0					
Mean	**43.1**	**1.8**	**75.2**					
SD	**11.4**	**0.1**	**15.9**					

Table 2: Results of mixed-design analysis of variance (ANOVA) comparison of postural sway parameters during quiet sitting balance for the high-thoracic SCI (SCI_H), low-thoracic SCI (SCI_L), and able-body (AB) groups during hands on thighs (HT), arms crossed on chest (AC) and arms extended (AE) sitting postures.

Measure		Group	Posture			Statistics				
			HT	AC	AE	Within-subject: Posture effect		Between-subject: Group effect		Interaction
MD (mm)	**RD**	**SCI_H**	2.05 (1.13)	2.72 (1.11)	3.39 (1.02)	***	HT-AC HT-AE AC-AE	**	SCI_H-AB SCI_L-AB	
		SCI_L	1.62 (0.60)	2.74 (1.08)	3.35 (2.40)					
		AB	1.46 (1.94)	1.33 (0.87)	2.05 (1.68)					
	AP	**SCI_H**	1.34 (0.93)	1.65 (0.73)	2.11 (0.58)	***	HT-AC HT-AE AC-AE			
		SCI_L	1.09 (0.50)	2.11 (1.18)	2.82 (2.47)					
		AB	1.26 (1.90)	1.07 (0.76)	1.62 (1.36)					
	ML	**SCI_H**	1.32 (0.60)	1.82 (0.87)	2.18 (0.97)	***	HT-AC	***	SCI_H-AB SCI_L-AB	
		SCI_L	0.95 (0.43)	1.22 (0.46)	1.24 (0.35)					
		AB	0.51 (0.35)	0.59 (0.34)	0.95 (0.89)					
AREA-CE (mm^2)	**CE**	**SCI_H**	47.25 (64.79)	83.85 (63.40)	151.71 (94.20)	***	HT-AC HT-AE AC-AE	**	SCI_H-AB SCI_L-AB	
		SCI_L	29.02 (19.75)	69.71 (54.26)	103.83 (107.74)					
		AB	31.99 (71.81)	23.20 (31.56)	64.12 (116.94)					
MV (mm/s)	**RD**	**SCI_H**	4.64 (2.32)	9.66 (3.36)	15.39 (5.16)	***	HT-AC HT-AE AC-AE			**
		SCI_L	4.66 (1.15)	8.57 (4.00)	12.74 (6.25)					
		AB	6.66 (4.20)	7.39 (3.96)	9.84 (5.97)					
	AP	**SCI_H**	3.45 (1.73)	6.50 (2.20)	10.67 (3.98)	***	HT-AC HT-AE AC-AE			**
		SCI_L	3.53 (0.93)	6.76 (3.31)	10.00 (5.40)					
		AB	5.39 (3.73)	5.90 (3.70)	7.57 (5.70)					
	ML	**SCI_H**	2.42 (1.28)	5.78 (2.20)	8.77 (3.31)	***	HT-AC HT-AE AC-AE			**
		SCI_L	2.30 (0.72)	3.96 (1.89)	5.85 (2.52)					
		AB	2.95 (1.58)	3.35 (1.36)	4.71 (2.08)					
MFERQ (Hz)	**RD**	**SCI_H**	0.40 (0.08)	0.62 (0.16)	0.76 (0.28)	*	HT-AE	***	SCI_H-AB SCI_L-AB	*
		SCI_L	0.52 (0.17)	0.53 (0.18)	0.68 (0.25)					
		AB	1.03 (0.30)	0.99 (0.25)	0.88 (0.26)					
	AP	**SCI_H**	0.62 (0.28)	0.83 (0.22)	0.91 (0.34)			*	SCI_L-AB	*
		SCI_L	0.70 (0.26)	0.68 (0.20)	0.78 (0.38)					
		AB	1.19 (0.37)	1.13 (0.33)	0.93 (0.30)					
	ML	**SCI_H**	0.37 (0.15)	0.65 (0.26)	0.80 (0.36)	***	HT-AE	***	SCI_H-AB SCI_L-AB	*
		SCI_L	0.51 (0.21)	0.69 (0.39)	0.84 (0.21)					
		AB	1.18 (0.27)	1.13 (0.38)	1.21 (0.41)					
CFREQ (Hz)	**RD**	**SCI_H**	0.83 (0.18)	1.09 (0.20)	1.26 (0.27)	**	HT-AE	***	SCI_H-AB SCI_L-AB	*
		SCI_L	1.02 (0.22)	1.00 (0.18)	1.21 (0.27)					
		AB	1.59 (0.19)	1.48 (0.22)	1.51 (0.23)					
	AP	**SCI_H**	0.92 (0.24)	1.05 (0.17)	1.09 (0.21)			***	SCI_H-AB SCI_L-AB	
		SCI_L	0.97 (0.22)	0.88 (0.14)	1.05 (0.29)					
		AB	1.44 (0.26)	1.24 (0.18)	1.34 (0.18)					
	ML	**SCI_H**	0.68 (0.13)	0.91 (0.26)	1.07 (0.30)	***	HT-AE AC-AE	***	SCI_H-AB SCI_L-AB	*
		SCI_L	0.87 (0.21)	0.95 (0.27)	1.12 (0.22)					
		AB	1.41 (0.25)	1.34 (0.32)	1.47 (0.29)					
FREQD (-)	**RD**	**SCI_H**	0.74 (0.04)	0.72 (0.05)	0.69 (0.04)			***	SCI_H-SCI_L SCI_H-AB	
		SCI_L	0.68 (0.04)	0.68 (0.03)	0.65 (0.02)					
		AB	0.66 (0.02)	0.68 (0.03)	0.68 (0.06)					
	AP	**SCI_H**	0.73 (0.05)	0.71 (0.08)	0.69 (0.05)			*	SCI_H-SCI_L	
		SCI_L	0.68 (0.08)	0.66 (0.04)	0.65 (0.05)					
		AB	0.66 (0.04)	0.69 (0.02)	0.70 (0.06)					
	ML	**SCI_H**	0.72 (0.05)	0.70 (0.09)	0.68 (0.06)			*	SCI_H-AB	
		SCI_L	0.63 (0.05)	0.66 (0.06)	0.62 (0.06)					
		AB	0.62 (0.05)	0.65 (0.07)	0.62 (0.08)					

*$p<0.05$; **$p<0.01$; ***$p<0.001$

Table 3: Spearman's rank correlation coefficients between postural control parameters and clinical evaluations among individuals with thoracic SCI (both high- and low-thoracic SCI groups combined). Shown are the results for hands on thighs (HT), arms crossed on chest (AC) and arms extended (AE) sitting postures.

Measure		Posture	Neurological level of injury	AIS	ASIA Motor (/100)	ASIA Sensory (/224)	Time since Injury (years)
MD (mm)	RD	HT					
		AC					
		AE					
	AP	HT					
		AC					
		AE					
	ML	HT					
		AC					
		AE	0.682**		-0.568*	-0.568*	
AREA-CE (mm^2)	CE	HT					
		AC					
		AE			-0.525*		
MV (mm/s)	RD	HT					
		AC					
		AE			-0.576*		
	AP	HT					
		AC					
		AE			-0.576*		
	ML	HT					
		AC					
		AE	0.599*		-0.513*		
MFERQ (Hz)	RD	HT					
		AC		-0.570*			
		AE					
	AP	HT					
		AC	0.590*	-0.505*	-0.588*	-0.641**	
		AE					
	ML	HT					
		AC					
		AE					
CFREQ (Hz)	RD	HT					
		AC		-0.618**			
		AE					
	AP	HT					
		AC	0.536*			-0.585*	
		AE					
	ML	HT					
		AC					
		AE					
FREQD (-)	RD	HT				-0.621*	
		AC					
		AE					
	AP	HT		0.559*			
		AC					
		AE					
	ML	HT	0.566*			-0.678**	
		AC					
		AE					

$^{*}p<0.05$; $^{**}p<0.01$

Figure Captions

Figure 1: Experimental setup showing postures of the subject during performance of the different postural tasks: both hands resting on their thighs (HT); both arms crossed over their chest (AC); and both arms elevated (AE). Representative 15 sec of COP sway are also shown during quiet sitting for one individual with high-thoracic SCI (SCI_H); one individual with low-thoracic SCI (SCI_L); and one able-body individual (AB). AP represents anterior-posterior and ML medial-lateral sway direction.

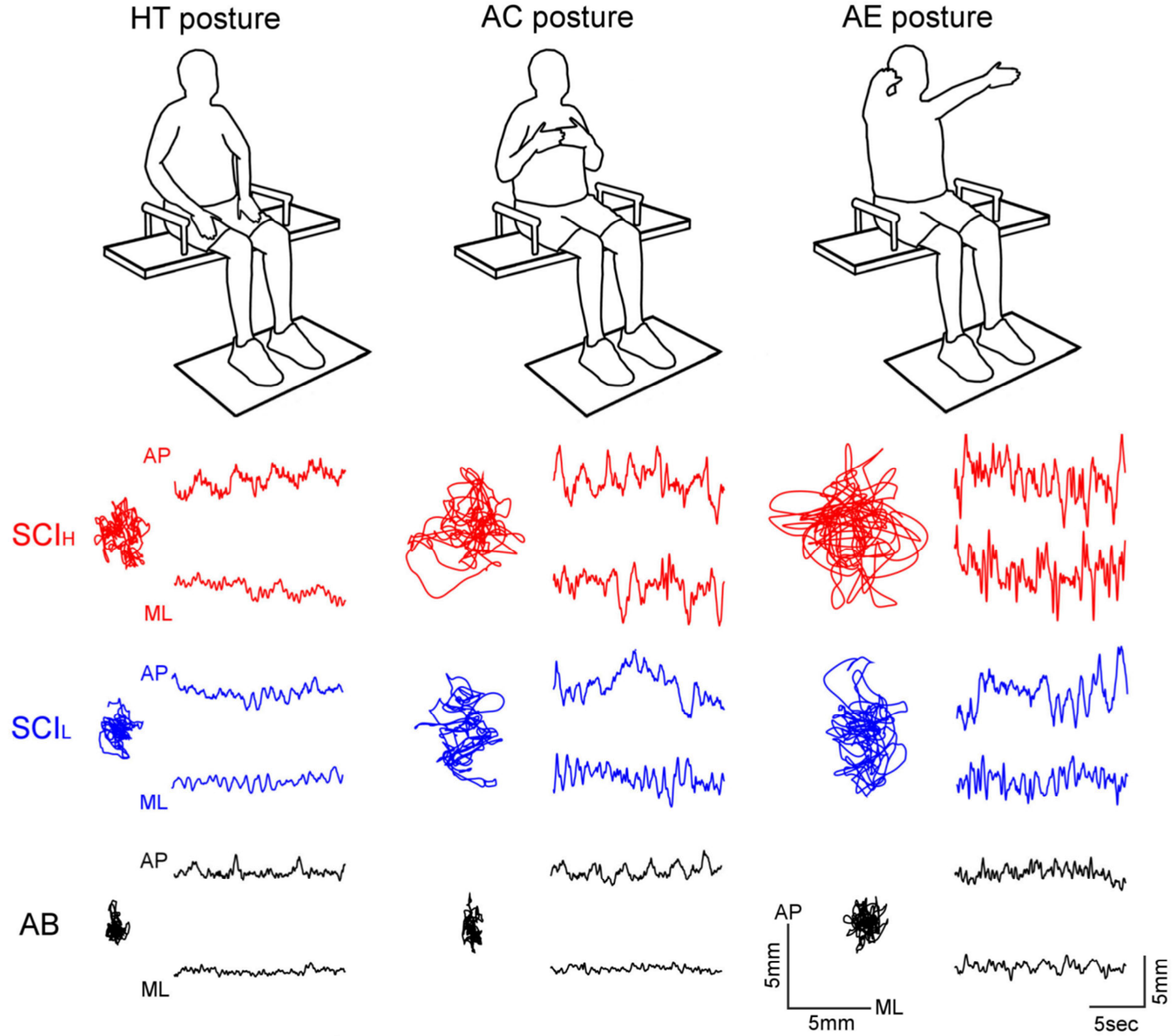
HT posture
AC posture
AE posture
SCI_H
SCI_L
AB
AP
ML
5mm
5mm
5sec

Figure 1