Gait & Posture 36 (2012) 572–579

Contents lists available at SciVerse ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Effects of upper limb positions and weight support roles on quasi-static seated postural stability in individuals with spinal cord injury

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ARTICLE INFO

Article history:
Received 2 December 2011
Received in revised form 15 April 2012
Accepted 21 May 2012

Keywords:
Biomechanics
Postural control: Rehabilitation
Spinal cord injury
Body equilibrium

ABSTRACT

Seated postural stability has not been studied extensively in individuals with spinal cord injury (SCI). The main purpose of this study was to compare the effects of upper limb (U/L) positions and U/L weight support roles on quasi-static postural stability between individuals with SCI and healthy controls. Fourteen individuals with SCI and 14 healthy controls sat on an instrumented seat with their feet resting on force plates and randomly maintained five short-sitting positions for 60 s with or without hand support. Center-of-pressure (COP) measures based on displacement and frequency series were computed. Individuals with SCI exhibited greater mean COP displacement and velocity measures compared to healthy controls, as well as lower COP frequency measures, irrespective of the U/L positions and weight support roles, confirming reduced stability and a difference in preferential postural regulation strategies. The use of U/L support is a compensatory strategy that influences seated stability in individuals with SCI.

1. Introduction

Individuals who sustained a spinal cord injury (SCI) experience sensorimotor impairments affecting the upper limbs (U/Ls), lower limbs and trunk. Consequently, the ability to efficiently perform daily activities in sitting that challenge balance and postural control may be altered in individuals with SCI [1]. These individuals need to develop new strategies to address the needs for stability and for trunk mobility while performing functional tasks.

Only a few studies have quantitatively investigated seated stability in individuals with SCI [2,3,7] or associated it with functional performance [4,5] despite its relevance in clinical practice [6]. Shirado et al. [7] studied the long sitting position with and without hand support in individuals with SCI. The unsupported sitting position was found to be the most unstable position for individuals with SCI due to a longer displacement of center-of-pressure (COP) compared to healthy controls. Since the kinetic data were recorded using only one force plate underneath the buttocks and the kinematic data were studied only in the sagittal plane, the forces under the feet [8] and the change in the frontal plane were not accounted for. Moreover, the usual sitting position in a wheelchair or any other seat from which most functional activities are performed, is not with the legs extended but with them flexed (short sitting position), which influences pelvic and trunk position.

Interestingly, Chen et al. [9] compared sitting stability between individuals with complete high (T1–T6) and low (T7–T12) thoracic SCI during unsupported short sitting (quasi-static stability) and weight-shifts during leaning tasks (dynamic stability). Although participants with low thoracic SCI demonstrated better dynamic sitting stability than individuals with high thoracic SCI, no significant difference was revealed between the groups during the quasi-static position (potential ceiling effect). The lack of details regarding the level of the injury of the participants and the unequal number of participants in each group might have also biased the results. Additionally, no standardized U/Ls position across participants during the sitting position was described though the picture showed both U/Ls flexed at approximately 45° in the sagittal plane which may not be sufficient to challenge seated stability and discriminate across individuals with SCI. Once

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http://dx.doi.org/10.1016/j.gaitpost.2012.05.021

again, the ground reaction forces under the feet did not account for the displacement of the COP. Further studies investigating additional sitting positions and quantifying additional measures of postural stability are needed to further characterize seated stability in individuals with SCI.

The main objective of this study was to compare quasi-static postural stability between individuals with SCI and healthy controls during short-sitting positions performed using five distinct U/L positions and weight support roles. The secondary objective of this study was to evaluate the association between clinical variables and quasi-static seated postural stability measures. It was hypothesized that individuals with SCI would demonstrate reduced seated postural stability compared to healthy controls that would progressively worsen as the U/L positions reduced their ability to support their body weight. It was also anticipated that the severity of the sensorimotor impairments and the time since injury would be associated with the ability to maintain quasi-static seated postural stability among individuals with SCI.

2. Methods

2.1. Participants

Fourteen individuals with SCI and 14 gender-matched healthy controls (Table 1) participated in this study. Individuals were eligible to participate if they were able to independently maintain a short-sitting position with feet resting on the floor with no U/L support and had an activity tolerance of at least 60 min. None of the participants reported having a musculoskeletal impairment (other than the consequences of the SCI) or any other condition that might have altered their ability to maintain a short-sitting position. The study was conducted at the Pathokinesiology Laboratory of the Institut de réadaptation Gingras-Lindsay-de-Montréal (IRGLM). Ethical approval was obtained from the Research Ethics Committee of the Center for Interdisciplinary Research in Rehabilitation of Greater Montreal (CRIR). All participants read and signed the informed consent.

2.2. Experimental tasks

Participants sat on a height-adjustable seat with their buttocks centrally positioned and with 75% of the length of their thighs supported. Their knees were flexed at 85° and their feet rested on the floor. Participants were instructed to randomly maintain a sitting position for 560-s long trials that were randomly selected from the following pool of postures: (1) with both hands resting on their thighs; (2) with the dominant hand on the ipsilateral thigh and the non-dominant shoulder flexed at 70° and horizontally abducted at 45°; (3) with the non-dominant hand on the ipsilateral thigh and the dominant shoulder flexed at 70° and horizontally abducted at 45°; (4) with both U/Ls crossed over the chest, and (5) with both shoulders flexed at 70° and horizontally abducted at 45°. The position of the lower limbs and of the U/Ls (i.e.; shoulders) was verified by an evaluator using a goniometer before each task. Tasks 1–3 reflected supported sitting positions and tasks 4–5 unsupported sitting positions. During all tasks, participants were requested to sit upright and to fix a stationary target set at eye level, three meters in front of them. A two-minute rest period was offered between trials.

2.3. Instrumentation and data conditioning

Kinetic data were recorded (600 Hz) using a sophisticated height-adjustable instrumented seat that has two force plates each under one buttocks (Fig. 1). The accuracy of the instrumentation was verified in previous studies [10,11]. The triaxial components of the ground reaction forces underneath the left and right

Table 1
Description of participants.

Groups	Participants	Age	Height (cm)	Weight (kg)	Time since injury (years)	AIS motor (/100)	AIS sensitive (/224)	Level of injury	AIS	BOS[a] (m^2)
Individuals with SCI (right-handed)	1	23.2	1.68	86.3	0.88	92	220	C3	D	0.33
	2	49.1	1.73	84.5	1.73	70	176	C5	D	0.37
	3	25.2	1.83	76.48	2.08	20	40	C6	A	0.32
	4	32.6	1.75	65.1	3.09	50	92	C7	B	0.25
	5	40	1.70	59.30	0.15	69	122	C7	B	0.24
	6	46.6	1.83	109.1	5.02	50	155	L1	C	0.39
	7	53.0	1.78	129.6	5.14	50	110	T10	A	0.36
	8	44.4	1.7	73.8	2.67	50	104	T10	A	0.27
	9	57.9	1.88	98.2	2.99	19	42	T10	B	0.33
	10	30.2	1.88	98.1	3.33	50	92	T10	A	0.34
	11	26.1	1.63	46.8	2.78	50	144	T11	A	0.25
	12	25.3	1.8	52.9	2.77	50	100	T4	A	0.25
	13	72.0	1.87	105.6	2.56	68	174	T6	D	0.39
	14	49.9	1.83	78.1	25.9	50	88	T7	B	0.31
	Mean	**41.10**	**1.78**	**83.13**	**4.36**					**0.31**
	SD	**14.67**	**0.08**	**23.34**	**6.34**					**0.05**
Control group (right-handed)	1	21	1.63	45.6						0.23
	2	23	1.74	76.9						0.31
	3	67	1.74	70.2						0.31
	4	25	1.75	123.5						N/A
	5	60	1.66	80.9						0.26
	6	53	1.7	73.7						0.31
	7	33	1.74	78.6						0.30
	8	38	1.81	83.6						0.33
	9	50	1.67	65.8						0.28
	10	35	1.78	86.3						0.37
	11	37	1.78	87.5						0.39
	12	30	1.79	94						0.38
	13	43	1.65	78.6						0.33
	14	33	1.89	74.3						0.35
	Mean	**39.14**	**1.74**	**79.96**						**0.32**
	SD	**13.89**	**0.07**	**17.02**						**0.05**
Comparisons between groups (paired sample *t*-test)		$p = 0.77$	$p = 0.25$	$p = 0.69$						$p = 0.70$

A system of four synchronized motion analysis camera bars (4x Optotrak model 3020; NDI Technology Inc., Waterloo, Ontario, Canada) recorded the 3D coordinates of 18 skin-fixed infrared light emitting diodes (LEDs) used to define the upper/lower segments, trunk and head. Ten additional LEDs fixed on the instrumented seat to locate it within the global referential and a total of 24 specific bony landmarks were also digitized using a 6-marker probe to further define principal axes of segments as well as the contour of the feet and buttocks to calculate the area of the BOS.

[a] BOS = base of support.

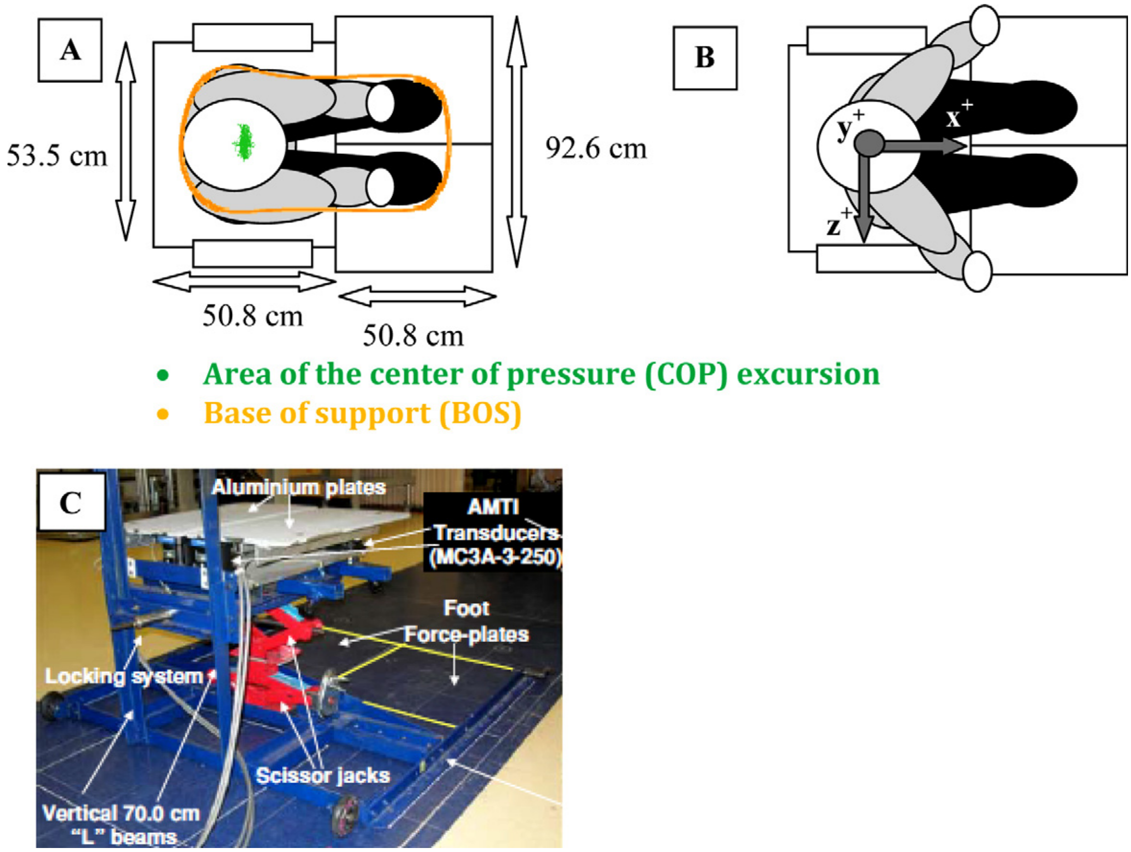

Fig. 1. Schematic representation of the position (A) with both hands on thighs and (B) with both U/L abducted at 45° and flexed at 75° with the coordinate system. (C) View of the instrumented chair. The sitting surface comprises four AMTI (Advanced Mechanical Technology, Inc., Newton, MA, OR6-7-1000) with strain gauge transducers (MC3A-3-250), two for each thigh and two underneath the feet.

buttocks as well as underneath the left and right foot were continuously measured and indicated the local COP position at each instant at each force plate within their own referential. These components, which correspond to the anteroposterior (Fx), vertical (Fy) and mediolateral (Fz) directions, were then combined to compute the global 3D COP position at each instant expressed within a global laboratory referential (Fig. 1). Finally, only the 2D COP projected about the x and z axes (horizontal plane) were retained and further decomposed for the anteroposterior and mediolateral analyses, respectively. Data were filtered with a fourth-order Butterworth zero-lag filter, with a cut-off frequency of 5 Hz prior to computing the measures.

2.4. Seated postural stability measures

A 30-s period (15th to 45th second) was used to compute all measures: mean velocity (MVELO), average distance from the mean COP (MDIST), sway area (AREA-SW), centroidal frequency (CFREQ) and median power frequency (50%-PFREQ) of the COP. Measures were computed using the resultant distance (RD) in the horizontal plane as well as the anteroposterior (AP) and mediolateral (ML) components. The frequency measures were calculated for the frequency range from 0.15 to 5 Hz [12,13]. These measures were determined from previous work [14].

The stability is characterized by the COP distance measures which defined stability performance [15,16] and velocity which is defined as an index of postural activity (or amount of postural adjustments) [17,18]. It is suggested in the literature that an increase in COP displacement reflects a low stability performance as it moves the COP near the limit of BOS [16]. Additionally, it is suggested that an increase in COP velocity requires an increase in postural control demand. Moving the COP faster near the limits of BOS can thus be considered as an important indicator of risk of falling, suggesting that stability become precarious. As for the frequency domain measures, they characterize the area or shape of the power spectral density of the COP (stabilogram). The 50%-PFREQ is the frequency below which 50% of the total power is found and is often associated to change in preferential postural regulation strategies (i.e., how the body moves around the joint torques) [19,20]. The centroidal frequency is referred to the zero crossing frequency and is also linked to the inertia of the system (i.e., trunk of individuals in sitting position) [21,22]. Indeed, in sitting position, the body can be considered as an inverted pendulum that rotates about the hip joints, implying that the COP displacement corresponds to spontaneous trunk sway and its control during quiet stance [22]. Since it has been reported that the natural frequency of the inverted pendulum is inversely proportional to the root of the moment of inertia, an increase in moment of inertia will induce smaller oscillation frequency [23] (i.e. reduced centroidal frequency thus indicates decreased postural control demand).

2.5. Statistical analysis

A Shapiro–Wilk test confirmed that all COP measures followed a normal distribution. Thereafter, two-factor repeated measures ANOVAs were computed for each measure to identify differences across groups, tasks or both. If any task X group interaction was revealed, Bonferroni post hoc tests with adjusted p-values were performed. Spearman correlation coefficients were computed among individuals with SCI to determine the association between clinical variables and all COP measures for each task. Correlation coefficients above 0.70 were interpreted as demonstrating a strong correlation. Two-tailed tests were selected for all statistical analysis and p-values of 0.05 or less confirmed statistical significance. Statistical analyses were performed using SPSS®.

3. Results

Quasi-static COP measures are summarized in Table 2. Between-group differences for a given task and between-task comparisons for a given group are presented in Tables 2 and 3, respectively. The relationship between the seated postural stability measures and the clinical variables are revealed in Table 4.

3.1. Comparisons between groups

Individuals with SCI exhibited greater MDIST and MVELO measures compared to healthy controls, irrespective of the U/L position and weight support roles. They also presented lower

Table 2
Mean ± standard deviation of all COP-related outcome measures.

	COP-related outcome measures		Supported sitting positions			Unsupported sitting positions		Between-group differences for each task				
			Task1	Task2	Task3	Task4	Task5	Task1	Task2	Task3	Task4	Task5
Distance-domain	MDIST-RD	CTL	1.24(1.14)	1.35(1.15)	1.20(0.88)	1.37(1.29)	1.65(1.27)		*	*	*	**
		SCI	1.80(1.00)	2.20(1.01)	2.47(1.91)	2.62(1.29)	3.12(2.14)					
	MDIST-AP	CTL	1.07(1.09)	1.15(1.18)	0.92(0.91)	1.17(1.30)	1.35(1.25)				*	*
		SCI	1.12(0.59)	1.48(0.57)	1.61(1.20)	1.78(0.97)	2.33(1.67)					
	MDIST-ML	CTL	0.45(1.18)	0.49(0.16)	0.55(0.21)	0.49(0.24)	0.70(0.35)	**	***	*	***	**
		SCI	1.18(0.92)	1.39(0.87)	1.58(1.56)	1.50(1.00)	1.69(1.35)					
	MVELO-RD	CTL	4.90(2.36)	5.10(1.77)	4.95(1.61)	4.87(2.22)	6.01(2.16)					**
		SCI	4.02(1.55)	6.34(2.52)	6.05(2.56)	6.68(3.56)	8.29(3.21)					
	MVELO-AP	CTL	3.88(1.88)	3.64(1.19)	3.47(1.11)	3.64(1.67)	4.21(1.37)		*		*	
		SCI	2.68(0.86)	3.99(1.33)	3.72(1.21)	4.73(2.79)	5.82(2.60)					
	MVELO-ML	CTL	2.21(1.21)	2.82(1.17)	2.79(1.02)	2.49(1.21)	3.41(1.44)		*			**
		SCI	2.40(1.24)	4.10(2.03)	3.95(2.21)	3.67(1.86)	4.66(2.02)					
	AREA-SW	CTL	2.18(3.02)	2.45(3.62)	2.06(2.51)	2.23(2.81)	3.59(5.08)		*	*	*	**
		SCI	2.56(2.10)	4.88(3.84)	5.10(4.86)	6.26(6.85)	7.89(5.52)					
Frequency domain	CFREQ-RD	CTL	1.40(0.47)	1.38(0.30)	1.38(0.34)	1.22(0.29)	1.33(0.24)	***	*	**	**	***
		SCI	0.89(0.21)	1.10(0.33)	1.04(0.32)	0.93(0.20)	1.08(0.28)					
	CFREQ-AP	CTL	1.27(0.42)	1.23(0.30)	1.32(0.29)	1.02(0.29)	1.16(0.22)	***		*		***
		SCI	0.97(0.29)	1.08(0.33)	1.01(0.35)	0.92(0.23)	0.99(0.30)					
	CFREQ-ML	CTL	0.81(0.47)	0.65(0.33)	0.70(0.33)	0.54(0.24)	0.61(0.24)	***	**	***	***	***
		SCI	0.33(0.09)	0.50(0.29)	0.49(0.24)	0.38(0.15)	0.56(0.25)					
	50%-PFREQ-RD	CTL	0.70(0.41)	0.57(0.31)	0.64(0.33)	0.43(0.22)	0.49(0.24)					
		SCI	0.41(0.21)	0.54(0.36)	0.53(0.31)	0.45(0.19)	0.55(0.29)					
	50%-PFREQ-AP	CTL	0.78(0.19)	0.73(0.23)	0.69(0.22)	0.65(0.20)	0.70(0.27)				*	*
		SCI	0.42(0.29)	0.55(0.28)	0.50(0.24)	0.43(0.17)	0.51(0.23)					
	50%-PFREQ-ML	CTL	1.34(0.28)	1.28(0.26)	1.29(0.20)	1.28(0.25)	1.28(0.20)	**		*	**	
		SCI	0.80(0.25)	0.97(0.27)	0.94(0.26)	0.84(0.23)	1.01(0.23)					

Probabilities listed in the group column are for Bonferroni post hoc tests between groups for each task: $^{*}p < 0.025$; $^{**}p \leq 0.01$; $^{***}p \leq 0.001$. MVELO: mean velocity (mm/s), MDIST: mean distance from mean COP (mm); CFREQ: centroidal frequency (Hz); 50%-PFREQ: Median Power Spectrum; AREA-CE: 95% confidence ellipse area (mm^2); AREA-SW: sway area (mm^2/s). T1 = both hands on thighs; T2 = dominant hand on thigh; T3 = non-dominant hand on thigh; T4 = both U/Ls crossed over the chest; T5 = both shoulders abducted and flexed. RD = resultant; AP = anteroposterior; ML = mediolateral.

50%-PFREQ and CFREQ measures than healthy controls. Moreover, most of the COP measures among individuals with SCI confirmed ML postural instability when at least one U/L was supporting weight, whereas ML and AP postural instability occurred when the unsupported sitting positions were being maintained. Interestingly, a greater MVELO was found among individuals with SCI when maintaining a sitting position with the dominant hand on the thigh compared to healthy controls.

Table 3
Significant differences revealed in COP measures between tasks for each group.

			Tasks									
			T1/T2	T1/T3	T1/T4	T1/T5	T2/T3	T2/T4	T2/T5	T3/T4	T3/T5	T4/T5
Time-domain distance	MDIST-RD	CTL										
		SCI			**	**						
	MDIST-AP	CTL										
		SCI			**	**						
	MDIST-ML	CTL				**						
		SCI										
	MVELO-RD	CTL										
		SCI			**	***						
	MVELO-AP	CTL										
		SCI	**	***	**	***						
	MVELO-ML	CTL				***						
		SCI			***	***						
	AREA-SW	CTL										
		SCI				**			**		**	
Frequency domain	CFREQ-RD	CTL										
		SCI				**						
	CFREQ-AP	CTL								***		
		SCI										
	CFREQ-ML	CTL										
		SCI				**						
	50%-PFREQ-RD	CTL										
		SCI				**						
	50%-PFREQ-AP	CTL										
		SCI										
	50%-PFREQ-ML	CTL										
		SCI										

Probabilities listed in individuals with SCI and control group rows are for Bonferroni post hoc tests between groups for each task. $^{**}p < 0.005$; $^{***}p \leq 0.001$.

Table 4
Association between demographic/clinical variables and COP measures.

Tasks	Outcome measures	Age	Height	Weight	Time since injury	ASIA motor	ASIA sensitive	Lesion level	AIS
T1	MVELO-RD	$r = 0.552$ $p = 0.041$			$r = 0.556$ $p = 0.039$				
	MVELO-AP	$r = 0.547$ $p = 0.043$			**r = 0.714** **p = 0.004**				
T2	MDIST-AP	$r = -0.587$ $p = 0.027$							
	50%-PFREQ-RD	$r = 0.659$ $p = 0.010$							
	50%-PFREQ-AP	$r = 0.576$ $p = 0.031$							
T3	MDIST-RD					$r = -0.645$ $p = 0.013$	$r = -0.664$ $p = 0.010$		$r = -0.563$ $p = 0.036$
	MDIST-AP				$r = 0.574$ $p = 0.032$				$r = -0.619$ $p = 0.018$
	MDIST-ML						$r = -0.537$ $p = 0.048$		
	MVELO-RD						$r = -0.673$ $p = 0.008$		
	MVELO-AP				$r = 0.534$ $p = 0.049$	$r = -0.553$ $p = 0.040$	$r = -0.658$ $p = 0.011$		
	MVELO-ML						$r = -0.693$ $p = 0.006$		
	AREA-SW					$r = -0.645$ $p = 0.013$	$r = -0.664$ $p = 0.010$		$r = -0.563$ $p = 0.036$
	CFREQ-AP	$r = 0.565$ $p = 0.035$							
	50%-PFREQ-RD	$r = 0.546$ $p = 0.044$							$r = 0.599$ $p = 0.024$
	50%-PFREQ-AP	$r = 0.651$ $p = 0.012$							
	50%-PFREQ-ML	$r = 0.538$ $p = 0.047$							
T4	MDIST-RD					$r = -0.587$ $p = 0.027$			
	MDIST-ML					$r = -0.577$ $p = 0.031$	$r = -0.532$ $p = 0.050$		
	MVELO-RD				$r = 0.556$ $p = 0.039$	$r = -0.660$ $p = 0.010$	$r = -0.647$ $p = 0.012$		
	MVELO-AP				$r = 0.640$ $p = 0.014$	**r = −0.767** **p = 0.001**	$r = -0.623$ $p = 0.017$	$r = 0.554$ $p = 0.040$	
	MVELO-ML					$r = -0.633$ $p = 0.015$	**r = −0.700** **p = 0.005**		
	AREA-SW				$r = 0.565$ $p = 0.035$	$r = -0.674$ $p = 0.008$	**r = −0.706** **p = 0.005**		
	CFREQ-ML	$r = 0.569$ $p = 0.034$							
T5	MDIST-AP		$r = -0.571$ $p = 0.033$						
	MVELO-ML						$r = -0.675$ $p = 0.008$		
	CFREQ-RD				$r = 0.543$ $p = 0.045$				
	CFREQ-AP				$r = 0.569$ $p = 0.034$				
	50%-PFREQ-AP				$r = 0.604$ $p = 0.022$			$r = 0.650$ $p = 0.012$	

To simplify the presentation, only measures in which at least one significant result with an $r > 0.50$ are presented. Measures with $r > 0.70$ are in bold text. Differences in sitting stability associated with clinical variables were more obvious during sitting positions with the dominant shoulder flexed and abducted and with both U/Ls crossed over the chest. Bold results represent correlation coefficients above or equal to 0.70 interpreted as demonstrating a strong correlation.

3.2. Comparisons between experimental tasks

3.2.1. Healthy controls

A greater MDIST was found with respect to the ML component during the sitting position with both U/Ls flexed and abducted than with both hands on the thighs. MVELO-ML was greater when sitting with both U/Ls flexed and abducted than with both hands on the thighs. A greater CFREQ-AP was revealed when sitting with the dominant hand on the thigh than with both U/Ls crossed over the chest.

3.2.2. Individuals with SCI

MDIST-AP and MDIST-RD increased between the sitting position with both hands on the thighs and the unsupported sitting positions. MVELO for all directional components increased between the sitting position with both hands on the thighs and the unsupported sitting positions. MVELO-AP was also greater with unilateral hand support than with both hands on the thighs. Larger AREA-SW was found with both U/Ls flexed and abducted compared to the supported sitting positions. CFREQ-ML and CFREQ-RD was greater during the sitting position with the dominant hand on the thigh and both U/Ls flexed and abducted than with both hands on the thighs. Finally, 50%-PFREQ-RD increased with both U/Ls flexed and abducted compared to the sitting position with both hands on the thighs.

3.3. Relationship between seated postural stability and clinical/ demographic variables

Among clinical variables, only time from injury and the AIS scores strongly correlated with COP measures. The time from injury was positively correlated with MVELO-AP during the sitting position with both hands on the thighs and the same trend was observed with time-domain distance measures in all the other tasks except during the sitting position with both U/Ls flexed and abducted. The AIS motor and sensitive scores were negatively correlated to time-domain distance measures, particularly while sitting with the dominant U/L flexed and abducted and with both U/Ls crossed over the chest. The age was positively correlated with COP measures in all positions except during the unsupported sitting, defining mainly an increase in MVELO-AP during supported positions and in frequency measures when U/L support was reduced. As for the height and the weight, both were found to be uncorrelated with the COP measures.

4. Discussion

4.1. Differences between groups

Individuals with SCI demonstrated lower stability performance and greater postural control demand compared to healthy controls, irrespective of U/L positions and weight support roles, which confirm the hypothesis that they exhibit reduced stability. The ML instability during supported sittings and the additional AP instability during unsupported sittings suggest the potential role of U/L support while compensating for anterior instability. These results corroborate the lateral COP pattern found by Shirado et al. [7] in individuals with SCI during supported sitting and the central COP pattern during unsupported sitting.

When comparing unilateral hand support, lower stability performance and enhanced postural activity were revealed in individuals with SCI compared to healthy controls, with the dominant hand on the thigh. No difference in postural activity was observed between groups, while they kept their non-dominant hand on the thigh. Thus, in individuals with SCI, maintaining sitting stability with the dominant hand providing support was probably more difficult than when support is provided by the non-dominant hand. Individuals with SCI probably used their dominant U/L more often in daily activities (i.e., reaching, lifting and grasping tasks) while maintaining their seated stability with the non-dominant hand support. They may have developed excellent seated stability over time with the elevation of the dominant U/L while supporting part of their body weight with the non-dominant hand on the thigh. Therefore, maintaining the dominant shoulder flexed and abducted may be less tiresome than doing so with the non-dominant shoulder. A side effect in U/L support, supposing a dominant trunk stabilizer, might affect seated stability in individuals with SCI compared to healthy controls and suggest increasing non-dominant side training during a rehabilitation program.

Furthermore, the larger moment of inertia of the moving trunk [21,22] in individuals with SCI may be explained, in part, by the height of the COM that raises by about 5% of the body length compared to healthy controls which further increase the need for postural adjustments. Trunk muscle impairment reduced the ability to support the shift in trunk mass and increased the time for the COP to return to the initial position. The bilateral U/L support might compensate for this impairment and prevent instability in AP direction by creating a “locking” mechanism. Surprisingly, the centroidal frequency increased when U/L support was reduced, suggesting that the trunk inertia might be efficiently compensated by increased postural control since increased velocity was observed simultaneously. Thus, the bilateral U/L support required less postural adjustments to stabilize the trunk mass in the sagittal plane, thereby decreasing the risk of fatigue and increasing the ability to maintain seated stability over time.

The lower median power frequency found in individuals with SCI compared to healthy controls emphasized the difference in preferential postural regulation strategies [19,20,24]. Studies on postural control [25] found that median power frequency during quiet standing was lower in elderly adults who fell compared to young adults, particularly with respect to the ML component, due to a number of age-related deficits. These studies held that the greater number of degrees of freedom used to maintain AP stability (i.e., muscular adjustments at the ankle, knee and hip) in a standing position provided the individual with increased alternative strategies to adjust stability and compensate for perturbations. In the ML direction, the primary response occurred at the hip [26], suggesting reduced alternative strategies to compensate for instability. A similar conclusion could be drawn from the comparison of individuals with SCI and healthy controls. Compensation for instability via U/L support could not be efficient during unsupported sittings and was insufficient in compensating for ML instability, irrespective of the sitting position.

4.2. Effect of SCI on postural control strategies

Individuals with SCI might have adopted postural control strategies that differed from those observed in healthy controls when U/L support decreased. Similarly, Shirado et al. [7] showed that the COP shifted anteriorly in healthy controls with bilateral U/L flexion and posteriorly when individuals with SCI performed the same task. Based on this finding and the results of the present study, the elevation of one or both U/Ls increased the anterior moment, resulting in increased instability in the sagittal plane and, to a lesser extent, in the frontal plane depending on the symmetry of the U/L position. This additional load on the shoulder and trunk might be compensated in healthy controls by various mechanisms. Bilateral antagonistic recruitment of the rectus abdominis and latissimus dorsi muscles largely involved in the control of flexion and extension of the trunk, as well as bilateral antagonistic recruitment of the left and right obliqus abdominus externi and interni mainly involved in the control of lateral trunk motions, is highly plausible. The activity of the diaphragm and intercostal muscles is also probably coordinated for both respiratory and compensating trunk perturbations [27].

In individuals with SCI, muscular compensations are difficult or incomplete due to postural trunk muscle impairment [28]. Therefore, the posterior COP shift observed by Shirado et al. [7] linked to posterior pelvic tilting during unsupported sitting, may prevent anterior falling. This adaptive position generally accompanied by reduced lumbar lordosis and increased thoracic kyphosis, places the COP closer to the posterior limit of the base of support (BOS). As no backward fall was observed, participants may have learned effective compensatory strategies over time, such as the additional use of non-postural trunk muscles. In electromyography studies, Seelen et al. [29,30] described that these compensatory strategies rely in part on the increased use of the high thoracic part of erector spinae and non-postural muscles (e.g., latissimus dorsi and trapezius pars ascendes), as well as stabilizing effects of the scapular protractors (e.g., pectoralis major and serratus anterior).

4.3. Relationship between seated stability and clinical/demographic variables

Individuals with high AIS scores tended to have better sitting stability than individuals with low scores, as they have more residual muscles innervated and rely on greater sensorimotor afferences. Inversely, individuals with low AIS scores tended to have an increased control demand and a different control strategy, suggesting increased implication of non-postural muscles or other sensory feedbacks (e.g., vision) when maintaining a sitting posture. The greater influence of the sensitive score compared to the motor score, might be due to the fact that the AIS motor score does not capture the trunk muscle (i.e. AIS motor score remains unchanged for individuals with SCI between the 2nd or 12th thoracic vertebra). Additionally, individuals with the most long-standing SCI tended to exhibit increased control demand on the AP directional component with no altered effect on stability performance, irrespective of the sitting position, suggesting preferential and optimal use of non-postural muscles as a result of time and learning. Finally, despite the lack of correlation between the level and severity (i.e. completeness) of the SCI and COP measures (probably due to the small sample size in each type of lesion sub-groups), we may infer that individuals with high SCI (absence of abdominal/trunk muscles) would have greater postural stability reduction than individuals with low SCI. Additionally, we may also suppose that individuals with low SCI (partial or total use of abdominal/trunk muscles) would reach similar or close values as those obtained for healthy participants [31]. Moreover, among individuals with the same level of SCI, those with a complete motor lesion (AIS A or B) would be expected to present lower quasi-static seated stability than those with incomplete motor lesion (AIS C or D). However, further investigations are warranted to confirm these hypotheses.

As for the demographic characteristics in individuals with SCI, they did not clearly influence seated postural stability irrespective of the groups, except for the age. Indeed, the change observed in COP measures due to age corroborates previous studies on age-related change in postural steadiness in healthy human [12,17] and thus was not specific to people with SCI. Consideration for anthropometric measures (i.e. segments length) should be given as they may affect postural parameters. It would also have been interesting to define the margins of stability in a sitting position based on the COP excursion (i.e., the area of the COP excursion could be weighed against the base of support to provide an overall index of stability) among individuals with SCI and healthy counterparts. However, the quasi-static positions implied that no significant head-trunk-U/L movements were triggered. As a consequence, very small COP excursions were observed with respect to the area of the BOS (Fig. 1) which further explains why this approach was not used in the present study. Additionally, since no between-group difference was found for the area of the BOS or in the height or mass of participants, the outcome measures were not normalized.

Last, in a short-sitting position with feet supported on the floor, the feet are supporting part of the body weight. Thus, it would also have been interesting to test whether the amount of weight transiting through the feet may vary according to the different position and neurological characteristics.

5. Conclusion

Individuals with SCI experienced reduced seated postural stability compared to healthy controls, regardless of U/L position or weight support roles. In individuals with SCI, bilateral U/L support provided the greatest seated postural stability. Unilateral hand support led to comparable stability performance despite increased control demand, which suggests additional fatigue and a limited ability to maintain this position for a long time. Unsupported sitting positions challenged seated postural stability the most and significantly increased the risk of fatigue, hence limiting the ability to perform unsupported bilateral U/L functional tasks. The COP measures can provide useful information to rehabilitation professionals wishing to characterize change over time or measure the impact of various treatments on quasi-static seated postural stability.

Acknowledgments

We thank all participants for their time and Philippe Gourdou, Pierre Desjardins, Michel Goyette for their technical assistance.

Cindy Gauthier received a Summer Research Award from the Quebec Rehabilitation Research Network. Dany Gagnon, Géraldine Jacquemin, Kei Masani and Milos Popovic are members of the Quebec-Ontario Spinal Cord Injury Mobility (SCI-MOB) Research Group funded by the Quebec Rehabilitation Research Network and the Ontario NeuroTrauma Foundation.

Dany Gagnon holds a Junior 1 Research Career Award from the Fonds de la recherche en santé du Québec (FRSQ). The Pathokinesiology Laboratory was financed in part by the Canada Foundation for Innovation (CFI). The project was supported by the Quebec Rehabilitation Research Network (REPAR).

Conflict of interest statement

The authors declared no potential conflict of interest with respect to the authorship and/or publication of this article.

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