



Effects of sensorimotor trunk impairments on trunk and upper limb joint kinematics and kinetics during sitting pivot transfers in individuals with a spinal cord injury

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ABSTRACT

Background: Depending on the level and severity of the sensorimotor impairment in individuals with a spinal cord injury, the subsequent reduced seated postural stability and strength generating-capacity at the upper limbs could affect performance during sitting pivot transfer. This study aimed to determine the effects of sensorimotor impairments on head, trunk and upper limb movement and efforts during sitting pivot transfers.

Methods: Twenty-six individuals with a spinal cord injury participated and were stratified in two subgroups: with (N=15) and without voluntary motor control (N=11) of their lower back and abdominal muscles. Kinematics and kinetics of sitting pivot transfer were collected using a transfer assessment system. Mean joint angles and movement amplitudes and peak and average joint moments were compared between subgroups using independent Student t-tests ($P<0.05$) for the weight-bearing sitting pivot transfer phases.

Findings: The subgroup without voluntary control of their lower back and abdominal muscles had significantly greater forward trunk flexion compared to the other subgroup resulting in higher wrist extension and elbow flexion at both upper limbs. No significant joint moment difference was found between the subgroups.

Interpretation: Individuals with spinal cord injury who have no voluntary motor control of their abdominal and lower back muscles increase forward trunk flexion during sitting pivot transfers 1) to increase stiffness of their spine that may optimize the strength-generating ability of their thoracohumeral muscles and 2) to lower their center of mass that may facilitate lift-off and enhance the overall stability during sitting pivot transfers.

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1. Introduction

Many individuals who have sustained a spinal cord injury (SCI) must rely heavily on their upper limbs (U/L) to propel their wheelchair and perform numerous wheelchair-related functional tasks (e.g., overhead reaching, pressure-relief lifts, sitting pivot transfers (SPT)). Special attention should be paid to SPTs given that this wheelchair-related functional task is frequently performed (up to

40 per day) for different purposes (e.g., to get in and out of a bed, on and off a tub bench, in and out of a car, etc.) and within various physical environments (e.g., height and gap differences between seats, limited hand placement options, etc.) in daily life (Gagnon et al., 2009a). As a consequence, the U/L joints are exposed to repetitive and high loads that increase the risk of U/L secondary impairments during a SPT (Bayley et al., 1987; Pentland and Twomey, 1994). The development of such secondary impairments would most likely have deleterious consequences on the performance of many functional abilities among individuals with SCI that could eventually hamper societal participation. In order to gain additional evidence-based knowledge on SPTs and refine strategies currently proposed to minimize U/L secondary impairment risk exposure during this task (Gagnon et al., 2009a; Medicine, 2005), additional comprehensive biomechanical studies are needed.

When performing a SPT, individuals with a SCI will usually place one hand on the target seat (leading arm) and one hand just beside the

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buttocks (trailing arm) (Allison et al., 1996; Gagnon et al., 2008c; Koontz et al., 2011a). Then, a rapid forward trunk flexion movement, characterized by trunk angular velocity reaching up to 56°/s on average in individuals with SCI, generally initiates the SPT (Gagnon et al., 2008d). As the buttocks progressively lose contact with the initial seat (lift-off), the U/Ls support most of the body weight since approximately only 30% of the body weight is supported by the feet at this time (Allison, 1997; Allison et al., 1996; Gagnon et al., 2008b). While the U/Ls support most of the body weight, Gagnon et al. (2008c) reported peak shoulder flexion moments of 1.36 and 1.45 Nm/kg at the leading and trailing shoulder, respectively, during SPTs performed by individuals with SCI whereas Koontz et al. (2011a) reported peak flexion moment, averaged for both shoulders, of approximately 1.56 Nm/kg among able-bodied participants during SPTs. In addition to supporting most of the body weight during the weight-bearing phases of a SPT, the U/Ls also need to simultaneously participate in the dynamic stability requirements of a SPT, especially through the contribution of the large thoracohumeral muscles originating from the trunk (e.g., pectoralis major, trapezius, latissimus dorsi) to prevent loss of balance or falls with further increased levels of effort (Gagnon et al., 2012).

Individuals with SCI will experience, to varying degrees, sensorimotor impairments for which the severity will depend on the vertebral level and completeness of the lesion to the spinal cord. Depending on the severity of the lesion, particularly the vertebral lesion level, motor control and coordination of the trunk and U/L joints, as well as the strength-generating ability of the U/L muscles, can be affected to a various extent. Gauthier et al. (2012) have recently shown a decrease in multidirectional seated postural stability (i.e., limits of stability) for individuals with a higher lesion level (vertebral lesion level T7 and higher) compared to individuals with a lower lesion level (lower than T7) and to able-bodied individuals. Chen et al. (2003) have also shown that individuals with a higher lesion level (T6 and higher) have decreased dynamic sitting stability compared to individuals with lower lesion levels (T7 and lower). These authors associated this decreased stability to the partial and/or complete loss of voluntary control of the abdominal and lower back muscles for higher lesion levels. This muscle function loss and reduced dynamic stability could also affect the strength-generating ability and the muscle synergies at the U/Ls, especially those involving the thoracohumeral muscles (Chen et al., 2003; Potten et al., 1999; Powers et al., 1994). The diminished dynamic stability and potential reduction in strength-generating abilities could alter movement strategies as well as the load sustained at the U/L joints during SPTs for individuals with a neurological lesion level causing a paralysis of the abdominal and low back muscles.

To date, only one study has specifically investigated the influence of trunk musculature impairment on biomechanics during transfers (Gagnon et al., 2003). This study showed that during posterior transfers performed in a long sitting position, greater muscular demand is needed for individuals with SCI who have a high neurological lesion level compared to those with a low neurological lesion level to achieve the same transfer (Gagnon et al., 2003). No data is yet available regarding the most common transfer performed by individuals with a SCI: SPT. Since the movement strategies and U/L efforts observed during SPTs differ from those observed during posterior transfers, a better understanding of the SPT task is warranted (Consortium for Spinal Cord Medicine Clinical Practice Guidelines, 2005). Thus, the purpose of this study was to determine the effects of sensorimotor trunk impairments on head, trunk and U/L joint kinematics and kinetics during SPTs among manual wheelchair users who have sustained a SCI.

2. Methods

2.1. Participants

A convenience sample of 26 individuals who experience a complete motor impairment combined to a complete or incomplete

sensory impairment following a SCI (ASIA Impairment Scale A–B) between the C7 and L1 vertebrae was recruited (Maynard et al., 1997). To participate, participants had to have sustained the SCI more than 6 months prior to the study, use a manual wheelchair as their primary mode of locomotion, be able to transfer independently between two level surfaces without any technical aid and have no history of U/L pain over the last 6 months. Ethical approval was obtained from the Research Ethics Committee of the Centre for Interdisciplinary Research in Rehabilitation of Greater Montreal (CRIR-541-0810). Participants reviewed and signed an informed consent form prior to entering the study.

Following recruitment and completion of the experimental procedure (described below), the 26 participants were stratified into two subgroups: voluntary control of abdominal and lower back muscles (ABD) and no voluntary control of these muscle groups (NABD). Classification of both subgroups was carried out by an experienced physical therapist and was based on the ASIA (American Spinal Injury Association) motor and sensory scores obtained during a clinical assessment. Participants included in the NABD subgroup had to have a neurological level of T7 or higher with an ASIA impairment score of A or B, whereas participants in the ABD group had to have a neurological level lower than T7 with an ASIA impairment score of A or B.

2.2. Sitting pivot transfer assessment

After a brief familiarization period with the transfer assessment system during which at least two SPT were completed (Gagnon et al., 2008a), participants performed SPTs using their natural technique from the initial seat to the target seat on three occasions (3 trials) separated by a rest period. For each of the three SPTs recorded in the same direction, all participants used their right and left U/L as their leading and trailing U/L, respectively. Participants were asked to perform the SPTs using their habitual technique and no specific instructions were given in terms of speed and movement amplitude. The only constraint was that each hand had to remain on their hand force platform during the entire SPT.

2.3. Kinetics

An instrumented transfer assessment system that incorporates five separate force-sensing surfaces to measure the reaction force underneath the feet, buttocks (initial and target seats) and hands (leading and trailing) during the SPTs was used (Fig. 1). Two height-adjustable instrumented chairs were positioned beside one another with a 90° angle separating the two seats. For each participant, the two height-adjustable chairs used during the laboratory assessment were both fitted to match the height of their personal wheelchair (mean height = 0.42 SD 0.02 m). In order to simulate a transfer initiated from a wheelchair, a wheel was fitted on the right side of the initial seat. The hand force-sensing surfaces, attached laterally to each chair, were adjusted to replicate the width of the participant's wheelchair seat. All forces applied on these surfaces were continuously recorded, amplified and stored at a sampling frequency of 600 Hz during the SPTs. Subsequently, the forces recorded during these tasks were filtered using a fourth-order Butterworth zero-lag filter, with a cut-off frequency of 10 Hz and down-sampled to 60 Hz. Additional information regarding the instrumented transfer assessment system is available in a previous report (Gagnon et al., 2008a).

2.4. Kinematics

Kinematic parameters during the SPTs were recorded at a sampling frequency of 60 Hz, using a motion capture system consisting of six synchronized camera units (4 Optotrak model 3020 and 2 Certus camera units; NDI Technology Inc., Waterloo, Ontario, Canada). This system tracked the 3D trajectory of 60 non-collinear skin-fixed light emitting

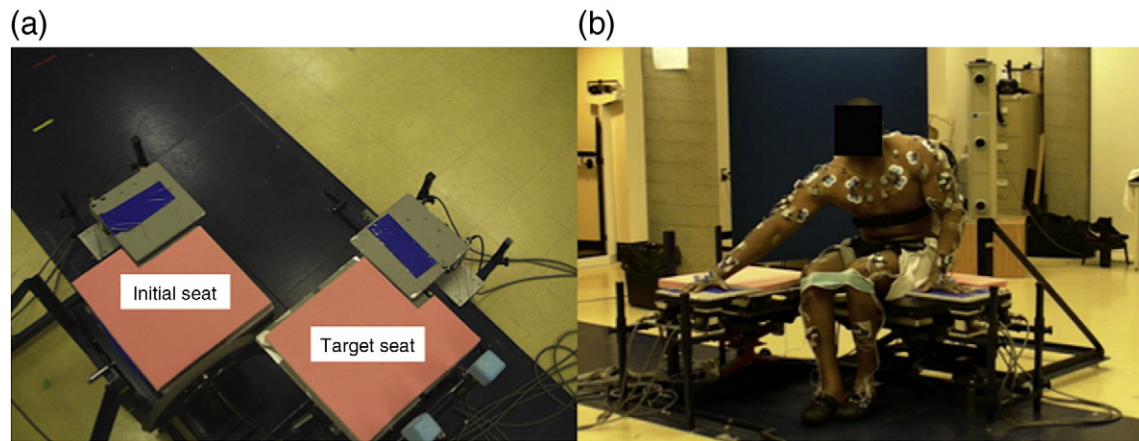


Fig. 1. (a) Transfer assessment system used. (b) A subject equipped with the 60 light emitting diodes before transfer.

diodes (LEDs) placed on rigid bodies, defining the head, trunk and upper and lower limb segments (Fig. 1). In addition, twenty-nine specific bony landmarks were digitized using a 6-marker probe to further define the articular centers and principal axes of segments (Gagnon et al., 2008d). The marker coordinates were smoothed with a fourth-order Butterworth zero-lag filter using a cut-off frequency of 6 Hz (Gagnon et al., 2008d).

2.5. Joint dynamics

Relative head motion was referenced to the trunk segment. The three anatomical landmarks used to define the head segment were the right and left tragi and C7 spinous process. The medio-lateral axis (Z) was defined by a vector pointing from the left to the right tragi; the anterior–posterior axis was obtained by the cross product between the Z vector and a vector pointing from the right tragi toward C7; and the supero-inferior axis was obtained by the cross product between the Z and X head axes. Relative motion was interpreted using a ZX'Y'' Cardan sequence. Relative trunk motion was referenced to the pelvis segment defined according to (Wu et al., 2002) and interpreted using a ZX'Y'' Cardan sequence. Head and trunk positive angles were in extension, right lateral inclination and left rotation.

To determine if the head or trunk was facing away from or toward the target seat during the SPT, a planar angle (horizontal plane) between the anterior/posterior axis of the head and of the trunk segments and the medio/lateral axis of the target seat was computed. A positive angle means that the head and/or trunk are facing away from the target seat, whereas a negative angle signifies that they are facing the target seat.

As for the bilateral relative movements of the U/L segments during the SPT, they were computed based on the recommendations of the International Society of Biomechanics (ISB) relating to the definition of joint coordinate systems (JCS) and segment definition (Wu et al., 2005). However, relative motion at the shoulder joint was computed by a ZX'Y'' Cardan sequence (Senk and Cheze, 2006) and referenced to a clavicle coordinate system (Wu et al., 2005). Bilateral positive joint angles were in flexion and ulnar deviation at the wrist, pronation and flexion at the elbow (0 degrees represented full extension), and adduction, internal rotation and flexion at the shoulder.

Three-dimensional net joint moments at the leading and trailing wrists, elbows and shoulders were estimated using a recursive Newton–Euler approach and obtained with respect to the laboratory coordinate system (Gagnon et al., 2008c). The resultant of the moment vector was then computed to represent the overall load sustained at each joint and then normalized to body weight.

Time series kinematic and kinetic components were obtained for both trials at each joint. Then, those time series were normalized to 100 data points (100%) according to a method recently proposed by Desroches et al. (2012), automatically identifying four key SPT phases (i.e., pre-lift, U/L loading, lift-pivot and post-lift), representing 35% (0–35), 15% (36–50), 35% (51–85) and 15% (86–100) of the entire SPT cycle (100%), respectively. Automatic identification of the four phases relies on key kinematic and kinetic parameters (i.e., C7 linear velocity, the forces measured at the trailing hand and at both seats). After time-normalization, both trials were averaged together for each participant.

2.6. Outcome measures and statistics

The dependent variables for the analyses were the absolute time of the SPT phases and of the entire SPT cycle, and the mean and movement amplitude (i.e. maximum–minimum) for each kinematic component (i.e., leading and trailing wrist, elbow, shoulder, trunk, and head). Dependent variables also included the peak and mean values for each resultant net joint moment (i.e., leading and trailing wrists, elbows, and shoulders). Descriptive statistics were computed to obtain the group mean (1SD) for the clinical characteristics and the dependent variables for the NABD and ABD subgroups. The clinical characteristics between subgroups were compared using a two-tailed Student *t*-test for independent samples ($P < 0.05$). To determine if a difference existed between the NABD and ABD subgroups during the SPT phases requiring the greatest effort at the U/Ls (i.e., U/L loading and lift-pivot phases), two-tailed Student *t*-tests for independent samples were performed whenever the dependent variable met the normality criteria (Kolmogorov–Smirnov Test: $P > 0.05$). Whenever the normality criterion was not met, Mann–Whitney tests were performed on the dependent variable. The significance level was set at $P < 0.05$. All statistical analyses were performed using the SPSS software (Version 18.0 for Windows).

3. Results

3.1. Participants

The mean clinical characteristics are presented in Table 1 for both subgroups. Based on the stratification criteria, 15 individuals were included in the ABD subgroup (T9–L1; AIS A–B) and 11 in the NABD subgroup (C7–T7; AIS A–B). Individuals in the NABD subgroup presented significantly more severe sensory impairments than individuals in the ABD subgroup. No other significant differences for clinical characteristics were found between either subgroup.

Table 1
Participants' characteristics (mean (1 SD)).

	ABD (n = 15)	NABD (n = 11)
Age	42.9 (12.1)	43.8 (10.7)
Height	1.78 (0.07)	1.75 (0.09)
Weight	83.5 (21.5)	73 (16.0)
Time since injury	10.1 (10.8)	14.7 (13.6)
Lesion level	2 T9, 8 T10, 2 T11 2 T12, 1 L1	1 C7, 1 T3, 2 T4, 1 T5, 3 T6, 3 T7
AIS	13 A, 2 B	8 A, 3 B
Gender (M/F)	13/2	11/0
ASIA motor score (/100)	51.3 (5.2)	48.3 (6.8)
ASIA sensory score (/224)	150.7 (16.7)*	122.9 (34.2)*

* Significant difference ($P < 0.05$).

3.2. Duration of the phases

Both subgroups completed the SPTs in a similar period of time (ABD: 1.96 SD 0.49 s; NABD: 2.02 SD 0.60 s) and almost all phases (except for the post-lift phase) had a similar duration (Table 2). Overall, the pre-lift, U/L loading, lift-pivot and post-lift phases represented 35%, 14%, 37% and 13% of the entire SPT cycle, respectively.

3.3. Kinematics

3.3.1. Trunk and head

The time-normalized (100%) group mean kinematic time series for the trunk and head are depicted in Fig. 2. For both subgroups, the head was in flexion, tilted to the left and slightly rotated to the right with respect to the trunk during each phase of the SPT (Fig. 2, a–c). Individuals with SCI had their trunk flexed, tilted and rotated to the right while transferring (Fig. 2, e–g). During the entire SPT cycle, the head and trunk were always facing away from the target seat in both subgroups (Fig. 2, d,h).

No significant differences were found in mean kinematics for relative motion between the head and the trunk throughout the entire SPT (Table 3). A significantly greater forward trunk flexion angle relative to the pelvis was found during the U/L loading and lift-pivot phases in the NABD subgroup compared to the ABD subgroup (Table 3). In fact, an average difference of approximately 12° in trunk flexion over the entire SPT cycle was found between both subgroups, which represents a 30% increase for the NABD subgroup. However, no significant differences between the subgroups were

Table 2
Average phases' time (s) (1 SD).

	Groups				
		ABD		NABD	
		Time (s)	%	Time (s)	%
SPT phases	Pre-lift	0.73 (0.30)	37.0 (11.5)	0.68* (0.32)	32.6 (10.7)
	U/L loading	0.29 (0.12)	14.5 (4.1)	0.29 (0.15)	14.7 (6.0)
	Lift-pivot	0.71 (0.28)	36.4 (10.8)	0.76 (0.24)	38.3 (6.9)
	Post-lift	0.23 (0.08) ^a	12.1 (3.0)	0.30 (0.20) ^a	14.4 (7.1)
SPT cycle	1.96 (0.49)	100 (0.0)	2.02 (0.60)	100 (0.0)	

* Significant difference ($P < 0.05$).^a Non parametric test used.

highlighted for trunk and head movement amplitudes despite significantly different trunk starting positions (Table 3).

3.3.2. Leading upper limb

Time-normalized (100%) group mean kinematic time series for the leading U/L joints are depicted in Fig. 3a–g. Significantly greater wrist extension was found for the NABD subgroup compared to the ABD subgroup during the lift-pivot phase (−59.55° vs. −78.58°) at the leading U/L (Table 4). Greater elbow flexion was also found at the leading U/L for the NABD subgroup during the U/L loading (50.04° vs. 58.20°) and lift-pivot (46.93° vs. 55.19°) phases. No other kinematic variables or joint movement amplitudes were found to be significant between the subgroups at the leading arm.

3.3.3. Trailing upper limb

For the trailing U/L (Table 4), a significantly greater elbow flexion angle was found for the NABD subgroup compared to ABD subgroup during the U/L loading phase (56.91° vs. 65.69°). No other significant differences were found for the other kinematic variables at the trailing arm. The NABD subgroup had greater elbow and shoulder flexion/extension movement amplitude than the ABD subgroup at the trailing U/L (Table 4).

3.4. Kinetics

The time-normalized (100%) group mean (SD) net joint moments at the wrist, elbow and shoulder of the leading and trailing U/Ls, measured during the entire SPT cycle, are presented in Fig. 3, h–j. The average (1 SD) of the mean and peak resultant net joint moments at the wrist, elbow and shoulder for the SPT phases is reported in Table 5.

3.4.1. Leading arm

No significant difference for peak or mean resultant joint moment was found between the subgroups at the leading arm. The highest peak moment was found at the shoulder followed by the elbow and wrist, which occurred at 73.5 SD 10.3%, 66.0 SD 21.0% and 75.2 SD 13.4% of the SPT cycle, respectively (i.e., lift-pivot phase).

3.4.2. Trailing arm

No kinetic variables were significantly different between both groups at the trailing arm during the U/L loading and lift-pivot phases. The highest peak net joint moments were at the shoulder followed by the elbow and the wrist and occurred at 50.9 SD 4.2%, 54.8 SD 11.1% and 48.8 SD 5.7% of the SPT cycle, respectively (i.e., U/L loading phase).

4. Discussion

The objective of the current study was to determine the influence of sensorimotor trunk impairments on the head, trunk and U/L movement strategies and efforts during the performance of SPTs between seats of similar height. The NABD subgroup (complete sensorimotor lesion at T7 and higher) displayed significantly greater forward trunk flexion than the ABD subgroup (complete sensorimotor lesion lower than T7). This greater forward trunk flexion was compensated by increased elbow flexion and wrist extension angles at the leading and trailing U/Ls. Although a movement strategy difference was revealed, U/L joint efforts remained comparable between both subgroups during the performance of SPTs.

4.1. Impact of trunk impairments on overall biomechanics

It is difficult to compare the relative trunk motion computed in this study to previous studies because, to our knowledge, no other study has reported the relative motion between the trunk and the pelvis; comparisons have only been made relative to a fixed global

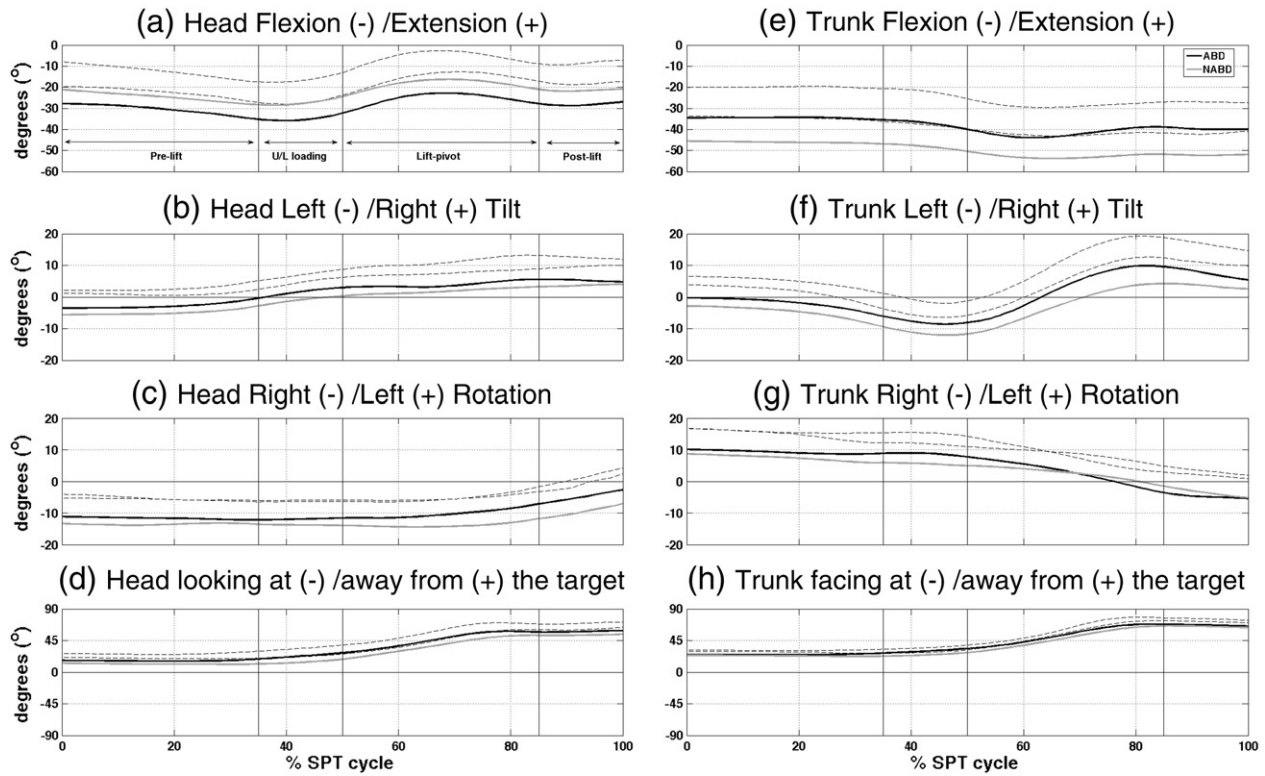


Fig. 2. Average (thick line) and standard deviation (dashed line) evolution for the (a) head flexion/extension, (b) head left/right tilt, (c) head right/left rotation, (d) head looking at/away from the target, (e) trunk flexion/extension, (f) trunk left/right tilt, (g) trunk right/left rotation and (h) trunk looking at/away the target. Black lines represent the time-series for the ABD subgroup and the gray lines for the NABD subgroup.

(laboratory) reference system. However, in terms of trunk movement amplitude, our results (14°) compare well with the excursion reported for 10 SCI individuals by Gagnon et al. (2008d) (18°) for SPTs between seats at the same height. In a more recent study, Koontz et al. (2011b) also reported trunk movement amplitudes of approximately 15° for five individuals with SCI transferring from their wheelchair to a target seat. The movement amplitudes for

trunk tilt and axial rotation documented in this study also compare well with those computed by Koontz et al. (2011b).

The significantly greater forward trunk flexion found for participants in the NABD subgroup might compensate for the absence of abdominal or low back contraction needed to increase trunk stiffness. Increasing forward trunk flexion would induce passive stretching of the posterior postural chain that actively helps to stiffen the spine.

Table 3
Mean (1 SD) head and trunk joint angles (degrees) and movement amplitudes.

		Flexion		Left tilt		Right tilt		Right rotation		Left rotation	
		ABD	NABD	ABD	NABD	ABD	NABD	ABD	NABD	ABD	NABD
Head	U/L loading	-34.91 (8.08)	-27.33 (11.02)	-3.93 (2.34)	-3.07 (3.48)	4.66 (2.61)	3.18 (2.70)	-11.94 (5.46)	-13.79 [‡] (7.86)	N.A.	N.A.
	Lift-pivot	-25.65 (9.64)	-19.09 (12.20)	-4.40 (4.36)	-3.48 (3.27)	7.26 (2.62)*	4.63 (2.90)	-10.46 (4.44)	-13.90 (7.70)	N.A.	N.A.
Movement amplitude		Flexion/extension 16.18 (5.81) 14.80 (4.51)		Left/right tilt 13.47 (6.16) 10.07 (3.89)		N.A. N.A.		Right/left rotation 12.03 (6.10) 11.89 (5.79)		N.A. N.A.	
Trunk	U/L loading	-37.19 (14.81)*	-48.29 (10.36)*	-9.37 (6.54)	-12.53 (6.17)	N.A.	N.A.	N.A.	N.A.	9.62 (5.58)	7.34 (3.96)
	Lift-pivot	-41.60 (13.19)*	-52.73 (10.55)*	-8.26 (6.93)	-11.53 (6.54)	10.55 (9.49)	4.85 (8.68)	N.A.	N.A.	5.98 (2.84)	4.95 (3.38)
Movement amplitude		Flexion/extension 14.15 (6.96) 14.07 (4.61)		Left/right tilt 20.38 (6.64) 18.62 (4.69)		N.A. N.A.		Right/left rotation 17.54 (7.55) 15.07 (3.64)		N.A. N.A.	

N.A.: No peaks could be computed during this specific phase.

[‡] Non parametric test was used.
* Significant difference ($P < 0.05$).

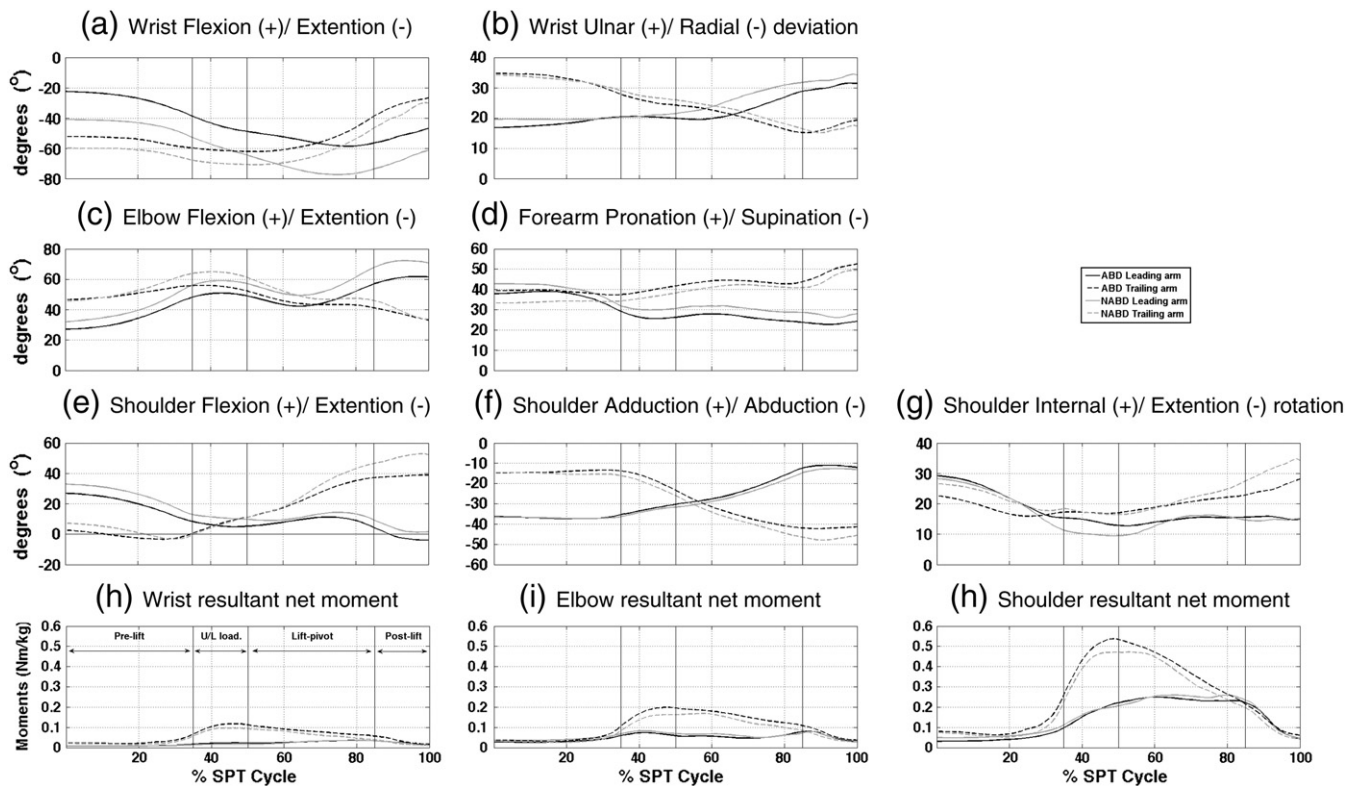


Fig. 3. Average time-series for the U/L joints kinematics and kinetics for the ABD subgroup (black lines) and NABD subgroup (gray line) for the leading U/L (thick line) and trailing U/L (dashed lines).

This increased spine rigidity will facilitate fixation of the scapula and enable the thoracohumeral muscles to have a more stable anchoring point on the trunk to allow greater thoracohumeral muscle force-generating ability (Potten et al., 1999; Powers et al., 1994). This could explain why no significant differences in joint loads were found between the two groups of participants during the U/L loading and lift-pivot phases. Moreover, the increased forward trunk flexion in the NABD subgroup might also serve to increase stability during the SPT by placing the body's center of mass closer to the ground to facilitate seat-off for individuals without abdominal muscles (Gagnon et al., 2008d). Based on the potential impact of trunk movements on U/L movements and efforts during SPTs, it would be interesting to determine the influence of various trunk movement strategies (i.e., greater or less forward trunk flexion) during SPTs in individuals with SCI on biomechanical outcome measures of interest (e.g., U/L kinetics) to possibly identify an optimal strategy.

4.2. Head and trunk face away from the target seat during SPTs

The results of the present study confirmed that the head and trunk of individuals in both subgroups faced away from the target seat during the entire SPT cycle. The axial twists of the head and trunk away from the target seat during SPTs may facilitate the overall body rotation needed to orient the buttocks (i.e., pelvis) toward the target seat and may ensure a safe landing. Such a movement strategy may indicate that visual information, especially with regard to the distance and orientation of the target seat and the surrounding environment required to safely achieve a habitual SPT must be acquired before the beginning of the SPT cycle. This movement strategy is also compatible with the existence of an internal model for habitual SPTs (e.g., between seats of similar height with no gap) that would allow adequate pre-planning of the movement as proposed by Gagnon et al. (2009b). Reliance on this information could be indicative of the experience level of the individual with SCI and on the level of familiarity

with the environment where the SPT is being performed. It would be interesting to evaluate this head/trunk relationship relative to the target seat in novice individuals with a SCI during the learning process or in a "novel environment" in order to determine if this could be a predictor of future motor performance. Moreover, combining this head/trunk relationship relative to the target seat with the frontal plane movement strategy definition proposed by Allison et al. (1996) (i.e., translatory or rotatory movement) may provide a better understanding of movement strategies used during a SPT.

4.3. U/L kinematics and loads

The movement patterns reported at the U/L joints in the present study compare well to those previously reported in individuals with SCI during SPTs (Gagnon et al., 2008a,d; Koontz et al., 2011b). As reported in previous studies, the leading and trailing U/Ls, especially the shoulders, work in an opposite direction in the frontal plane (i.e., adduction-abduction) and in a similar direction in the sagittal plane (i.e., flexion) confirming their respective pulling/pushing and supporting roles. The asymmetrical motion between the U/Ls increases the complexity of the movement, especially when the individual has to maintain balance while his or her body weight is only supported by the feet and U/Ls (i.e., lift-pivot phase) (Gagnon et al., 2008d).

Relative joint motions were almost similar between both subgroups, except for greater wrist extension and elbow flexion angles during the U/L loading and lift-pivot phases in the NABD subgroup. Gagnon et al. (2003) also reported similar shoulder and elbow kinematics between individuals with high and low lesion levels during a leveled posterior transfer. The increased angles found in the current study at the wrist and elbow in the NABD subgroup might be a consequence of greater forward trunk flexion. Some ergonomic studies have proposed wrist joint angle thresholds over which the discomfort or the risk of musculoskeletal disorders would be high (Louis et al.,

Table 4
Mean ± (1 SD) upper limb joint angles (degrees) and movement amplitudes.

		Wrist				Elbow				Shoulder					
		Extension		Ulnar deviation		Flexion		Pronation		Flexion		Abduction		Internal rotation	
		ABD	NABD	ABD	NABD	ABD	NABD	ABD	NABD	ABD	NABD	ABD	NABD	ABD	NABD
U/L loading	Leading	−46.58 (19.24)	−59.19 (11.24)	22.26 (13.64)	26.57 (14.93)	50.04 (10.15)*	58.20 (9.39)*	26.82 (11.77)	30.26 (10.24)	10.70 (6.95)	14.66 (9.96)	−32.77 (9.08)	−33.44 (15.43)	16.25 (8.95)	10.93 (10.12)
	Trailing	−61.23 (19.03)	−69.74 (8.13)	28.86 (22.14)	27.14 (13.38)	54.95 (11.11)*	63.65 (8.74)*	39.45 (18.49)	35.82 (15.19)	10.79 (9.16)	14.01 (7.66)	−18.03 (10.90)	−20.87 (9.05)	20.73 (12.59)	20.87 (13.64)
Lift-pivot	Leading	− 57.59 (19.70)*	− 73.59 (10.16)*	25.45 (14.28)	32.78 (14.85)	46.93 (8.72)*	55.19 (10.87)*	26.29 (12.76)	31.26 (11.13)	12.41 (10.63)	12.76 (9.78)	−23.11 (5.43)	−25.15 (13.59)	16.40 (12.12)	14.59 (13.12)
	Trailing	−55.45 (21.77)	−63.46 (9.36)	23.87 (23.55)	22.20 (14.50)	45.04 (10.54)	50.47 (11.45)	43.49 (18.75)	41.20 (16.80)	25.25 (12.36)	30.04 (17.37)	−34.80 (8.64)	−37.91 (9.05)	20.80 (16.61)	22.50 (14.65)
		Flexion/extension		Radial/ulnar dev.		Flexion/Extension		Pronation/supination		Flexion/extension		Adduction/abduction		Internal/external rot.	
Movement amplitude	Leading	38.08 (13.57)	38.60 (9.81)	19.08 (5.60)‡	18.86 (5.92)‡	38.71 (11.97)	46.57 (15.90)	22.32 (8.28)	21.56 (4.85)	34.06 (12.62)	37.56 (12.69)	29.93 (9.11)	28.23 (6.54)	23.43 (9.32)	25.51 (8.44)
	Trailing	39.97 (9.53)	43.83 (8.28)	25.11 (7.09)	23.10 (7.57)	26.17 (8.60)*	36.69 (9.35)*	20.38 (7.51)	21.48 (6.31)	46.16 (13.42)*	60.55 (12.92)*	32.31 (10.59)	37.20 (6.05)	20.20 (12.39)	23.76 (7.33)

‡ Non parametric test was used.

* Significant difference ($P < 0.05$).

Table 5
Mean and average peak ± (1 SD) resultant net moment (Nm/kg) at the upper limb joints.

		Wrist				Elbow				Shoulder			
		Mean		Peak		Mean		Peak		Mean		Peak	
		ABD	NABD	ABD	NABD	ABD	NABD	ABD	NABD	ABD	NABD	ABD	NABD
U/L loading	Leading	0.08 (0.05)*	0.06 (0.02)	0.10 (0.06)‡	0.07 (0.02)‡	0.26 (0.11)	0.29 (0.11)	0.31 (0.15)	0.33 (0.11)	0.64 (0.28)	0.63 (0.12)	0.85 (0.35)‡	0.78 (0.13)‡
	Trailing	0.40 (0.15)	0.33 (0.17)	0.48 (0.17)	0.39 (0.19)	0.66 (0.24)	0.53 (0.23)	0.80 (0.28)	0.65 (0.28)	1.72 (0.44)	1.50 (0.35)	2.10 (0.50)	1.83 (0.35)
Lift-pivot	Leading	0.11 (0.07)	0.10 (0.03)	0.16 (0.09)	0.14 (0.04)	0.21 (0.10)	0.23 (0.05)	0.37 (0.16)	0.37 (0.10)	0.90 (0.31)	0.92 (0.11)	1.15 (0.39)	1.13 (0.12)
	Trailing	0.31 (0.11)	0.25 (0.13)	0.44 (0.15)	0.36 (0.16)	0.60 (0.24)	0.50 (0.23)	0.79 (0.28)	0.67 (0.27)	1.49 (0.40)	1.32 (0.27)	2.08 (0.51)	1.83 (0.32)

* Significant difference ($P < 0.05$).

‡ Non parametric test was used.

2009; Veeger et al., 1998). The authors propose that joint angles over 5° of radial deviation and 10° of ulnar deviation could potentially be harmful, whereas, for wrist flexion/extension angles, those values would be over 15°. Since hand placement was restricted in the current study (i.e., on the platforms), the absolute value reported here cannot be directly compared with the thresholds proposed as numerous hand placement strategies are possible in natural environments. However, in terms of the relative increase between both subgroups, wrist extension in NABD subjects was greater by approximately 18° compared to ABD subjects. This increase is well over the proposed thresholds and, combined with the high and repetitive forces, could increase the risk of musculoskeletal impairments.

As previously reported, resultant net joint moments were greater at the trailing arm compared to the leading arm (Gagnon et al., 2008c; Koontz et al., 2011a; Perry et al., 1996). As highlighted by the peak joint moments during the weight-bearing phases (i.e., U/L loading and lift-pivot), the trailing U/L joints sustain more than twice the load compared to the joints of the leading U/L. Over an extended period of time, transferring only in one direction could have a deleterious impact at the trailing U/L joints (Medicine, 2005). Moreover, peak resultant moment timing at the U/L joints over the SPT cycle confirms that the trailing U/L initiates the SPT (peaks occur during the U/L loading phase), while the leading U/L supports the weight that is gradually transferred until the cycle is completed (peaks occur during the lift-pivot phase).

4.4. Study limitations

The current study has some limitations. Mainly to control the hand position of each subject, participants were asked to perform the SPT with their hands on the platforms. Of course, this is only one of the many possible hand placements during a SPT. However, no instructions were given for hand orientation, thus, the resulting position of elbow and shoulder joints was not imposed. The number of participants in each subgroup was low, which could therefore limit the generalization of the findings. However, overall, twenty-six individuals with SCI were evaluated, which, to our knowledge, represents the largest biomechanical assessment of SPTs among manual wheelchair users with impairments and disabilities.

5. Conclusion

Individuals with SCI who had no voluntary control of their abdominal and low back muscles performed SPTs between an initial and target seat set at a similar height with significantly greater forward trunk flexion, accompanied by greater wrist extension and elbow flexion angles, compared to participants who had voluntary or partial control of those muscle groups. The reason for this increased forward trunk flexion may be twofold: (1) to increase the force generating ability of the thoracohumeral muscles; and (2) to augment overall stability during the SPT and to facilitate lift-off and pivot phases. Clinicians should take into consideration the neurological level during the rehabilitation process in order to customize movement strategies taught during SPT training (i.e., technique) depending on the residual sensorimotor function. Based on these findings, future research projects focusing on the effects of increased or reduced forward trunk flexion on U/L kinematics and kinetics appear to be promising.

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