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Short communication

Measuring dynamic stability requirements during sitting pivot transfers using stabilizing and destabilizing forces in individuals with complete motor paraplegia

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ABSTRACT

Dynamic stability requirements have never been quantified when long-term manual wheelchair users transfer themselves in a seated position from an initial surface to a target surface, a functional task commonly referred to as sitting pivot transfers (SPTs). Ten individuals with spinal cord injury (SCI), who rely on a manual wheelchair for mobility, underwent a comprehensive biomechanical SPT assessment. SPTs performed toward a target seat of same height (even) and a seat 10 cm higher than the initial seat (uneven), repeated three times for each task, were assessed. A dynamic equilibrium model, continuously measuring the theoretical forces required to move the center of pressure to the limit of the base of support (*destabilizing force*) and to neutralize the kinetic energy and stop the displacement of the center of mass at the limit of the base of support (*stabilizing force*) at each instance during the performance of SPTs, was used to identify the phases of greatest instability during the SPT tasks. The greatest levels of instability were reached around the time the buttocks lost contact with the initial seat and around the time the buttocks landed on the target seat (pre- and post-lift transition phases). These transition periods, characterized by the lowest destabilizing force (424.7–487.1 N) and the greatest stabilizing force (24.2–33.2 N), confirmed the greatest level of instability. The height of the target seat had no significant effect ($p=0.278$–0.739) on dynamic postural stability requirements during the SPTs. During SPTs towards even and uneven target seats, the greatest postural instability occurs during the transition phases in individuals with complete motor thoracic SCI.

1. Introduction

Many individuals with spinal cord injury (SCI) use a manually-propelled wheelchair as their primary source of mobility and performed numerous wheelchair-related functional activities. Among those, they often have to transfer themselves from their wheelchair to a target surface (e.g., bed, bench, toilet, car) in a seated position (sitting pivot transfer–SPT). While doing so, the technique used often varies given the fact that it is influenced by the numerous personal characteristics (e.g., spasticity), the use of technical aids (e.g., transfer board, transfer bars), the amount of human assistance available (e.g., caregiver), and other factors (e.g., wheelchair frame, architecture, height difference and gap between seats) (Allison, 1997; Nyland et al., 2000). Nonetheless, the large number of transfers performed daily, along with the excessive physical strains measured at the wrist, elbow and shoulder joints while performing SPTs, likely contributes to the development or perpetuation of secondary U/E musculoskeletal impairments over time (Consortium for Spinal Cord Medicine Clinical Practice Guidelines, 2005). Moreover, the added upper limb strains that may be required to compensate for dynamic seated postural instabilities during functional activities also deserve attention in this population.

Individuals with SCI need to achieve two key tasks when performing sitting pivot transfers (SPTs) between their wheelchair (initial seat) and a target seat or surface (e.g., bed, tub bench, toilet, couch, car, etc.): (1) generate substantial upper extremity moments to lift and pivot themselves from an initial seat toward a target seat; and (2) simultaneously control dynamic stability to avoid loss of balance or a fall. While much research has been done over the past decade to better understand mechanical load on the upper extremity during SPTs (Gagnon et al., 2009), no study has

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quantified dynamic stability during SPTs among long-term manual wheelchairs. However, the increased risk of instability, even of fall, while performing SPTs and the considerable burden of secondary fall-related impairments and disability in long-term manual wheelchair users are reason enough for conducting research in this field (Kirby et al., 1994; Nelson et al., 2010).

Duclos et al. (2009) have recently proposed a new equilibrium model, that measures the destabilizing and stabilizing forces, to quantify dynamic balance requirements required while performing a functional task. The uniqueness of this model, based on a comprehensive biomechanical assessment of a functional task, is that the level of dynamic balance requirements is continuously computed and modulated according to the ever-changing base of support (BOS) and movement direction. To date, this model has been primarily used to quantify dynamic postural stability requirements when individuals walked at self-selected natural and self-selected maximum gait speeds (Duclos et al., 2009). Aside from identifying gait sub-phases during which the greatest instability occurs, the preliminary results confirm that the proposed model varies according to gait speed changes and successfully classifies a group of individuals walking at a similar speed based on dynamic stability requirements. Applying such a model during the assessment of SPTs may allow one to investigate the interaction between upper limb strain and dynamic balance requirements while using various SPT techniques, for example.

The main objective of this brief communication is to use this new equilibrium model to quantify dynamic stability of individuals with SCI while they perform SPTs toward a target seat of same height (Task #1: *even SPT*) and one set 10 cm higher than the initial seat (Task #2: *uneven SPT*). It is hypothesized that the dynamic stability requirements will peak during the transition phases of the SPTs, that is, around the time the buttocks loose contact with the initial seat (*seat-off*) and around the time the buttocks land on the target seat (*seat-on*). It is also anticipated that even SPTs will be more stable than the uneven SPTs.

2. Methods

2.1. Participants

Ten males with complete motor impairments resulting from a traumatic SCI sustained at least one year earlier volunteered to participate to this study. All participants used a manual wheelchair as their primary source of mobility and routinely performed SPTs between seats of similar height independently in daily life (Table 1). Potential participants were excluded if they presented any clinical evidence of secondary impairments or conditions that may have limited their ability to perform the SPTs. Ethical approval was obtained from the Research Ethics Committee of the Center for Interdisciplinary Research in Rehabilitation of Greater Montreal. The sample size was not based on a formal calculation since no previous study had been conducted and only a homogenous sample of participants was recruited.

2.2. Sitting pivot transfer tasks

Participants transferred from one firmly cushioned instrumented height-adjustable chair toward another one in a sitting position using their habitual initial hand/feet position and movement strategies. While doing so, their hands were positioned flat on two hand force plates separately attach to each chair and their feet were resting on two force plates embedded into the floor Details on the instrumented SPT system are available (Gagnon et al., 2008a, 2008c). Initially, the height of both instrumented chairs was set at 50 cm for all participants (*even SPT*) whereas the hand force plates were adjusted to assure that the width of the seats corresponded to that of their own wheelchair. The height of the target seat was then raised by 10 cm (uneven *SPT*). After a familiarization period, three transfer trials were recorded for each experimental task.

2.3. Comprehensive biomechanical assessment

Kinematic parameters were continuously recorded (60 Hz) during each SPT using five synchronized Optotrak motion analysis camera bars (model 3020; NDI Technology Inc., Waterloo, Ontario, Canada). This motion capture system recorded at 60 Hz the three-dimensional (3D) coordinates of the all skin-fixed infrared light emitting diodes (LEDs) used to define the head, trunk, bilateral upper and lower extremity segments at all time. Additional 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 used to calculate the area of the BOS. Kinetic parameters were computed (600 Hz) using an instrumented transfer assessment system (Gagnon et al., 2008a) integrating five force-sensing surfaces. Additional information on the kinematics (Gagnon et al., 2008a, 2008d) and kinetics (Gagnon et al., 2008a, 2008b, 2008c) of SPT tasks is available.

2.4. Dynamic postural stability

A new model measuring destabilizing and stabilizing forces was used to quantify dynamic postural stability during the SPTs (Duclos et al., 2009). The *destabilizing force* ($\vec{F}_D$) is the theoretical force (N) applied to the body in the direction of the velocity of the center of mass (COM) required to move the center of pressure (COP) to the limit of the BOS during each moment of the SPT:

$$\vec{F}_D = \left(\frac{\vec{F}_r.\vec{n}}{h_{COM}}\right)\vec{D}_{COP}$$

where $\vec{F}_r$ is the ground reaction force, $\vec{n}$ is the unitary vector normal to the contact surface, h_{COM} is the height of the COM from the supporting surface and $\vec{D}_{COP}$ is the horizontal distance from the COP to the limit of the base of support in the direction of COM velocity. The lower the destabilizing force, the easier it is to move the COP to the limit of the BOS and, consequently, the more unstable an individual may be. The *stabilizing force* ($\vec{F}_{ST}$) reflects the theoretical force (N) needed to neutralize the kinetic energy to stop the displacement of the COM at the limit of the BOS and to maintain balance at each moment of the SPT:

$$\vec{F}_{ST} = -\frac{m_{global}\,\vec{v}_{COM}\,\vec{v}_{COM}}{2D^2_{COP}}\vec{D}_{COP}$$

where m_{global} is the mass of the subject, $\vec{v}_{CM}$ is the linear velocity of the COM reflecting the derivative of the position of the COM determined from the weighted mean of the position of all the body segments and $\vec{D}_{CP}$ is the horizontal distance from the COP to the limit of the base of support in the direction of COM velocity.

Table 1
Description of participants.

Participants	Age (years)	Height (m)	Weight (kg)	Time since injury (years)	Motor-Asia score (/50)	Sensory-Asia score (/224)	Level of injury	Number of transfers (/day)
1	39.0	1.85	105.2	5.3	50	112	T7	22
2	44.8	1.73	105.3	5.0	50	144	T11	18
3	49.3	1.78	86.1	4.8	50	88	T4	24
4	54.1	1.7	63.8	31.7	50	104	T6	22
5	51.7	1.88	88.7	33.5	50	144	T11	11
6	33.8	1.83	80.7	2.4	50	92	T4	24
7	27.5	1.75	64.4	3.6	50	100	T5	16
8	38.1	1.73	51.3	6.9	50	92	T4	22
9	31.8	1.68	75	2.8	50	88	T4	35
10	41.6	1.72	93.6	3.2	50	96	T5	20
Mean	**41.2**	**1.77**	**81.4**	**9.9**	**50.0**	**106.0**		**21.4**
SD	**8.8**	**0.07**	**18.0**	**12.0**	**0.0**	**21.4**		**6.2**