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Lateral Trunk Displacement and Stability During Sit-to-Stand Transfer in Relation to Foot Placement in Patients With Hemiparesis

Cyril Duclos, PhD, Sylvie Nadeau, PhD, and Julie Lecours, MSc

Background. In hemiparetic individuals, sit-to-stand (STS) transfer is characterized by asymmetric weight-bearing and altered trunk kinematics that can be improved by positioning the affected foot behind the nonaffected one. *Objective*. To examine the influence of frontal trunk kinematics on medio-lateral displacements of the center of pressure (CP) during STS performed with the feet placed in 2 different positions, as well as relationships between these parameters, medio-lateral stability, and clinical scores of the participants. *Methods*. Eighteen patients with chronic stroke and 15 control individuals were evaluated during sit-to-stand transfers either in spontaneous foot position or with their affected or dominant foot placed behind, respectively. Medio-lateral CP, pelvis, and shoulder displacement were analyzed using 3D kinematic and kinetic data recordings of the whole task. Motor and sensory impairment, spasticity, muscle strength, and equilibrium were evaluated by standard scales. The possible time during which a participant could prevent a fall (minimal time-to-contact) was used as a stability index. *Results*. Spontaneously, the deviation of the CP of stroke participants paralleled the tilt of the trunk toward the nonaffected side, as early as the first third of the task. With the affected foot placed behind, trunk position did not differ from those of control participants who executed the transfer spontaneously. Hemiparetic participants were less stable than control participants. Placement of the feet had no significant effect on the stability of either group. Stability was strongly associated with better motor scores on the Chedoke-McMaster Stroke Assessment. *Conclusions*. In hemiparetic individuals, improving STS symmetry by positioning the affected foot behind the nonaffected one did not decrease medio-lateral stability, which was associated with the level of stroke-related motor impairments.

Key Words: *Foot position—Postural stability—Trunk kinematics—Stroke—Fall.*

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The transfer from sit-to-stand (STS) is a major functional ability, which is extensively affected in stroke individuals. This daily activity contributes to the incidence of falls in this population.[1,2] Compared to healthy individuals, individuals with chronic hemiparesis need more time to complete the task.[3-8] Moreover, because of the asymmetrical nature of stroke-related deficits, most of the altered movement patterns during the task were observed in the medio-lateral plane: hemiparetic individuals exhibit asymmetrical weight-bearing,[3-11] side differences in knee joint moments,[12] and increased medio-lateral oscillations of the center of pressure[7,9] and center of mass.[5]

Symmetry of movement is often a primary goal in rehabilitation after a stroke to improve stability and avoid the development of a nonuse syndrome. It also prevents overload on the nonparetic joint, which could accelerate musculoskeletal problems. Asking hemiparetic individuals to stand up with their weight evenly distributed,[4] after imagining doing so,[6] or to stand up with their affected foot behind the nonaffected one[8,11] are among the strategies to correct weight-bearing asymmetry. Moreover, at seat-off, a strong association was found between trunk position and weight-bearing asymmetry in healthy individuals and after stroke for spontaneous foot positioning and with the dominant or affected foot behind.[13] These authors suggested that clinicians could infer the degree of weight-bearing asymmetry from the frontal trunk position at seat-off. However, since Roy et al (2006)[8] have shown that weight-bearing asymmetry is observed before seat-off, an examination of trunk displacement in the medio-lateral plane during the entire transfer and the effect of changing foot position is needed. Moreover, if trunk kinematics can be presented concomitantly with the center of pressure position expressed in relation to the base of support, these data would help to identify at which point during the task individuals are less stable, and could provide observable clinical signs of the risk for falling throughout the task.

In this study, biomechanical analysis was used to measure and compare the medio-lateral displacements of the

Table 1. Mean Clinical Characteristics of the Stroke Participants (n = 18)

Sex	Age	Paretic Side	Berg /56	Chedoke Total / 14 (Leg; Foot)	Spasticity Total / 32 (Knee; Ankle)	Movement Sensation Total / 6 (Knee; Ankle; Big Toe)
6 F/12 M	50 ± 11	13 L/5 R	51 ± 6	8.4 ± 2.5 (4.6 ± 1.1; 3.8 ± 1.4)	12.6 ± 6.4 (5.9 ± 3.2; 6.7 ± 3.7)	4.7 ± 1.8 (1.7 ± 0.6; 1.6 ± 0.7; 1.4 ± 0.9)

M = male; F = female; R = right; L = left. Mean ± SD.

center of pressure, pelvis, and shoulders during the transfer from STS. Hemiparetic participants and healthy volunteers were assessed when the feet were spontaneously positioned and when the affected or dominant foot was placed behind the other one. The level of asymmetry could be related to the position of the trunk during the task, because of the proportion of body mass it represents. Therefore, changing the position of the affected foot in stroke participants could make the center of pressure displacements more symmetrical. In addition, because of their particular relevance for clinical practice, correlations between clinical scores and kinematic and kinetic data regarding stability were examined.

MATERIALS AND METHODS

Participants

Eighteen participants (12 men, 6 women) with hemiparesis due to stroke were included. Mean age was 50 ± 11 years (range from 27 to 73), and poststroke time was between 6 months and 8 years. Thirteen presented a left hemiparesis. Mean body mass and height were 77.4 ± 15.0 kg and 169.5 ± 7.1 cm, respectively. Inclusion criteria were as follows: more than 6 months poststroke; independent STS transfer from a standard chair without using arms or hands; tolerance for 2 hours of physical activity with appropriate rest periods; residual muscular weakness and motor impairment of the affected lower limb (Chedoke-McMaster Stroke Assessment score[14] at leg and foot < 12). Exclusion criteria were as follows: cognitive impairments and cerebellar, musculoskeletal, and neurological disorders other than stroke.

Fifteen healthy participants (7 men, 8 women, 56.1 ± 10.9 years old, 73.9 ± 16.5 kg, 168.4 ± 9.8 cm) were included as control participants. All participants gave their informed consent before the experimentation, according to the protocol approved by the Ethics Committee of the Center for Interdisciplinary Research in Rehabilitation of Greater Montreal and in accordance with the Helsinki Declaration.

Clinical Evaluation

The stroke participants were evaluated by a senior physical therapist specializing in neurology. Physical impairment was measured with the lower extremity (leg and foot) component of the Chedoke-McMaster Stroke Assessment.[14] Balance was evaluated with the Berg Balance Scale.[15] Spasticity at knee and ankle was evaluated with the Composite Spasticity Index.[16] Static hip abduction and adduction and trunk side flexion muscle strength were assessed with a Biodex dynamometer, in a side-lying and sitting position, respectively, on both sides in a static neutral position. Position and movement sense was evaluated with a matching task, at the knee, ankle, and big toe (no movement detection = 0, incomplete matching = 1, good matching = 2; see Table 1 for mean group scores).

Laboratory Equipment

The chair without back or armrest developed in our laboratory[17] was instrumented with 4 AMTI strain gauge transducers (MC3A-3-250, Advanced Mechanical Technology, Inc, Newton, Massachusetts) to record orthogonal forces under each thigh. The chair was fixed to the floor to dissipate any vibration. The seat height was adjusted to each individual's leg length (distance from lateral femoral condyle to ground). Two AMTI force plates (OR6-7-1000) embedded in the floor were used to record the forces under each foot. Data were collected at 600 Hz, filtered with a fourth-order Butterworth zero-lag filter with a cutoff frequency of 10 Hz, and resampled at 60 Hz to match the kinematic data.

Kinematic data were recorded using 3 noncollinear infrared markers placed over each body segment defined (feet, legs, thighs, pelvis, trunk, and head). The 3-dimensional position of these markers was sampled at 60 Hz by an Optotrak 3020 system (Northern Digital Inc, Waterloo, Canada) during the STS task (for details, see Roy et al[12]).

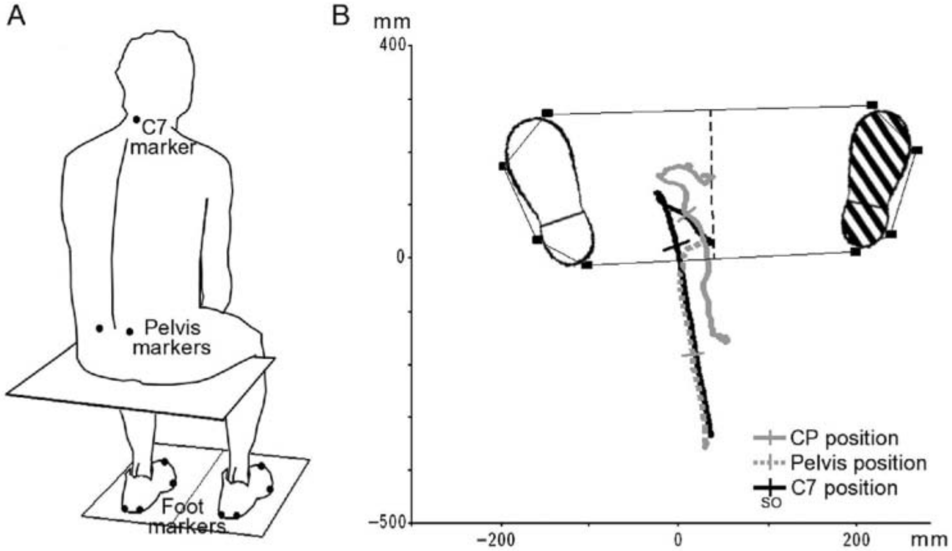

Figure 1. Experimental setup. Marker position (black dots) used to define the base of support (foot markers) and measure the displacements of the pelvis and shoulders (pelvis and C7 markers) relative to the reference point between the heel markers (A). Schema of the displacements of the 3 parameters (center of pressure [CP], pelvis, and C7) with respect to the base of support from the beginning to the end of the task (B). SO, seat-off.

The Sit-to-Stand Task

Both groups followed the same protocol. They sat on the chair, centered, with each thigh and foot on one force plate. They were then asked to stand up at their natural speed, with their arms crossed over their chest, while looking at a target on the wall 3 meters in front of them. Two different foot positions were used, spontaneous and asymmetrical, with the nonaffected foot placed half a foot-length ahead of the affected one for the hemiparetic participants, or with the nondominant foot placed half a foot-length ahead of the other for the control participants. The spontaneous condition was realized first. Two trials were analyzed in each condition. The position of the feet was controlled, and their markers did not generally move more than 1 mm during trials.

Variables and Data Analysis

The center of pressure was computed from vertical forces and moments measured by the strain gauges embedded in both the seat and the floor. Because these 2 measurement surfaces were at 2 different heights, a virtual surface was determined for the calculation of CP coordinates.[18] Only the coordinates in the medio-lateral plane are reported here.

The coordinates of the CP, pelvis, defined as the midpoint between the 2 postero-superior iliac spine markers, and shoulders, defined as the marker placed on the seventh vertebra (C7; Figure 1), and medio-lateral forces measured at the force plates were analyzed. They were standardized in time from 0%, the first change in the reaction forces at the beginning of the task, to 50%, the seat-off time (no force left on the seat), and 100%, the end of the task, defined by the beginning of stability of hip extension angles in standing. Seat-off actually happened between 42% and 45% of the task for both groups and both conditions. Center of pressure, pelvis, and shoulder coordinates were also standardized in space to the midpoint between the postero-lateral markers at the heels, and can thus be interpreted as lateral deviations by reference to this point. Trunk displacements were defined as follows: pelvis translation was lateral deviation of the pelvis, and trunk tilt, as a difference between the lateral deviation of the shoulders and the pelvis. Overall deviation of the shoulders (C7) thus included the lateral translation and tilt of the trunk.

As an index of stability, the CP time-to-contact (TtC)[19,20] was computed in the medio-lateral plane. This variable represents the maximal time before the CP reaches the limit of the base of support, that is, the maximal time in which the individual could prevent a fall during the task. At each sampled point of the task, TtC was calculated from the medio-lateral distance between the CP and the lateral limit of the base of support (represented by the postero-lateral marker of the heel of the affected hemiparetic leg or the dominant leg of control individuals) and CP instantaneous velocity in the medio-lateral direction (Figure 2). The minimal value of the TtC at each trial, and the percentage at which this minimum appeared during the task, were defined as

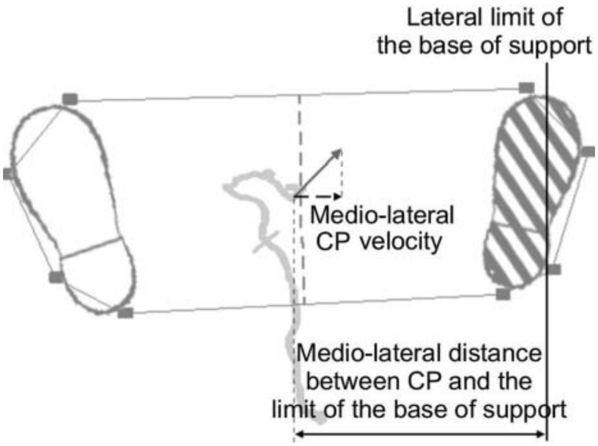

Figure 2. Illustration of the different terms used to measure the center of pressure (CP) time-to-contact variable.

instability variables. In addition, the mean CP velocity (RMS velocity) was measured during the STS at the period where the index was minimal for the 2 groups.

Descriptive statistics (mean ± SD) were calculated for the demographic and anthropometric data. Repeated measure analysis of variance (ANOVAs), completed with *t* tests, were applied to the following factors: parameter (CP, pelvis, and shoulders), foot position (spontaneous, asymmetrical) on repeated measures (every 5% of the task, from 0% to 100%), with the group as a between factor. A first linear regression analysis (stepwise method) was applied on the data of hemiparetic patients (n = 14, because strength data were missing for 4 participants) to determine whether the clinical sores (impairment at leg and foot [Chedoke score], balance [Berg score], movement sense, strength at lower limbs [hip abductors and adductors], and at trunk [side flexion] or spasticity score) and the kinematic data (CP, pelvis, and shoulders mediolateral displacements) could predict the stability level in the spontaneous foot condition (minimal value of the TtC index). A second linear regression was used to test how the maximal deviation of CP can be predicted in the spontaneous foot position from the displacements of the shoulders, pelvis, lateral trunk tilt, or strength at the trunk and lower limbs in the stroke group (n = 14). The variables were entered in the model with a significance level of $P \leq .15$ and removed from $P \geq .2$. Other statistical thresholds for significance were set at $P = .05$.

RESULTS

Center of Pressure, Pelvis and Trunk Displacements for 2 Different Foot Positions

In the spontaneous foot position, the medio-lateral displacements of the CP, pelvis, and shoulders were different between the 2 groups during the whole transfer, with the stroke participants showing larger deviations than the control participants before seat-off (2-way repeated measure ANOVA: 0%-50% phase, Parameter × Percent interaction: $F_{(18,31)} = 24.1$, $P < .001$, group effect: $F_{(1,31)} = 5.9$, $P = .021$) and after seat-off (50%-100% phase, Parameter × Percent interaction: $F_{(18,31)} = 13.6$, $P < .01$, group effect: $F_{(1,31)} = 11.9$, $P = .002$) (Figure 3A and B). In the control participants, the CP and pelvis moved fairly similarly over the midpoint between the heels whereas a deviation of the shoulders appeared toward the dominant foot, mainly before seat-off (from 30% to 55% of the task, paired *t* tests, $P < .05$). For the stroke participants, CP and shoulder and pelvis position deviated at different times, explaining the mentioned interactions. For most of the task (from 30% to 90%), CP and shoulders moved more over the nonaffected foot compared to controls. The pelvis was in translation over the nonaffected foot only after seat-off, from 60% to 90% of the task compared to controls' pelvis position, which showed on average less than 2 cm of translation (independent samples *t* tests, $P < .05$). The trunk of stroke participants was tilted in the frontal plane as revealed by the deviation of the shoulders, which differed from pelvis from 25% to the end of the task.

When the 2 groups stood up with 1 foot behind instead of their spontaneous foot position, significant changes appeared in the lateral displacements of their CP, pelvis, and shoulders before (Foot position × Parameter interaction: 0%-50% phase, $F_{(2,56)} = 6.63$, $P = .003$) and after seat-off (50%-100% phase, $F_{(2,56)} = 10.11$, $P < .001$) (Figure 3C and D). For the 15 stroke participants able to stand up with the affected foot behind the nonaffected one, lateral deviations were reduced in most of the task for displacements of the CP (from 35% to 80%) and shoulders (from 15% to the end) ($P < .05$, except at 85% and 90% for the shoulders, where $P = .079$ and $.082$) in comparison to the spontaneous foot position. No significant changes appeared in the pelvis displacements of stroke participants when the 2 foot positions were compared. Trunk tilt was only present in the first 25% of the task ($P < .05$), and not after seat-off as opposed to the spontaneous foot condition. In control participants, shoulders moved toward the dominant side until seat-off (from 30% to 50%), compared to the spontaneous foot position condition. Their pelvis was in translation over the dominant foot placed behind, just before and after seat-off (from 40% to 80%), whereas no significant changes appeared in their CP displacements between the 2 foot positions, despite a tendency to increase movements toward the dominant side. The overall timing of both the task and the 2 phases in the 2 foot position conditions is presented in Table 2.

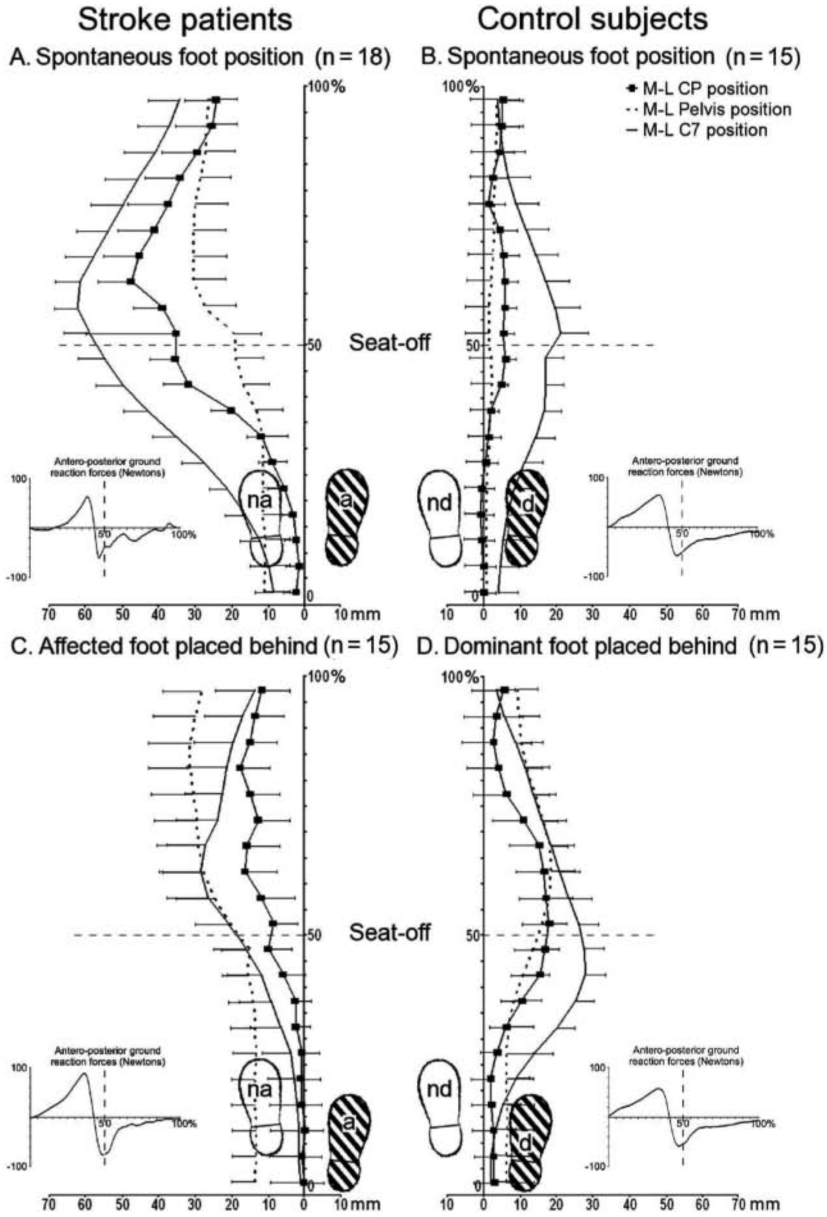

Figure 3. Medio-lateral distance (mean ± SEM) in millimeters of the center of pressure (CP, solid line with squares), pelvis (dashed line), and shoulders (C7, solid line) to the midpoint between the heels over the whole sit-to-stand transfer (0%-100%) in stroke participants (left column, n = 18 and 15) and control participants (right column, n = 15), in spontaneous foot condition (A, B) and with the nondominant foot (nd), for control participants, or nonaffected foot (na), for stroke participants, placed half a foot length ahead of the other foot (C, D). Antero-posterior ground reaction forces are presented in each condition to help determine the different events of the task. The data were standardized to represent the seat-off at 50% of the task.

Table 2. Durations of the 2 Phases of the Transfer, for the 2 Groups, in the 2 Foot Position Conditions

	Spontaneous Foot Position		Foot Placed Behind	
	0%-50%	50%-100%	0%-50%	50%-100%
Hemiparetic participants	1.1 ± 0.4 s	1.6 ± 0.6 s	1.4 ± 0.9 s	1.7 ± 0.5 s
Control participants	1.0 ± 0.2 s	1.2 ± 0.3 s	1.0 ± 0.3 s	1.3 ± 0.3 s

0%-50% = beginning to seat-off; 50%-100% = seat-off to end. Mean ± SD.

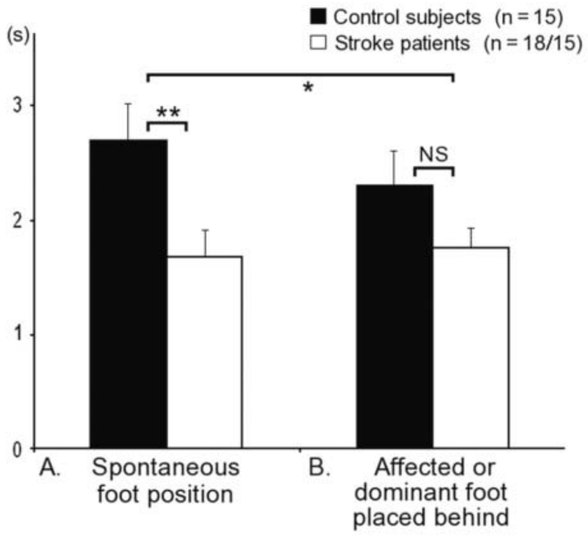

Figure 4. CP Time-to-Contact to the base of support. Minimal value (mean ± SEM) of the center of pressure (CP) time-to-contact (TtC) in seconds during the sit-to-stand transfer in spontaneous foot position (A) and with the nondominant (control participants) or nonaffected foot (stroke participants) placed half a foot length ahead of the other foot (B). Black bars: control participants (n = 15), white bars: stroke participants (n = 18 [A] or 15 [B]). $^*P < .05$; $^{**}P < .01$. NS, nonsignificant difference.

The minimal values of the TtC index were observed in the 20% following seat-off (50%-70%). In spontaneous foot position, it was shorter for the stroke participants (1.68 ± 0.2 s) than for the controls (2.69 ± 0.3 s, $t = 3.33$, $P = .002$) (Figure 4A). The stroke participants also presented a faster medio-lateral CP velocity compared to that of control participants (RMS velocity over the 20% after seat-off: 67.4 ± 9.2 mm.s^{-1} vs 32.8 ± 3.1 mm.s^{-1}, mean ± SEM, independent-samples t tests, $t = 3.83$, $P = .003$). In the asymmetrical foot position, the TtC index was not significantly altered compared to the spontaneous foot position in the 2 groups (controls: $t = 1.26$, $P = .23$, stroke participants: $t = 0.56$, $P = .59$) (Figure 4B). Center of pressure velocity in stroke participants did not change significantly (67.4 ± 9.2 vs 71.6.2 ± 9.5 mm.s^{-1}, $t = 0.152$, $P = .881$) but increased in control participants (32.8 ± .3.1 vs 47.8 ± 4.1 mm.s^{-1}, $t = 3.23$, $P = .006$), though still smaller than that of stroke participants ($t = 2.96$, $P = .010$).

To test whether the asymmetrical foot condition of the stroke participants resulted in values similar to those of control participants performing spontaneously, their data for the asymmetrical foot condition were compared to that of the control participants executing the spontaneous foot condition. Except for a tendency of their pelvis to be more lateral after seat-off (from 60% to 95%, $.052 < P < .079$), there was no longer any statistical difference between the 2 groups in the absolute displacements of the CP, pelvis, and C7 ($P > .10$), even if the strategy still differed in direction compared to the asymmetrical condition for the control participants. The TtC index remained shorter for the stroke participants in comparison to the control group ($t = 2.50$, $P = .019$) (Figure 4A and B).

From the regression analysis, it appeared that the Chedoke score alone accounted for 61.8% of the variance in TtC in the spontaneous transfer ($R^2 = 0.618$, b = 0.301, $P = .001$) (Figure 5A). The other clinical data items entering into the model explaining TtC variance were spasticity score ($R^2 = 0.730$, b = –0.072) and strength in trunk lateral flexion on the affected side (b = 0.013, $R^2 = 0.823$) who brought the explained variance to 73.0% and 82.3%, respectively. Regarding the maximal medio-lateral CP displacement, the best model included only the pelvis medio-lateral translation, which accounted for 59.3% of its variance ($R^2 = 0.593$, b = 0.803, $P < .005$) (Figure 5B).

Regarding the result for the medio-lateral reaction, the forces measured were very low (7.4 ± 4.2 N). No association was found with any variable of interest.

DISCUSSION

For the stroke group, the spontaneous transfer from STS was asymmetrical in the medio-lateral plane, with the center of pressure moving toward the nonaffected side. When participants stood up with their affected foot behind, no major amplitude difference was observed, compared to the spontaneous transfer of healthy participants, though in the opposite directions. This corroborates the reduced weight-bearing asymmetry observed by Roy et al[8] using the same foot position and further confirms their view that positioning the affected foot behind the nonaffected one forces the stroke participants to use more their affected leg and leads to a more symmetrical STS.

Regarding the role of the trunk during the STS task with spontaneous foot placement, the main factor contributing to maximal CP deviation from the center of the base of support was the medio-lateral pelvis translation. In addition to this translation, the trunk of stroke participants was tilted toward the nonaffected side. With the affected foot behind, trunk tilt was largely decreased and the absolute displacements of the CP of stroke participants were similar to those of controls in spontaneous foot position. Hence the observed displacements of the CP are probably explained by the position of the trunk during the task, and the mass this body segment represents. These results corroborate those obtained with hemiparetic individuals in the same task[5,21] and during treadmill walking.[22] Timewise, it is

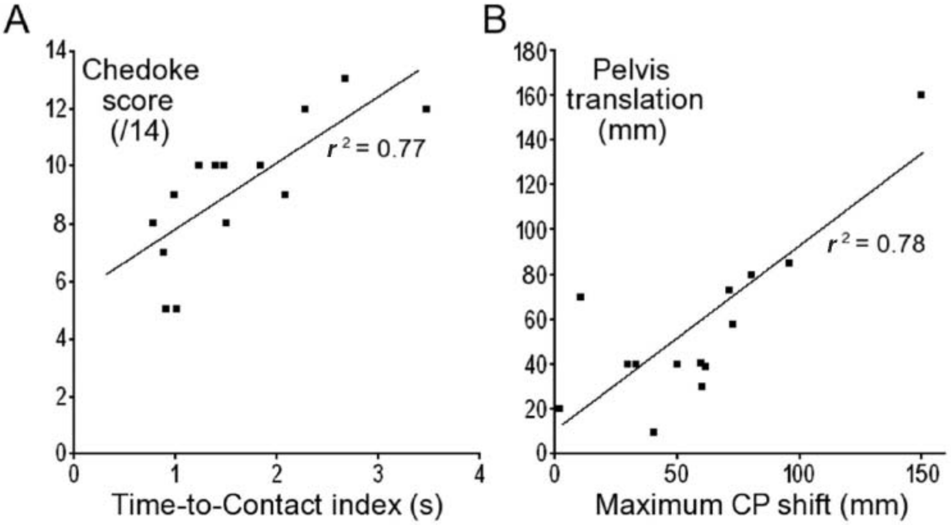

Figure 5. Scatter plots showing the association between Chedoke score (/ 14) and the time-to-contact index in seconds (A) and between the pelvis translation and the maximal center of pressure (CP) shift in mm (B) in 14 hemiparetic participants, in the spontaneous foot position condition.

interesting to note that in the spontaneous foot condition, the shoulders of the stroke group were significantly shifted during the first third of the spontaneous task at the same time as the CP. Kinematic reorganization of the task is thus visible very early on, well before the seat-off or the maximum CP lateral deviation.

Despite these kinematic alterations with a foot placed behind, postural stability defined by the TtC index did not change significantly in the stroke and control groups. Stroke participants remained more unstable than control participants, regardless of foot position. However, even if the TtC index may not be sensitive enough to the possible impact of foot placement, the values obtained were over 1.5 seconds, which is well above the 500 to 550 ms needed by elderly people to step in such a way as to avoid falling.[23] It thus appears that the individuals with hemiparesis in our study were not at high risk of lateral fall during the STS task. On the other hand, we found that the variance of the TtC index was largely explained by the Chedoke score and to a lesser extent by the strength of the trunk muscles and the level of spasticity. This is in line with previous results in higher fall-risk elderly people, which showed that when a backward slip was induced during STS, falls were more related to a deficit in limb support.[24] Because limb support of hemiparetic individuals during STS is characterized by weight-bearing and moment deficits[12] associated with knee muscle strength, it is likely that for more impaired individuals than in our experimental group, the risk of falling would be higher, explaining the high rate of fall during STS.[1,2]

The fact that the model of stability used in our study was defined in inverted pendulum conditions may limit the precision of the results concerning stability during the STS task. Indeed, the TtC values reported here were highest when the center of pressure was the most asymmetrical, within 20% after the seat-off time. The center of mass was thus still transferring upward, meaning that the body was not in an inverted pendulum situation (see Hirschfeld et al[25] for a description of the kinematics of the STS transfer). According to Yang et al,[26] simple models such as TtC are not sufficient for assessing tasks with asymmetrical posture, such as walking. However, no existing biomechanical model as yet seems suitable for assessing postural stability in such complex tasks. In particular, the STS presents different phases, with large forward and upward movements of the center of mass putting equilibrium at stake in several directions, especially in pathological populations. The stability level assessed here may thus be a rough estimate of the actual one. In addition, the high TtC values obtained may be due to the relatively high functional level of the hemiparetic group that participated in this study, and may have been overestimated because stability was not measured in the antero-posterior direction of the STS transfer. Studying hemiparetic participants with greater impairments who, for example, need assistance to transfer might better explain the role of instability in functional difficulties, but necessitates a more complex experimental setup and analysis. To summarize, in addition to showing that spontaneous transfer from sit to stand involves asymmetrical weight-bearing,[3-11] with lower moment at the affected knee,12 our study revealed that hemiparetic individuals present altered frontal trunk kinematics and center of pressure displacements well before seat-off. Their lateral trunk movements are probably associated with the deviation of the center of pressure observed early on and during most of the task. They tilt their trunk toward the nonaffected side early in the task and also use pelvis translation near seat-off and after. Interestingly, positioning the affected foot behind the nonaffected one reduced lateral deviation of the trunk and of the CP during the whole task, though without completely normalizing the strategy in comparison to controls. The degree of stability of subjects with hemiparesis following a stroke partly depended on their level of impairment and was not significantly modified when their spontaneous foot position was altered. Along with providing insight into weight-bearing asymmetry,[13] an early lateral tilt of the trunk during the STS transfer may still serve as a good clinical sign of center of pressure deviation for practitioners, and a warning of risk for falls in patients with marked lower leg impairments.

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