Quantitative Analysis of the Limits of Stability in Sitting

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This study defines the limits of stability in sitting, and quantitatively assesses two measures of postural control relative to these limits. Young, healthy subjects sat, feet unsupported, on an elevated force plate. The limits of stability were determined by a least square fit of an ellipse to the center of pressure (CoP) excursion during maximal leaning in 8 directions. These were highly symmetrical and centered within the base of support. The ellipses had a mean eccentricity of 0.66 (major axis in the sagittal plane) and covered an area approx. 1/3 of the base of support. The CoP was then monitored over 4 min of quiet sitting, during which the postural sway covered an area <0.05% of the limits of stability and was closely centered within the latter. Finally, target-directed trunk movements were performed, in 5 directions, at 4 movement speeds and 3 target distances. Increased target distance and movement speed both decreased the margin of stability (distance between the CoP and the limits of stability), as did movement in the frontal plane, reflecting the eccentricity of the limits of stability. These combined findings support the validity of this quantitative method of defining the limits of stability in sitting, for healthy individuals.

Keywords: postural control, balance, trunk

Postural control of the trunk has received a great deal of attention of late, due largely to the functional implications of impaired trunk control. These are most evident in neurological conditions, such as spinal cord injury (Seelen et al., 1997, 1998; Kukke & Triolo, 2004), stroke (Verheyden et al., 2007; Hsieh et al., 2002; Reisman & Scholz, 2007), or Parkinson's disease (van der Burg et al., 2006). The functional implications of impaired trunk control may also be relevant to conditions such as idiopathic low back pain (Radebold et al., 2001; Luoto et al., 1996; Henry et al., 2006), suggesting a potential neuromusculoskeletal link.

While most functional tasks are not isolated to the trunk, those which challenge balance and postural control in sitting require a high level of trunk control (Cholewicki et al., 2000; Preuss et al., 2005), or, when this is impaired, the development of less effective compensatory strategies (Seelen et al., 1998). One means of assessing the success of the postural strategies used in sitting is by monitoring the center of pressure (CoP) throughout the task (Kerr & Eng, 2002; Nichols et al., 1996; Reisman & Scholz, 2007; Dean et al., 1999a, 1999b; Messier et al., 2004). A subject's aptitude for sitting balance may then be determined by their ability to regulate the position of the CoP, which represents the reactive forces at the support surface that ultimately determine the position and motion of the whole-body center of mass (CoM). While this approach does not directly assess the complex neuromuscular strategies used in the maintenance of balance and postural control, it may provide valuable insight into their functional relevance for clinical research and practice.

CoP position and velocity alone, however, do not fully describe the challenge to postural stability presented by a given task, as these must be viewed within the context of the available base of support (BoS), and of the subject's ability to generate forces at the BoS. Popovic et al. (2000) have demonstrated that CoP excursion in standing is constrained to an area much smaller than the BoS, and that these limits of stability differ between subjects. In a follow-up study, Tortolero et al. (2007) demonstrated a linear relationship between the peak velocity of the CoP and the eventual point of maximum CoP excursion. The limits of stability for slow movements, therefore, were found to be valid regardless of the velocity of movement. A stepping response, however, might occur in anticipation of the CoP position exceeding the limits of stability, based on the relationship between CoP position and velocity.

The primary purpose of the current study was to establish an approach to quantitatively define the limits of stability in sitting, for a well defined BoS, using healthy subjects. We hypothesized that, as in standing, these limits of stability would be much smaller than the available BoS. Postural sway in quiet sitting was also assessed, in relation to these limits of stability, as a means of contrasting the inherent stability of the sitting and standing postures. We hypothesized that the area of postural sway in sitting would be smaller than previously

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reported values for standing, based on the lower height of the CoM in relation to the BoS, which decreases the gravitational potential energy of the system. Finally, the subjects were asked to perform a series of target-directed trunk movements, at different directions, distances and speeds, to establish the construct validity of the established limits of stability. This was based on the premise that, over the course of any task, the minimum distance between the CoP and the limits of stability can be interpreted as the margin of stability for the task: the smaller the margin, the greater the challenge to postural stability. We hypothesized that this margin of stability would be decreased by increasing the target distances, necessitating an increase in CoM excursion, and by increasing the speed of the target-directed movements, increasing the moment of force required to decelerate the CoM. Both would necessitate an increase in the peak excursion of the CoP, thus decreasing the margin of stability.

Methods

Subjects

Eleven volunteers participated in the study, recruited from a convenient sample of research staff and students at a rehabilitation hospital. Subject demographic information is presented in Table 1. Subjects were excluded if they reported any of the following: back pain at the time of testing; a prior history of back pain persisting for more than 3 months, and interfering with daily activity; previous diagnosis of any musculoskeletal condition affecting the spine (such as spondylolisthesis or scoliosis) or hips; history of any neurological, vestibular or other conditions affecting balance. All subjects provided

written, informed consent before participation. Ethics approval for this study was received from the local ethics committee.

Test Position

Subjects sat, with their feet unsupported, on a rectangular AMTI (Watertown, USA) force plate (OR6–7) mounted on a stiff wooden frame. Subjects were asked to keep their arms folded across their chest, with their hands just below the opposite clavicle. The thighs were kept parallel, with 75% of their length (from the greater trochanter to the lateral epicondyle of the femur) supported on the force plate. Reflective markers (15 mm in diameter) were placed bilaterally over the posterior superior iliac spines (PSIS), the greater trochanters of the femur, and on the lateral thighs, in line with the edge of the force plate. The length of the BoS was defined as the distance from the PSIS markers to the lateral thigh markers, in the sagittal plane. The width of the BoS was defined as the distance between the greater trochanter markers, in the frontal plane. The area of the BoS was approximated as the product of these two values. These dimensions are presented in Table 1.

Data Acquisition

For all tasks, force plate data were acquired at 1080 Hz. Positions of the reflective markers used to define the BoS, as well as the target markers (described below), was acquired using a six-camera Vicon (Oxford, U.K.) 512 motion analysis system (sampling frequency, 120 Hz). Marker positions were low-pass filtered using an 8th-order, dual-pass Butterworth filter, with a low-pass cutoff frequency of 2 Hz.

Table 1   Subject demographic and anthropometric characteristics

Subject	Gender	Age	Sitting Height (m)	BoS—Length (m)	BoS—Width (m)	BoS—Area (m²)
1	M	24	0.72	0.45	0.39	0.17
2	F	30	0.76	0.43	0.42	0.18
3	F	30	0.76	0.45	0.43	0.19
4	M	24	0.75	0.48	0.44	0.21
5	M	26	0.79	0.49	0.43	0.21
6	M	34	0.71	0.48	0.38	0.18
7	F	29	0.71	0.45	0.43	0.19
8	M	26	0.76	0.46	0.42	0.19
9	M	32	0.82	0.48	0.43	0.20
10	M	31	0.80	0.52	0.49	0.26
11	F	28	0.72	0.45	0.46	0.21
Mean		28.5	0.75	0.47	0.43	0.20
St. Dev.		3.3	0.04	0.03	0.03	<0.00

Note. BoS = base of support; sitting height = BoS to base of occiput.

Tasks

Limits of Stability. The limits of stability for voluntary trunk movements, in sitting, were determined by asking the subjects to lean as far as possible, without moving their legs, in 8 directions, at 45° intervals around the full circle (Figure 1A). Reflective targets were hung from the ceiling, beyond the subjects' reach, in the anterior, anterior-diagonal, and lateral directions, to provide an initial visual reference for the direction of motion (for the posterior and posterior-diagonal directions, the subjects looked at the anteriorly placed targets). The subjects, however, were instructed to not look at the target throughout the full range of movement, so as not to constrain the movement of the cervical and upper thoracic spine.
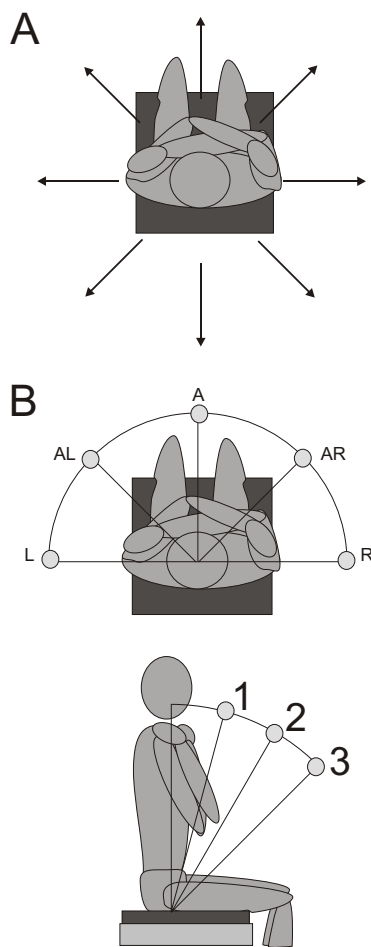

Figure 1 — (A) Eight directions of maximum voluntary trunk leaning, at 45° intervals, to determine the limits of stability in sitting. (B) Top: Five target directions for the target-directed trunk movements. L & R: Frontal plane movements to the left and right, respectively. A: Sagittal plane movement in the anterior direction. AL& AR: Movements at 45° anterior to the frontal plane; anterior-left and anterior-right, respectively. Bottom: Three target distances and heights for the target-directed trunk movements. These were at 15° intervals, based on movement of the trunk as an inverted pendulum.

Subjects performed each of the 8 movements in a random order. This was repeated a total of 3 times, with a short break between each set. The maximum excursion of the CoP for each of the directions of movement, across the 3 trials, was used to determine the limits of stability. These were modeled by fitting an ellipse to these 8 data points, using the direct least square fitting approach described by Fitzgibbon et al. (1999). To allow for comparison between subjects, all values were normalized to the dimensions of the BoS (see Table 2 for details).

Quiet Sitting. For 9 of the 11 subjects, CoP data were acquired during quiet sitting. Subjects were instructed to sit in an upright, but relaxed position, to look straight ahead, and to try to minimize the amount of movement. Once the subjects had settled into a comfortable position, data were acquired for a period of 4 min.

The parameters of the postural sway during this period of quiet sitting were then modeled by fitting an ellipse to these CoP data. A least square fitting approach (Fitzgibbon et al., 1999) was initially used. The lengths of the major and minor axes derived from this method were then doubled, to describe an ellipse which contained the majority of the CoP data points. This elliptical fit was performed for the entire 4 min period and for each 1 min interval within this period. As above, all values were normalized to the dimensions of the BoS (see Table 2 for details).

Target-Directed Movements. For the target-directed movements, subjects were instructed to lean toward a reflective target suspended from the ceiling, touch it with their head, and return to the initial upright sitting position. Targets were placed in 5 directions: anterior, and bilaterally at 45° and 90° from anterior (Figure 1B—top). Target distance and height was determined, for each subject, based on the distance from the support surface to the base of the subject's occiput (sitting height—Table 1). The targets were placed at 3 distances and heights, representing 15° intervals of angular motion for the subject, assuming movement of the trunk as an inverted pendulum (Figure 1B—bottom).

Target-directed movements were performed at 4 speeds. For three of the movement speeds, the subject's movement was paced by a metronome at 10°/s, 20°/s, and 30°/s, based on the target distance. For the fourth speed, subjects moved at a self-selected pace.

Trials were begun at the closest target distance. The targets were then moved to the next distance once all trials at the previous distance had been completed. For each distance, 3 trials were performed for each of the 4 movement speeds, in a randomized order. The peak excursion of the CoP was determined for each trial. The mean of the 3 trials for each movement condition (distance, direction and speed) was used for further analysis.

For each movement condition, the minimum distance between the peak CoP excursion and the ellipse representing the limits of stability was taken to represent the margin of stability. These values were then normalized to

Table 2   Ellipse parameters for the limits of stability and for quiet sitting—mean (*SD*)

	Center (M/L)	Center (A/P)	X-Axis	Y-Axis	Theta	Eccentricity	Area (BoS)	Area (LoS)
Limits of Stability	45.5 (1.5)	54.9 (4.5)	26.9 (3.9)	35.7 (3.4)	–2.0 (5.3)	0.66	32.7 (0.4)	
Quiet Sitting								
4 Minutes	48.1 (1.1)	52.3 (4.1)	0.45 (0.19)	1.02 (0.54)	–6.7 (21.4)	0.90	0.0155 (0.0036)	0.0474 (0.0110)
Minute 1	48.3 (1.0)	52.5 (3.8)	0.41 (0.16)	0.66 (0.25)	–2.1 (14.4)	0.78	0.0092 (0.0014)	0.0281 (0.0043)
Minute 2	48.1 (1.1)	52.4 (4.0)	0.33 (0.18)	0.45 (0.16)	–11.2 (25.5)	0.68	0.0051 (0.0010)	0.0156 (0.0031)
Minute 3	48.0 (1.2)	52.3 (4.3)	0.39 (0.28)	0.43 (0.15)	6.8 (18.4)	0.42	0.0057 (0.0015)	0.0174 (0.0046)
Minute 4	48.0 (1.2)	52.1 (4.3)	0.33 (0.13)	0.42 (0.19)	1.8 (14.3)	0.62	0.0047 (0.0009)	0.0144 (0.0028)

Note. Center (M/L): as a percentage of the width of the base of support, measured from the left; Center (A/P): as a percentage of the length of the base of support, measured from the back; X- and Y-axis: as a percentage of the length of the base of support; Theta: rotation of the X-axis from frontal plane (degrees); Eccentricity = sin[arccos(X-axis/Y-axis)]; Area (BoS): as a percentage of the area of the base of support; Area (LoS): as a percentage of the area of the limits of stability.

the length of the BoS, and compared for each movement condition at an α-level of 0.05. Three-way ANOVA were used, with target distance, movement speed, and target direction as the independent variables.

Results

The normalized dimensions of the ellipses representing the limits of stability in sitting are provided in Table 2. These are also illustrated for a representative subject (Figure 2A), as well for the mean of the study population (Figure 2B).

The major axis of the ellipse representing the limits of stability, for each subject, was aligned near the sagittal plane. The area represented by these limits of stability was centered slightly anterior and left of the center of the BoS, and covered an area approximately 1/3 the size of the latter. The mean eccentricity of this ellipse was 0.66 (length of minor axis was approx. 0.75 of major axis), indicating a greater range of displacement for the CoP in the sagittal plane than in the frontal plane, within these limits of stability.

The normalized dimensions (means and standard deviations) of the ellipses fit to the CoP position during quiet sitting are provided in Table 2. Postural sway in quiet sitting for a representative subject (Figure 2A), as well as for the mean of the study population (Figure 2B), are also illustrated.

These ellipses tended to be centered slightly left and anterior of the center of the BoS. The orientation of the area of postural sway also tended to be oblique, but was not consistently oriented to one side or the other. Over the full 4-min period of quiet sitting, postural sway was minimal, covering a mean of 0.0155% of the area of the BoS (0.0474% of the limits of stability). For each 1-min interval, the area of sway was smaller and less eccentric, covering on average 0.0047–0.0092% of the area of the BoS (0.0144–0.0281% of the area of the limits of stability). These differences appear to reflect a slow drift of the subjects' average CoP position over the duration of the task. This drift was generally posterior, closely following the major (Y) axis of the postural sway ellipse for the full 4-min period of quiet sitting.

All subjects successfully completed the target-directed movements, for all movement speeds, directions, and distances, with the exception of distance 3 (Figure 1B—bottom). At this farthest target distance, none of the subjects was able to reach the laterally placed targets, at any movement speed.

The results of the 3-way ANOVA indicated that the margin of stability—the minimum distance between the maximum point of CoP excursion and the ellipse representing the limits of stability—was significantly affected ($p < .001$) by all three of the independent variables tested: target distance, movement speed, and the direction of movement. Significant interaction effects were also present between distance and speed ($p = .001$), and distance and direction ($p = .036$). There was, however,
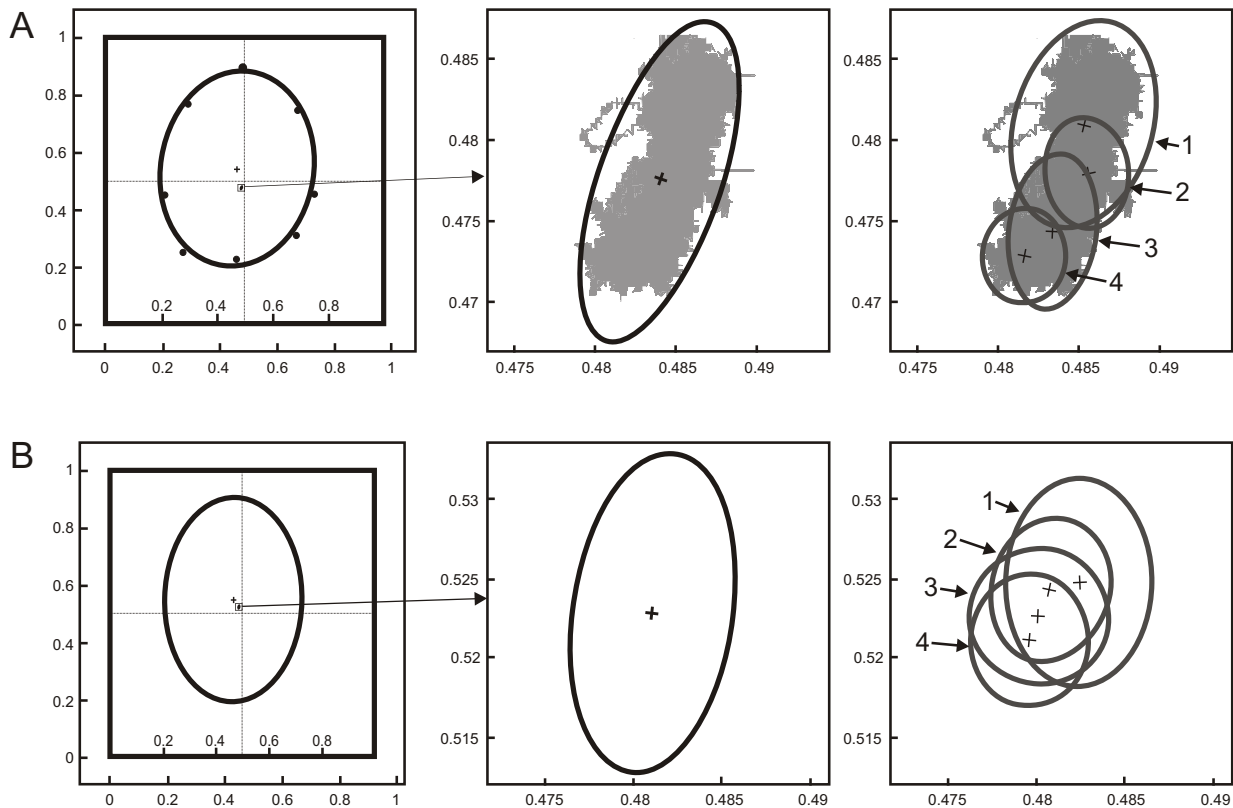
Figure 2 — Ellipses fit to the limits of stability and to CoP sway during quiet sitting. (A) Values for a representative subject. *Left*— Large inner rectangle: Base of support divided at its midpoints (dashed lines), with the X-axis scaled to the width of the base of support. The outer scale (outer rectangle) shows scaling for the X- and Y-axes in proportion to the length of the BoS. Large ellipse: Limits of stability fit to the 8 points of maximum CoP excursion (circular marks), and centered at the "+". Small ellipse inside the box: Area of postural sway during quiet sitting, centered posterior and to the left of the center of the BoS. *Center*—Enlarged view of the center of pressure position over the 4 min period of quiet sitting, along with the ellipse representing this period of postural sway, centered at the "+". The scale is to the length (Y-axis) and width (X-axis) of the BoS. *Right*—Enlarged view of the center of pressure position over the 4 min period of quiet sitting, with ellipses fit to each 1-min interval of quiet sitting (1 = first minute, 2 = second minute, etc.). (B) Mean values for the study population, illustrated as for (A).

no interaction effect between speed and direction ($p = .999$), and no 3-way interaction effect ($p = 1$), indicating that the effect of speed was independent of the direction of movement.

The mean (± 1 *SD*) margin of stability for the study population, represented as a percentage of the length of the BoS, is illustrated in Figure 3. Figure 3A illustrates the margin of stability for the self-paced movements. This figure clearly illustrates that the significant effect of movement direction is indicative of a greater margin of stability for movements in the anterior direction (sagittal plane) than for the lateral directions (frontal plane), with the margin for the anterior diagonals falling in between. This figure also illustrates a decreasing margin of stability with increasing target distance. The significant interaction between distance and direction is also somewhat evident, largely in the narrowing of the relative margin of stability for the different target directions as target distance is increased (especially between distance 2 and 3). Figure 3B illustrates the margin of stability for the target-directed

movements at the 3 distances, for each of the metronome-paced speeds. The effect of movement speed is clearly evident at distance 1 and 2, with a decreasing margin of stability at the faster movement speeds. The interaction effect between distance and speed can also be seen in this figure, as the effect of movement speed is clearly more evident at the first two target distances than at the third, where the effect of movement speed appears to be negligible. The relative margin of stability, for the different target directions, however, appears to be largely maintained at the different movement speeds.

Discussion

The results of this study support each of the hypotheses presented above, indicating that the limits of stability, as determined from the CoP excursion during maximum voluntary leaning, provide an effective and valid construct within which to assess the challenge to postural stability presented by different tasks in sitting.
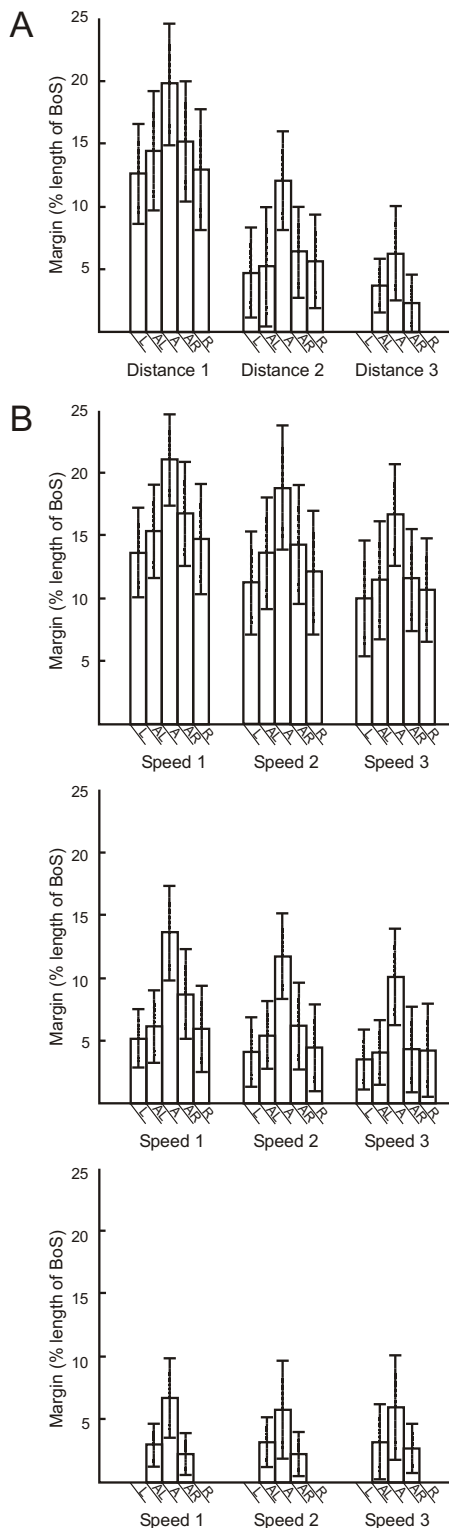
Figure 3 — Mean and standard deviation of the margin of stability, for the study population, during target-directed trunk movements. (A) Movements at the self-selected pace, for the 5 directions and 3 target distances. (B) Movement for the 3 target distances (top—distance 1; middle—distance 2; bottom—distance 3) for the 5 directions and 3 metronome-paced movement speeds (speed 1 = 10°/s; speed 2 = 20°/s; speed 3 = 30°/s).

The limits of stability, in sitting, were symmetrical and centered within the BoS, covering approximately 33% of the area of the latter. This finding supports our initial hypothesis regarding the size of the limits of stability relative to the BoS, and compares well with the stability zones described by Popovic et al. (2000) in standing. In this previous study, the "low preference" zone was also relatively symmetrical and centered within the BoS, and when combined with the "high preference" zone covered approximately 30% of the area of the BoS. Unlike sitting, however, these limits of stability in standing were wider in the frontal plane than in the sagittal plane. This most likely reflects some basic biomechanical differences between sitting and standing. For one, the dimensions of the BoS will limit the potential distribution of the limits of stability. In a comfortable standing posture, the BoS is generally wider in the frontal plane than in the sagittal plane (Popovic et al., 2000), which might predispose the limits of stability to similar relative dimensions. In the current study in sitting, however, the mean width of the BoS was 92.0% of its length, while the minor axis of the ellipse representing the limits of stability was only 75.4% of the length of the major axis. The dimensions of the BoS, therefore, do not fully explain those of the limits of stability. The determining factor for these is the subjects' ability to generate force against the BoS. In standing, movement of the CoP in the frontal plane is facilitated by abduction / adduction at the hips, and by movement of the trunk, with the CoP generally able to move freely between the ankles. The CoP in the sagittal plane, however, often falls anterior to the ankles, requiring greater moments of force about this joint, with a much longer lever arm to control the movement of the body's CoM than in sitting. As such, in standing, a mechanical advantage exists for the transfer of weight in the frontal plane versus the sagittal plane. In sitting, however, lateral movements occur predominantly in the trunk, while anterior and posterior movements involve both the hips and trunk. In both cases, the lever arm to the body's center of mass is relatively short. The greater range of CoP movement in the anterior-posterior direction in the current study, therefore, likely reflects the added contribution of the hips to the sagittal plane moment of force at the support surface.

The results of the current study also fit well with those of Kerr and Eng (2002), who looked at maximal reaching in sitting, in the sagittal and frontal planes, in healthy older adults. In the feet unsupported condition described by these authors (with 80% of the length of the thigh supported), the mean CoP excursion was similar to the current study. These authors reported symmetrical CoP movement in both the frontal and sagittal planes, with mean ranges of approx. 0.125 m and approx. 0.132 m respectively. Corresponding values in the current study are 0.126 m and 0.168 m. The difference in the sagittal plane excursions may reflect the age of the study populations—mean of about 65 years in the previous study versus <30 years in the current study—suggesting that the eccentricity of the limits of stability might decrease with age. As the dimensions of the sitting BoS

are unlikely to change in the sagittal plane, a decrease in the limits of stability would indicate a decrease in the subjects' ability to generate force against the BoS. The hypothesis that age related changes may occur, however, must be confirmed with further testing. Kerr and Eng (2002) also reported very good test-retest reliability for their measures of CoP excursion (ICC 0.74–0.94). This bodes well for the psychometric properties of the limits of stability described in the current study. The reliability of this measure, however, requires further confirmation for specific subject populations.

A similar approach to testing sitting stability, using CoP excursion, has also been conducted with hemiparetic subjects (Nichols et al., 1996). These authors compared their findings to those of a clinical test—the functional independence measure (FIM)—concluding that only a poor to moderate relationship existed between the two measures. Unfortunately, while the subjects in this previous study were seated on a height-adjustable chair, placed on a force transducer system, the subject's feet were positioned on the floor. As such, only a portion of the BoS was monitored for surface reaction forces. As the lower limbs can make a significant contribution to sitting balance when the feet are supported (Dean et al., 1999a; Dean et al., 1999b), these authors cannot have accurately measured CoP position. As such, the relationship between CoP measures of stability and clinical measures of sitting balance has yet to be accurately established, and presents an important opportunity for future research.

Postural sway in quiet sitting was notably less than previously reported values in standing, supporting our second hypothesis. In the current study, the unnormalized area of the quiet sitting ellipse ranged from 13.4 mm^2 to 118.4 mm^2, equal on average to less than 0.02% of the area of the BoS, and less than 0.05% of the area of the limits of stability (Table 2). The area of the "high preference" zone reported by Popovic et al. (2000) for the nonfatigued, eyes open condition in standing ranged from 324 mm^2 to 1981 mm^2. This dramatic difference reflects the inherent stabilities of the two postures. The increased height of the CoM in standing versus sitting produces a dramatic increase in the gravitational potential energy of the system, relative to the BoS. Reducing the area of postural sway in quiet standing to one similar to quiet sitting would, therefore, require a drastic increase in the stiffness of the system to counter the greater energy transfer associated with postural sway in standing.

Despite the vast difference in size between the area of postural sway in sitting and standing, the shape and orientation of the ellipses fit to this area was similar between the two postures. In the current study, the mean eccentricity of the ellipses fit to the full 4-min period of quiet sitting was 0.90, with the major axis oriented an average of 6.7° from the sagittal plane. In standing (Popovic et al., 2000), the mean eccentricity was 0.89, with a mean rotation of 2.3° from the sagittal plane over a 5-min period. In both cases, however, the orientation of this ellipse was highly variable across subjects, with a standard deviation of 21.4° in both sitting (current study) and standing (Popovic et al., 2000).

For the target-directed movements of the trunk, the relationship between the margin of stability, the target distance and the speed of movement (Figure 3) supports our final hypothesis, and provides a degree of construct validity to the limits of stability described above. As expected, a significant decrease in the margin of stability occurred with an increase in target distance (main effect of distance) and movement speed (main effect of speed). The latter fits with previous findings in standing, which indicate a linear relationship between peak CoP velocity and excursion (Tortolero et al., 2007). The importance of movement velocity to postural stability in sitting has also been previously suggested (Kerr & Eng, 2002), with the results of the current study providing statistical confirmation.

The elliptical shape of the limits of stability also produced a significant effect of target direction that was not initially hypothesized. More interesting, however, were the interaction effects between distance and speed, and distance and direction (Figure 3). These suggest that the subjects' were likely to have adapted their movement patterns to accommodate the requirements of the task within the available limits of stability. The interaction between distance and speed (Figure 3B), in particular, suggests that the acceleration profile of the CoM must have been altered, along with the increased target distance (e.g., rapid acceleration with a more gradual deceleration). This would be necessary to minimize the moment of force required to decelerate the CoM, thus minimizing the distance by which the CoP excursion would exceed the CoM excursion. Further study is required to fully understand the exact adaptations in movement strategy that occurred to produce the significant interaction effects observed in this study.

For the target-directed movements, only the laterally placed targets, at distance 3, were not reached by the subjects, with the margin of stability tending toward zero at all movement speeds (Figure 3). A loss of stability would therefore have occurred had the subjects attempted to reach these targets.

These results indicate that the limits of stability in sitting, in the current study, have good construct validity, with previously published data (Kerr & Eng, 2002) suggesting that the approach used to determine these limits is likely to have very good test-retest reliability. These measures also compare well with previously published data describing the limits of stability in standing (Popovic et al., 2000). These limits of stability, and specifically the margin of stability relative to these limits, can therefore be viewed as a means to quantitatively interpret the challenge to postural stability in sitting posed by a variety of tasks, such as voluntary movements and/or external postural perturbations.

Acknowledgments

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