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NORMAL VARIABILITY OF POSTURAL MEASURES: IMPLICATIONS FOR THE RELIABILITY OF RELATIVE BALANCE PERFORMANCE OUTCOMES

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ABSTRACT. The reliability of outcome measures obtained using the Balance Master™ and the limits of stability in anterior, posterior, and lateral directions were evaluated in 70 healthy subjects aged 20 to 32 years. Data relating to static sway and the ability to shift the centre of gravity to preset targets were collected on three occasions one week apart. The centre of gravity position and limits of stability were determined over three trials and data converted from a relative reference system to absolute displacements from vertical. Intraclass correlation coefficients revealed fair to poor reliability of static and dynamic sway measures (coefficients ≤ 0.55) and excellent reliability of limits of stability measures and the position of the centre of gravity (coefficients ≥ 0.75). The variability in outcome measures from tests which do not maximally challenge the postural control system may be a hallmark of normal balance performance. Further, the intersubject variation in resting centre of gravity position and in limits of stability supports the use of absolute performance measures as the interpretive value of data expressed relative to standard norms is limited.

Key words: balance, limits of stability, outcome measures, postural control, reliability.

INTRODUCTION

Balance retraining is a major component of rehabilitation programs for patients with neurological disorders, musculoskeletal impairments, and elderly people with balance deficits. Reliable and valid measures of balance performance are necessary in order to evaluate the extent of balance impairment and to determine the efficacy of balance retraining programs.

Commercial systems providing quantitative information and feedback of the position of the centre of gravity (COG) during static and dynamic postural adjustments have become increasingly available in rehabilitation clinics, although the technology has existed in laboratory settings for several decades. Such systems appear to be sensitive to therapy-induced changes in dynamic balance ability (7) but may not detect subtle differences in the mechanics of postural control between, for example, elderly subjects with and without underlying pathology (6), or young and elderly subjects (16).

The Balance Master is a rehabilitation tool designed to provide quantitative assessment of static and dynamic balance performance and visual feedback of the excursion and position of the COG. The system utilizes forceplate technology to determine the location of the COG within predefined (theoretical) limits of stability while adjusting for an individual subject's height (COG = 0.55 × height) (8). The software provides measures of postural sway and the ability to maintain the COG within a defined target area. Dynamic tests are also available which assess subjects' ability to control the direction, accuracy and speed of their COG movements during tasks requiring weight shifts toward preset targets. However, the reliability of such data is not well documented, although in stroke patients only the most challenging dynamic tasks were found to be reproducible (11).

The relative position of the targets and the data reflecting COG movement are presented in terms of theoretical limits of stability (LOS). Assuming that COG movement about a fixed ankle reflects an inverted cone, the theoretical LOS (i.e. 100% LOS) extend 6.25° anteriorly, 4.45° posteriorly, and 8.00° to each side relative to the normal mean COG resting position in standing position, which is defined as lying 2.3° anterior to the true vertical plane passing through the medial malleoli and at the centre (medio-lateral) of the base of support (8). The theoretical values and the resting COG position are derived from a normative database and subjects' data are expressed relative to the norm. While this may provide a standardized method for reporting data, the validity of the method relies on the accuracy of the assumptions, i.e. the LOS and the presumed rest position of the COG (2.3° anterior to vertical). It has been suggested that data reported relative to an established threshold norm may be less robust in terms of detecting differences in performance (16). The purpose of this study is twofold: first, to examine the reliability of the static and dynamic measures of balance using the standard Balance Master protocol; and secondly, to determine the maximal limits of COG excursion (i.e. the 100% LOS) in anterior, posterior, and lateral directions as well as the position of the COG relative to vertical during quiet stance.

METHODS

Subjects

Seventy healthy young subjects (54 females, 16 males) volunteered to participate in one or more aspects of this study. All were between the ages of 20 and 32 years (mean $\pm$ 1 SD: 24.3 ± 3.2 years) and were recruited by word of mouth from the university community. Subjects were screened to ensure that they had not previously used the Balance Master, and had no self-reported relevant history (e.g. lower extremity orthopaedic problems, inner ear infections) which could influence balance ability. All procedures were approved by the university ethics review board and subjects gave their informed consent prior to participating.

Protocol

All testing involved the use of the Balance Master. This device consists of two forceplates side by side (each approximately 23 cm $\times$ 46 cm) with transducers mounted along the front-to-back centre line of each plate. The output is digitized and the software provides the user with visual feedback of the COG location via a monitor positioned at eye level. Subjects stepped onto the forceplates (without shoes) positioning their feet by aligning the lateral border of the foot with the appropriate height line marked on the forceplates (i.e. short = 76–140 cm, medium = 141–165 cm, or tall = 166–203 cm). The medial malleoli were aligned with the transverse forceplate lines and subjects adopted a comfortable amount of forefoot splay.

Reliability testing. Fifty-two subjects were involved in evaluating the reliability of static measures of balance, which required subjects to be tested on three occasions approximately one week apart. Subjects were instructed not to move their feet and were asked to stand with their arms at their sides throughout the testing procedure. Three standard static balance tests were performed requiring subjects to look straight ahead while standing as still as possible, initially with eyes open, then with eyes closed, and finally focusing on the display monitor using visual feedback to maintain the position of a cursor (representing the subject's COG) within a central target box. The central target area was positioned 2.3° anterior to vertical. For each test, data relating to postural sway were recorded for a period of 20 seconds. The area of the sway was calculated and expressed as a percentage of the theoretical LOS.

A subgroup of 33 subjects was able to spend additional time on each of the three occasions allowing the evaluation of dynamic balance performance. Three standard dynamic tests requiring subjects to shift their COG within their base of support were performed. The first test involved rhythmic weight shifting side to side to targets positioned at 50% of the theoretical LOS at three- and two-second pacing. Subjects were instructed to match the timing and movement of a ball on the screen with the cursor representing their COG by shifting their weight side to side. The second test was similar to the first, except movement was in an anterior–posterior direction. Data reflecting the average magnitude of the movement path (expressed as a percentage of the LOS) were produced from six trials at each pace for each movement direction. The absolute error relative to the targets (set at 50% of the LOS) was calculated by subtracting 50 from the score obtained (50% indicating perfect execution) and recording it in absolute terms.

The final dynamic test involved weight shifting to eight targets positioned in an ellipse, the perimeter of which represented 75% of the theoretical LOS. The task required that subjects shift their COG such that it followed a ball to each target as it was highlighted, and that they remain at that target for three seconds before returning to the central target (2.3° anterior to vertical). Targets were highlighted in random order, but each target was selected only once. The maximum allowable movement time to reach a target was eight seconds. The movement time and path sway (in terms of percentage of the LOS) was recorded for each target.

Determining the maximal COG excursion. Thirty-eight subjects (20 of whom had participated in the reliability testing) were assessed on their ability to shift their COG as far as possible in forward and backward directions without altering their base of support. Maximal COG excursions to the left and right were available for 20 of these subjects. To determine the maximal COG excursion, targets were positioned as far anterior, posterior or laterally to the centre of the LOS ellipse as the software would allow. Subjects were instructed to shift their COG such that the cursor reached or surpassed the target, but their feet had to remain in full contact with the forceplates. The average of three trials in each direction was calculated.

Determining the position of the COG. The average position of the COG during quiet standing relative to the theoretical LOS was determined for each of the seventy subjects under varied conditions (eyes open, eyes closed, and while focusing on a central target). These data were used to evaluate the variability of the COG position across a group of healthy, young subjects under different conditions.

Statistics

The test–retest reliability of the data collected from the Balance Master (static and dynamic tests) was analysed using a univariate repeated measures analysis of variance (ANOVA). The between-subject and between-test day variability were used to calculate intraclass correlation coefficients ($ICC_{2,1}$) for each outcome measure to establish their reliability (17). The inferred reliability reflected by the ICC value was as follows: >0.75 excellent, 0.60 to 0.75 good, 0.40 to 0.59 fair, and <0.40 poor reliability (5, 14).

To determine the actual position of each subject's COG and the maximum achievable anterior, posterior, and lateral COG displacements, the data were converted from % theoretical LOS relative to a fixed position 2.3° anterior to vertical (8, 13), to the angular displacement relative to vertical. Conversions were performed as follows: anterior–posterior displacement from vertical = $[(\%LOS/100)(tLOS)(\cos\theta)] + 2.3°$ and lateral displacement from vertical = $(\%LOS/100)(8°)(\sin\theta)$, where θ is the position of the COG along a circular path (0°/360° corresponds to a position directly anterior, 90° indicates a rightward position)

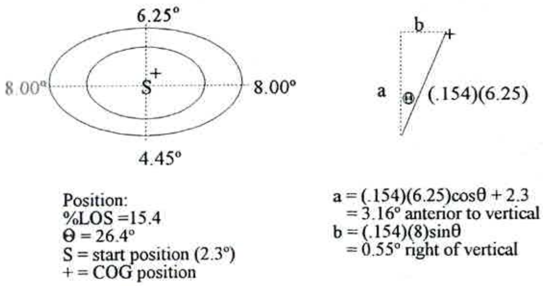

Fig. 1. Method of converting the theoretical position of the centre of gravity to the actual position relative to coordinate 0,0 (vertical). Note that θ is the angle subtended from point 'S': 0° (360°) is directly anterior and 90° is to the right.

and tLOS corresponds to the maximum theoretical excursion in the anterior direction if $270° < \theta < 90°$ (i.e. 6.25°) or in the posterior direction if $90° < \theta < 270°$ (i.e. 4.45°) (Fig. 1). An analysis of variance was used to determine whether the actual LOS varied according to direction. Post-hoc analyses were performed if findings were significant ($p < 0.05$).

Intraclass correlation coefficients were calculated on the basis of the three repetitions of each attempt to maximally displace the COG in order to determine the between-trial consistency of the measure. The distributions of the actual LOS and the resting COG position were plotted and the 5th and 95th percentiles noted.

RESULTS

Test-retest reliability

Static measures of balance reflecting postural sway with eyes open, eyes closed, and maintaining the COG within a defined target zone revealed significantly more sway when subjects closed their eyes than when their eyes were open or focusing on a target ($p < 0.001$). However, the reliability of these measures was fair to poor (ICCs ≤ 0.55), although in contrasting the mean sway values obtained on three separate occasions (Table I), no significant differences were found ($p > 0.12$).

The measures of dynamic balance ability were variable across test days (ICCs ranged from 0.10 to 0.48) and significantly so when subjects were required to displace their COG to reach targets positioned to the left, back, and to the right of centre ($p < 0.04$). The time taken to reach a target positioned to the right also differed across testing occasions ($p < 0.02$). The generally poor reliability related to both movement time measures and the path of the COG's displacement toward a fixed target (Table I).

Despite the low ICCs there appeared to be trends in the data suggesting that errors were greater when weight shifts were required in certain directions. A perfect linear

Table I. *Test–retest performance (mean ± 1 SD) and reliability on all measures of balance*

Variable	Week 1	Week 2	Week 3	$ICC_{2,1}$	P value*
EO Sway (%LOS)	0.05 (0.03)	0.05 (0.03)	0.05 (0.03)	0.45	0.92
EC Sway (%LOS)	0.11 (0.09)	0.08 (0.05)	0.09 (0.08)	0.38	0.12
Target Sway (%LOS)	0.04 (0.04)	0.04 (0.02)	0.04 (0.03)	0.55	0.67
WS LR 3 s (%error)	8.02 (6.46)	8.14 (6.48)	6.16 (4.22)	0.11	0.27
WS LR 2 s (%error)	9.02 (5.89)	9.12 (6.80)	9.99 (6.52)	0.29	0.72
WS FB 3 s (%error)	7.88 (6.27)	6.37 (4.82)	6.53 (5.42)	0.31	0.34
WS FB 2 s (%error)	10.21 (6.93)	7.28 (5.67)	7.60 (4.69)	0.17	0.05
F mvt time(s)	2.74 (0.81)	2.74 (0.71)	2.59 (0.80)	0.40	0.52
F path (%error)	169.97 (41.86)	165.78 (29.47)	158.85 (25.62)	0.31	0.26
RF mvt time(s)	2.70 (0.95)	2.62 (0.80)	2.60 (0.78)	0.35	0.80
RF path (%error)	173.98 (41.99)	174.44 (39.07)	167.16 (34.97)	0.27	0.61
R mvt time(s)	2.96 (1.22)	2.57 (0.80)	2.36 (0.64)	0.24	0.01
R path (%error)	175.65 (45.88)	156.39 (26.15)	156.74 (32.59)	0.24	0.02
RB mvt time(s)	2.68 (1.07)	2.60 (0.91)	2.84 (0.94)	0.35	0.46
RB path (%error)	200.47 (57.86)	217.82 (58.17)	217.46 (60.01)	0.34	0.25
B mvt time(s)	2.57 (1.13)	2.38 (0.90)	2.39 (0.83)	0.40	0.52
B path (%error)	204.03 (62.27)	185.31 (42.48)	179.72 (38.72)	0.39	0.03
LB mvt time(s)	2.91 (1.02)	2.50 (0.71)	2.90 (1.06)	0.17	0.09
LB path (%error)	227.22 (85.03)	205.96 (43.84)	216.99 (66.81)	0.28	0.32
L mvt time(s)	2.72 (1.55)	2.56 (1.20)	2.48 (1.08)	0.48	0.56
L path (%error)	182.57 (69.41)	167.09 (42.02)	157.70 (35.28)	0.41	0.04
LF mvt time(s)	2.62 (1.09)	2.52 (0.87)	2.60 (0.66)	0.21	0.87
LF path (%error)	175.64 (41.14)	170.40 (40.98)	169.51 (34.88)	0.10	0.77

* = The level of significance of variance between days (ANOVA).
EO = eyes open; EC = eyes closed; WS = rhythmic weight shift; L = left; R = right; F = front; B = back; 3/2 s = pacing; LOS = limits of stability; mvt = movement; ICC = intraclass correlation coefficient.

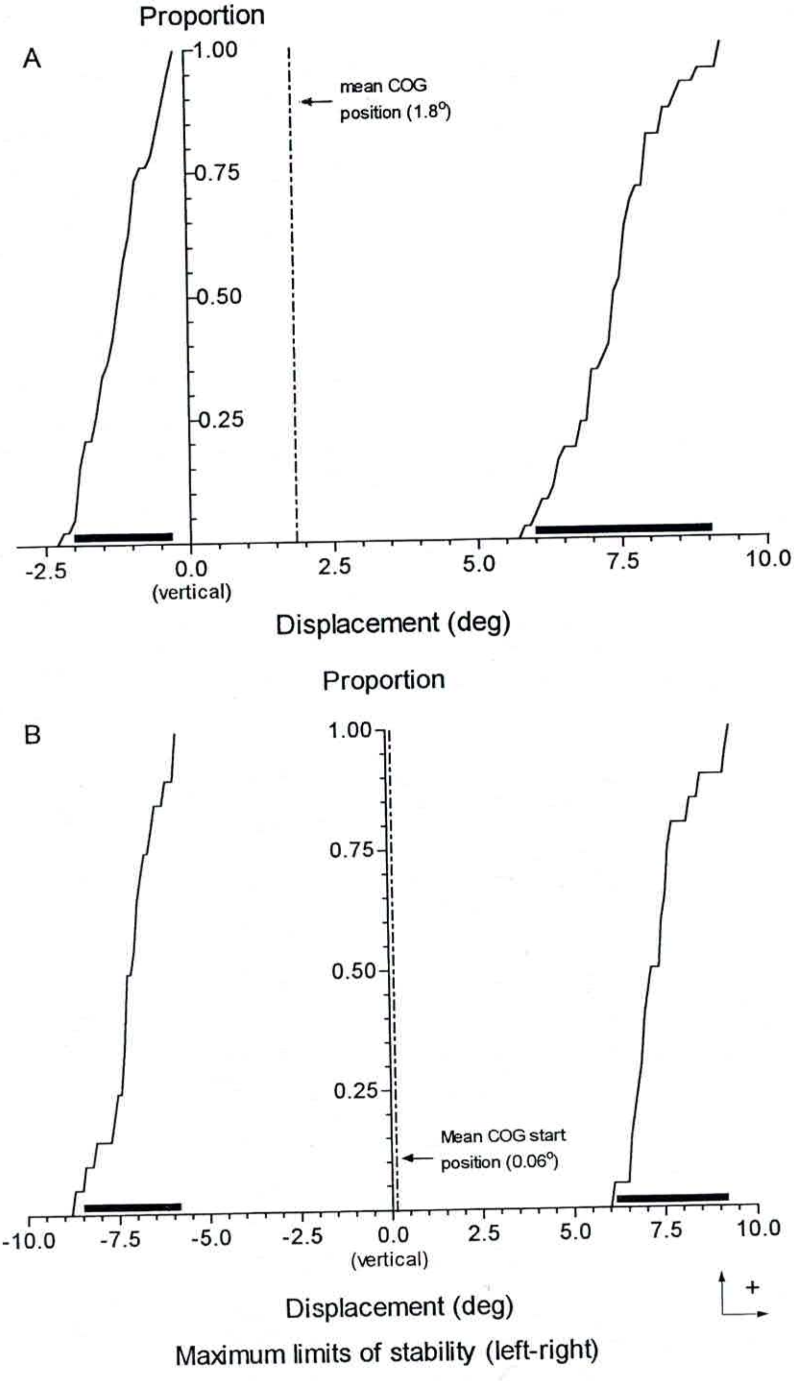

Fig. 2. Cumulative frequency plots associated with the maximal centre of gravity excursions relative to vertical (mean COG position included for reference only). The horizontal bars represent the spread of values delimited by the 5th and 95th percentiles spanning the scores achieved by 90% of the subjects. Maximal limits of stability in posterior and anterior directions (A) and lateral directions (B) are illustrated.

Table II. *Position and maximal excursion of the centre of gravity (in degrees) relative to the vertical (0,0)*

Variable		Mean	SD	95% CI	Intra-trial ICC
Eyes open	–AP	1.81	0.86	0.60–2.01	0.75
	–ML	0.06	0.53	–0.05–0.26	0.55
Eyes closed	–AP	1.95	0.82	1.76–2.15	0.76
	–ML	0.04	0.53	–0.05–0.28	0.59
Target	–AP	2.28	0.05	2.26–2.29	0.20
	–ML	0.04	0.07	0.01–0.06	0.21
Anterior		7.46	0.86	7.12–7.74	0.89
Posterior		1.12	0.56	0.94–1.31	0.93
Left		7.08	0.78	6.72–7.44	0.88
Right		7.46	0.89	7.05–7.88	0.88

path to a target scored 100% and the extent of the deviations from this path (the error) was denoted by the magnitude of the measured value (in percent). The path error was found to be strongly influenced by the position of the target relative to centre ($p < 0.001$). Post-hoc analysis revealed that the error in the COG path was greater when targets were positioned back, to the left and back, or to the right and back of centre than when targets were positioned either directly to the left or right or in any position in front of centre ($p < 0.01$).

Limits of stability

Relative to vertical, subjects were able to shift their COG forward to a greater extent than they could displace it posteriorly within the base of support (7.46° anterior vs 1.12° posterior, $p < 0.001$). In terms of lateral displacement, there was no difference in the maximal mean excursion of the COG to the right (7.46°) or to the left (7.08°) ($p > 0.80$). The spread in maximal COG excursion for all subjects was between ~1.5° and 3.0° (5th and 95th percentiles) in any given direction with the widest 90-percentile band corresponding to the anterior LOS (Fig. 2). The inter-trial reliability was excellent for all measures with ICC values ranging from 0.88 to 0.93 (Table II).

Static COG position

The mean COG position (± 1 SD) of all subjects tested ($n = 70$) was 1.81° ± 0.86° anterior to the vertical and slightly to the right of centre (0.06° ± 0.53°) under the "eyes open" condition. In terms of the mediolateral COG position there was little spread in the distribution; the COG of 90% of all subjects was between −0.81° (left) and 1.15° (right) of vertical. In the anteroposterior direction, the COG was always anterior to the vertical and fell between 0.30° and 3.38° in 90% of the cases (Fig. 3). The COG position did not change when subjects closed their eyes ($p > 0.05$), but shifted significantly further anterior (mean of 2.28° ± 0.05°) when subjects were instructed to maintain their COG position within a target area centred 2.3° anterior to vertical ($p < 0.05$ compared to eyes closed and $p < 0.001$ compared to eyes open). Intra-trial reliability within the same testing session was high in terms of anterior–posterior COG position (ICC = 0.75 and 0.76 for eyes open and closed, respectively), but only fair for mediolateral COG location (ICC = 0.55 and 0.59 for eyes open and closed, respectively). The reliability was poorest when attempting to maintain the COG within a central target

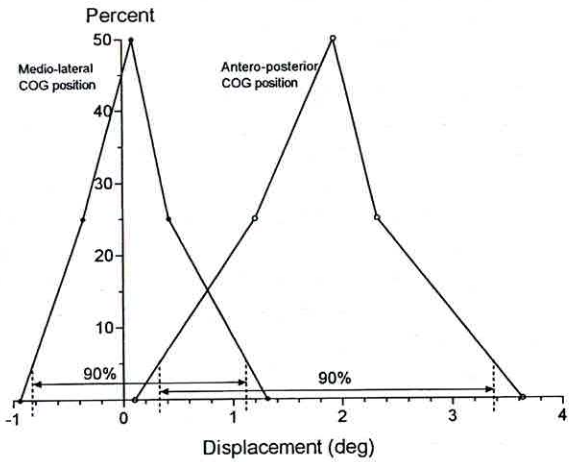

Fig. 3. Frequency distribution associated with the centre of gravity (COG) position relative to vertical for all subjects. The 5th and 95th percentiles are shown delimiting the central band where 90% of the values lie.

(ICC = 0.20, anterior–posterior, ICC = 0.21, mediolateral), likely a consequence of the low variance (17).

DISCUSSION

The findings of this study revealed that in young, healthy individuals the reliability of static and dynamic measures of postural stability and balance performance was generally fair to poor. Although the mean position of the COG within the base of support during quiet standing (eyes open) was consistent for a given individual, the area of sway and the performance of weight shifts (direction and speed) were variable both within and across subjects. The initial position of the COG within the base of support (12), the repertoire of balance strategies available (3), and the degree to which the postural control system is challenged (11) all have impact on balance performance.

In an optimally functioning system, healthy subjects are able to sway comfortably within a large sway envelope without threatening stability (3). Under static conditions it has been known for some time that accurate visual information provides a strong stabilizing influence such that when it is removed the amount of sway increases (9, 10, 18). The findings of the present study, which revealed less sway with eyes open and with visual feedback than with eyes closed, support this view. The eyes open condition was also associated with a reduction in intersubject variance. It is the significant intrasubject variability in standing body sway (1, 2), however, that makes measures of static posture poor indicators of change over time, since the magnitude of change has to exceed the inherent variability of the outcome. Dynamic postural tasks are considered more challenging and thus may result in increased consistency of the response pattern, but not necessarily of the performance itself (15).

Many combinations of movement may be adopted to maintain balance in response to displacements of the COG. The domain of possible movements depends on the nature of the task or balance disturbance, the initial COG position, strength, and neurological condition (12). For healthy, young adults the selection of a response pattern appears to be highly variable, as reflected by the fair to poor test–retest reliability for all dynamic balance tests. The ability to shift the COG well within the limits of stability (50% to 75% of the theoretical limits) fails to challenge the control system sufficiently so as to narrow the range of options available for postural adjustment to the extent that occurs when striving for maximal COG excursion. In subjects with balance deficits due to stroke, the reliability of dynamic balance measures has been good to excellent, improving as the demands of the weight shifting tasks increased (11).

An interesting observation from the present study is that significantly greater errors were associated with shifting the COG to targets positioned within the posterior sphere, i.e. back, back and to the right, and back and to the left. The average posterior limit of stability was found to be 1.12° from the vertical, or a mean of 2.7° from each individual's true resting COG position (95% confidence interval: 2.5°–3.0°) which lies, on average, 1.8° anterior to the vertical. To reach a target set at 75% of the theoretical LOS (4.45° posterior) would require subjects to shift their COG an estimated 3.3° back from a position 2.3° anterior to vertical (or ~1.0° from vertical), which in our sample would exceed the capabilities of approximately 40% of the subjects tested. As individuals' limits of stability are approached, undesirable responses may be elicited, manifested as reduced ability to control the smoothness of the COG trajectory (4). This was not an issue in relation to anterior or lateral COG shifts, as the 75% theoretical limits fell within the capabilities of the majority of subjects, resulting in less pronounced errors.

Recognizing that the initial position of the COG is fundamental in identifying an individual's movement space (12), the use of a predefined resting COG position (2.3° anterior to vertical) may reduce the reliability and sensitivity of the data. The ability to shift one's COG may pose differential levels of difficulty depending on the congruency of the actual COG position (see Fig. 3 for range) and the predefined location. Furthermore, the theoretical LOS are defined relative to the latter and may not reflect subjects' actual LOS. Such discrepancies may explain the tendency in the present study for almost all subjects' dynamic balance scores to fall below the 80th percentile of a normative database (13) and for some to be categorized as abnormal (<5th percentile) according to the Balance Master report summary.

Interpreting data relative to a clinically defined norm or in reference to predefined criteria compromises the sensitivity of the assessment. Shepard et al. (16) performed routine clinical interpretation of data obtained using dynamic posturography (EquiTest) and research use of the same equipment involving additional data processing which they then contrasted with laboratory findings. They found that comparing postural control data between healthy elderly and young people based on their relative performance to a clinically established normative database, the assessment was less sensitive than using subjects' absolute performance measures. The latter