Measures of Postural Stability

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CAMS Report 0304-13, Fall 2003

Center for Applied Mathematics and Statistics

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Abbreviated title for running head: Postural Stability

Key words: Posture, Equilibrium & Mathematical model

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Funding: Pilot grant to K. Quigley under parent grant U01AI 32247 to B. Natelson.

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Abstract:

Dynamic posturography has become an important tool for understanding standing balance in clinical settings. A key test in the NeuroCom dynamic posturography system, the Sensory Organization Test (SOT) provides information about the integration of multiple components of balance. The SOT test leads to an outcome measure called the equilibrium score (ES), which reflects the overall coordination of the visual, proprioceptive, and vestibular systems for maintaining standing posture. Researchers and physicians often use the ES from the SOT as a clinically relevant measure of standing balance. We discuss here the formula used for evaluating the ES and propose an additional measure of postural stability, called the Postural Stability Index (PSI) that takes into account additional biomechanical aspects of postural stability during quiet standing. We propose that this new measure provides a clinically important adjunct to the current SOT.

Introduction:

Postural control under static conditions is usually called postural steadiness, whereas the dynamic postural response to applied or volitional perturbations is called postural stability (1). Dynamic posturography has become an important tool for understanding standing balance in clinical settings. A key test in the NeuroCom dynamic posturography system, the Sensory Organization Test (SOT) provides information about the integration of the visual, proprioceptive, and vestibular components of balance which leads to an outcome measure called the equilibrium score (ES), reflecting the overall coordination of these systems to maintain standing posture. Postural stability is an essential component in assessing the efficacy of interventions for improving balance. Currently, physicians and researchers often use the equilibrium score (ES) from the SOT to assess the postural stability of a patient or subject. Because the SOT-based ES does not take into account some key biomechanical aspects of postural stability, we propose a new measure of postural stability, which we call the Postural Stability Index (PSI). We first provide a brief description of the NeuroCom EquiTest dynamic posturography system and the equilibrium score derived from this system. Then, we propose and describe a new index of postural stability that accounts for additional biomechanical properties of standing that should be reflected in a clinically meaningful score.

The NeuroCom EquiTest System consists of a support surface and a visual surround. The EquiTest device performs a sensory organization test (SOT) with six conditions: conditions 1, 2 and 3 with the platform fixed and conditions 4, 5, and 6 with the platform moving. When the platform moves, it is referenced to the subject's sway such that as the individual leans forward, the platform tilts forward to minimize the degree of changed proprioceptive input from the self-generated sway. This platform adjustment is called “sway-referenced motion”. Similarly, in conditions where the visual surround moves, the surround is referenced to the person’s sway so as to minimize the ability to obtain visually relevant information about how far the individual is from the vertical. In other conditions, visual input is removed instead by asking the subject to close his or her eyes. Participants are asked to stand quietly and steadily for 3 trials for each of the following 6 conditions: (1) eyes open, surround and platform stable, (2) eyes closed, surround and platform stable, (3) eyes open, sway-referenced surround, (4) eyes open, sway-referenced platform, (5) eyes closed, sway-referenced platform, and (6) eyes open, sway-referenced surround and platform.

The NeuroCom EquiTest device uses the Composite ES as an overall measure of postural stability, and we will refer to that composite score here simply as the ES. The ES is defined as:

$$ES = [12.5 \ - [Theta_{max} \ (ant) - (Theta_{max} \ (post)] \ / \ 12.5 \qquad (1)$$

where, Theta (ant) is the maximum anterior sway angle in degrees during a trial; Theta (pos) is the maximum posterior sway angle in degrees during the same trial; and 12.5 is the limit of sway in degrees in the sagittal plane for normal stance. 12.5 degrees is assumed to be the limit of stability for a normal individual (PO-5, Appendix,(2). However, this angle may vary depending upon the age, sex, mass and height of the individual. It is also known from experimental results (PO-3, Appendix, (3) that functional stability limits for the average adult subject are approximately 7 degrees anteriorly and 5 degrees posteriorly. Thus, there is an asymmetry in the usual limits of stability that is disregarded in the ES calculation.

No movement of the subject results in a perfect score of ‘100’. If the subject falls or the value of the ES is negative, the subject receives a score of ‘0’. Thus, the ES ranges between 0 and 100. However, for some subjects, the limit of sway may be more than 12.5 degrees, say 14 degrees, and in that case the ES will be negative, (although in practice, the ES is given a value of ‘0’). Thus, the assumptions about the overall magnitude of the limits of stability as well as the magnitude of anterior and posterior sway can introduce errors into the ES calculation for individuals whose limits of stability vary significantly from the age- and height-matched norms.

The ES is evaluated as a weighted average of the scores from the six conditions of the SOT of a subject, where each condition consists of three identical, 20 second trials with force data sampled at 100 Hz. Because the ES is composed of information from both static conditions (1, 2 & 3) and dynamic conditions (4, 5 & 6), this composite index may obscure important information about independent aspects of static and dynamic balance. In addition, many combinations of anterior and posterior sway across the same overall range can give the same ES. For example, the overall limit of stability of 6 degrees can be made up of the many combinations, (e.g., 6 degrees of anterior sway and 0 degree of posterior sway; or 3 degrees of anterior sway and –3 degrees of posterior sway, etc.). All of these combinations would result in the same composite ES. Yet, a subject with a +6/0 degrees of sway combination likely has a greater risk of falling than a subject with a +3/-3 combination, since the former is close to the functional stability limit on the anterior side, whereas the second combination is not close to the functional stability limit on either side. Therefore, the ES, which would be identical in these two situations can be insensitive to functionally relevant differences in postural stability. To assess postural stability, the formula for a stability measure should include important biomechanical information, such as mass and height of the subject and ankle torque produced to maintain stability. These are absent in the formula for ES. The purpose of this report is to devise a formula to reflect postural stability which incorporates a broader range of biomechanical aspects of upright stance, and does not have the ambiguities of the ES.

Postural Stability

Researchers have used measures other than ES, for assessing postural stability. A stability measure for quiet standing in able-bodied subjects was proposed by Popovic, et. al., (4). Measures of the center of pressure (COP) were used in finding four stability zones, i.e., high preference, low preference, undesirable and unstable zone. The boundaries of stability zones were modeled using ellipses to capture the two dimensional form and orientation of the stability zone. However, in practice it is difficult for physicians to identify these stability zones to assess postural stability of a patient. Alexander and colleagues (5) evaluated postural stability by measuring the rate at which consecutive peak values of the total angular momentum of all body segments about the ankles diminish when a standing person is subjected to various types of perturbations. Shepard and colleagues (6) used this method in comparing the instability of young and elderly adults. However, this method does not provide a defined measure of stability or instability.

We believe that in a clinical setting, a single number, or a small set of numbers representing postural stability is desirable so that physicians can quickly determine whether a patient requires a balance intervention or whether an intervention has been effective in improving postural stability. The purpose of the present paper is also to propose a single measure defining postural stability that is based on the physics of standing and that makes fewer assumptions than does ES.

Method:

To assess postural stability, we must consider the effort needed to maintain stability across an entire test of dynamic balance where the platform or visual environment is altered to perturb balance. We must consider the total value of the stabilizing torque to counteract the destabilizing torque due to gravity in quiet standing. Therefore, we propose and evaluate a new measure of postural stability called the postural stability index (PSI). We define the PSI as the percentage ratio of the total stabilizing ankle torque and the total destabilizing torque due to gravity (obtained from the product of the weight, height and the sway angle) during quiet standing in any of the six conditions. A value of 100 indicates perfect stability. The amount of instability is reflected in how much the PSI is less than 100, and the range of PSI is 0 to100. In mathematical terms, we have:

$$PSI = \Sigma \left| Mgh\theta \right| / \Sigma \left| \tau \right| \quad \text{OR} \quad \Sigma \left| \tau \right| / \Sigma \left| Mgh\theta \right| \qquad (2)$$

whichever is less than or equal to 1.

In (2), M is the mass of the subject, g is acceleration due to gravity, h is 0.55 times the height of the subject (the distance of COM from the platform), τ is the stabilizing torque at the ankle, the vertical bars indicate the absolute value, Σ is the summation of the values inside the bars, and θ (t) is the sway angle in radians at any time t during the test (see our two link model, (7). In equation (2), when the numerator and the denominator are equal, the PSI is 100%, and the subject is perfectly stable. In order that PSI is not more than 100%, the greater of the two expressions must take the denominator position in (2). Equation (2) can be used to independently calculate a PSI value for each condition. The parameters involved in equations (2) can be seen in Figures 1 & 2 below:

Insert Figure 1 about here

Insert Figure 2 about here

Here, F_F and F_R are the front and rear vertical ground reaction forces, F_H is the shear force. *d* and *e* are as shown in Fig.2 . *a* (see equation (4)) below is the perpendicular distance from the line through the ankle and pin joints to the center of mass of the foot (not shown in Fig. 2, because it is very small).

Recall that two individuals with different magnitudes of anterior and posterior sway, but with the same overall sway range will have the same ES (see equation 1), but a different PSI (see equation 2). That is because ES depends only on the overall sway range, whereas PSI depends on the entire sway history, and on the individual's mass, height and the torque at the ankle. Thus, the PSI relies on biomechanical data recorded from each individual, whereas the ES relies heavily on normative assumptions.

Results:

For the sake of an example, we take the data of a normal healthy subject (one of the authors of this manuscript) in a trial of 20 seconds duration for condition 1 of the SOT, for which we use our previously developed two link model (7). The values of the anthropometric parameters for this subject are:

$M = 73.235\ kg$, $m = 2.265\ kg$, I = 85.02 kg (meters)^2, h =0.933 meter, d = 0.107 meters, e = 0.065 meters and a = 0.0315 meters. The sampling frequency is 100 Hz. For this model, the sway angle θ and the torque τ at 2000 data points are given by:

$$\theta = \frac{Mh[(F_F - F_R)d + F_H e - mga] + I \cdot F_H}{M^2 gh^2 - I\left[(M+m)g - \frac{F_F + F_R}{k+1}\right]} \tag{3}$$

and

$$\tau = (F_F - F_R)d + F_H e - mga\cos\frac{k\theta}{k+1} \tag{4}$$

In equations (5) and (6), I is the moment of inertia about the ankle joint, k is the gain factor where k = 0 for test conditions1, 2 and 3, (i.e., when the platform is fixed), and k = 1, for conditions 4, 5 & 6 (i.e., when the platform is moving), and the last term in the denominator, i.e. (F_F + F_R) / k +1, (in equation 5) must be divided by 2, for a moving platform. Using equations (1)—(4), and the data from this same subject for all trials, the composite PSI and composite ES scores (reported by the NeuroCom device) are 59.4 and 51, respectively.

Note that ES is similar regardless of whether an individual spends most of the time at the boundary limit of stability or in the middle region, although there are more chances of falling in the former case. However, PSI is different for these two cases, since it is based on the sway angle throughout the test duration.

Data from civilians with chronic fatigue syndrome, veterans with medically unexplained symptoms, and healthy controls were also compared using the ES score computed by the NeuroCom EquiTest System and the PSI developed here. These subjects were given informed consent and the protocols were approved by the East Orange VA Medical Center IRB and the UMDNJ-Newark IRB. The figure shows that the relationship between ES and average sway angle, which would appear to be an important facet of balance, is small (R^2 = 0.07) and opposite the expected direction (i.e., as average sway angle gets larger, the ES is better). Conversely, as the average sway angle increased, the PSI decreases, as would be expected and this relationship is strong (R^2 = 0.50). These data document that PSI provides more useful information about balance since it is strongly related to an important aspect of stability, namely average sway angle, than is ES.

Insert Figure 3 about here

Discussion

We have developed a formula for a postural stability index (PSI) which includes the mass and height of the subject as well as the ankle torque explicitly. These parameters are absent in the formula for the NeuroCom EquiTest-derived ES, although the ES reflects the total anterior-posterior sway, which could be dependent on the cumulative effect of subject's mass, height, and ankle torque. However, the ES assumes an angle of 12.5 degrees as the limit of stability for all individuals, irrespective of mass, height, age, or sex, and is insensitive to different combinations of anterior and posterior sway. Moreover, the ES only takes into consideration the two extreme values of the sway angle in a given trial, not the sway angle at each data point. Thus, only two readings out of 2000 measurements are taken into account for a 20 second trial, whereas the PSI computation includes the sway angle at every data point for each trial. Thus, the PSI uses data derived from multiple time points for an individual and takes into account a greater array of biomechanical variables that affect postural stability during quiet standing than does the ES. In addition to evaluating PSI, our formula for PSI has the potential of studying variability of oscillations of center of mass (COM) in assessing stability (Richard, et al. 2002), which will be the subject of future research.

Conclusions

We propose here a new measure of postural stability, the PSI, which provides a biomechanically-based measure of postural stability that uses data from each sampled time point rather than simply from the minimum and maximum sway values. Individual differences in postural stability thus are taken into account without appeal to normative assumptions about sway limits. We propose that the PSI provides a more biomechanically sound measure of postural stability that may have good clinical utility.

Acknowledgments

The authors would like to thank Christina Rumage, Chrissy Giubilo, and Caixia Zhao for assisting in the data collection.

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Figure 1. Free body diagram of body (above ankle). The ankle is at the small open circle.

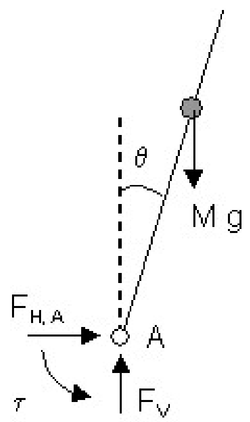

Figure 2. Free body diagram of feet with force plate.

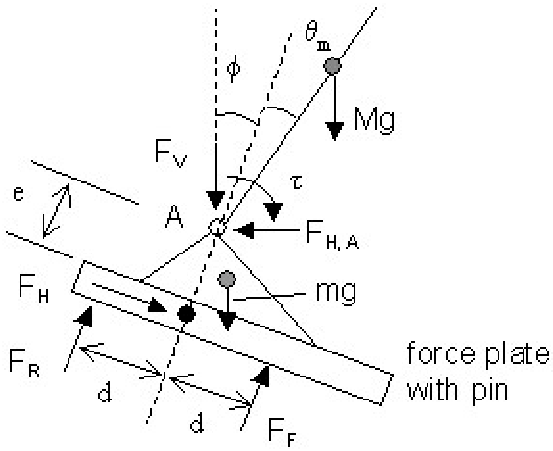

Figure 3. Relationship between PSI (squares) and average angle of sway, and between ES (diamonds) and average angle of sway.