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Postural stability index is a more valid measure of stability than equilibrium score

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Abstract—Researchers, therapists, and physicians often use equilibrium score (ES) from the Sensory Organization Test, a key test in the NeuroCom EquiTest System (a dynamic posturography system) to assess stability. ES reflects the overall coordination of the visual, proprioceptive, and vestibular systems for maintaining standing posture. In our earlier article, we proposed a new measure of anterior-posterior (A-P) postural stability called the Postural Stability Index (PSI), which accounts for more biomechanical aspects than ES. This article showed that PSI provides a clinically important adjunct to ES. In the present article, we show that PSI can provide an acceptable index even if a person falls during the trial, whereas ES assigns a zero score for any fall. We also show that PSI decreases as ankle stiffness increases, which is intuitive, while ES exhibits the opposite behavior. Ankle stiffness is generally recognized as an indicator of postural stability. These results suggest that PSI is a more valid measure of A-P stability than ES.

Key words: ankle stiffness, balance, center of pressure, dynamic posturography, equilibrium score, mathematical model, postural stability, sensory organization test, stabilizing torque, sway angle, sway-referenced motion, two-link model.

INTRODUCTION

Understanding postural stability and balance is important because millions of people experience dizziness and balance problems in their lifetimes [1]. Populations with increased occurrence of balance problems include people with chronic fatigue syndrome (CFS) [2–5] and the elderly [1,6]. Balance also tends to decline with age. The cost of falls due to balance problems is high and is likely to increase as the population ages. Evaluation of postural stability is important for clinicians to diagnose balance problems early and to evaluate the effects of interventions to treat these problems.

Dynamic posturography [7–8] has become an important tool for understanding standing balance in clinical settings. The Sensory Organization Test (SOT) is a key test in the NeuroCom EquiTest System (a dynamic posturography system) that provides information about the integration of

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Abbreviations: A-P = anterior-posterior, CFS = chronic fatigue syndrome, COM = center of mass, ES = equilibrium score, IRB = international review board, PSI = Postural Stability Index, SOT = sensory organization test.

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the visual, proprioceptive, and vestibular components of balance. The SOT involves quiet standing, with a person's eyes open or closed and the platform and surroundings fixed or moving. The SOT results in an outcome measure called the equilibrium score (ES), which is based on the maximum anterior-posterior (A-P) sway angles during SOT trials, reflecting the overall coordination of these components to maintain standing posture. Currently, physicians, therapists, and researchers often use the ES from the SOT to assess the postural stability of a patient or a subject, which is essential for assessing the efficacy of interventions for improving balance [9–10]. Because the SOT-based ES does not account for some key biomechanical aspects of postural stability, such as weight, ankle moment, and shear force, we proposed a new measure of A-P postural stability called the Postural Stability Index (PSI) [11]. PSI is defined as the percentage ratio of the destabilizing torque due to gravity and the stabilizing torque due to the ankle muscles.

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. [12]. Measures of the center of pressure (COP) were used in finding four stability zones, i.e., high preference, low preference, undesirable, and unstable. They modeled the boundaries of these stability zones using ellipses to capture their two-dimensional form and orientation. However, in practice, physicians find that quickly identifying these stability zones to assess postural stability of a patient is difficult. Alexander and colleagues suggested a single measure for postural stability by measuring the rate at which consecutive peak values of the total angular momentum of all body segments about the ankles diminished when a standing person was subjected to various types of perturbations [13]. Shepard and colleagues used this method in comparing the instability of young and elderly adults [14]. However, quantifying angular momentum and angular impulse accurately is difficult because it requires knowledge of the motion of several body segments [15].

We believe that in a clinical setting, a single number representing postural stability is desirable so that clinicians can quickly determine whether a patient requires a balance intervention or whether an intervention has been effective in improving postural stability. Keeping this concept in view, we developed, in our previous article [11], a single measure defining postural stability, PSI, based on the physics of standing. We showed, in that article, that ES may be the same whether an individual spends most of the time at the boundary (limit of stability) or in the middle region of the sway, even though the chances to fall are higher in the former. However, PSI is different for these two cases, as expected, since it is based on the sway angle throughout the test.

We also showed that PSI was strongly related to average sway angle, which is an important facet of balance [16–17], and as one might expect, PSI decreased as the average sway increased. Conversely, ES increased as the average sway increased and the correlation between ES and average sway was very small.

In the present article, we give more evidence based on investigation of the following two questions to establish that PSI is a more valid measure of A-P postural stability than ES:

1. "Can PSI be used for assessing stability even if a subject falls during a trial?" This contrasts with ES, in which all falls, regardless of whether they occur early or late in a trial, are given the same weight in computing the composite ES.
2. Ankle muscle stiffness has been found to be related to postural stability in clinical studies of subjects with Parkinson's disease [18] and Down's syndrome [19]. Greater ankle stiffness correlates with poor stability in these studies. Keeping this in view, we ask, "Which measure, PSI or ES, gives better agreement with the finding that as ankle stiffness increases, stability decreases?"

METHODS

Subjects

Data from 30 subjects, 10 civilians with CFS, 10 veterans with medically unexplained symptoms, and 10 healthy people, were used to compare the composite ES computed by the NeuroCom EquiTest System with the composite PSI developed in our earlier article [11]. Among 10 CFS subjects aged 23 to 55 years, 4 were male and 6 female and all of them were white. Among the 10 veterans aged 34 to 78 years, 8 were male and 2 female, and 5 were white, 1 black, 1 Asian, and 3 of unknown race. Among the 10 healthy subjects aged 22 to 55 years, 2 were male and 8 female and 8 were white and 2 black. The diagnostic group of individuals with CFS were chosen because these individuals have been suggested to have more balance problems than healthy individuals [2–5]. Because of this finding of balance problems in CFS individuals, we also speculated that veterans with medically unexplained symptoms (who often share symptoms with CFS) may also have balance problems. However, none of our test subjects had previously diagnosed balance problems and none of them were on medication that would impact balance. Rather, these individuals have medically unexplained symptoms, so we assessed whether they also have balance problems. We also studied a group of healthy persons with no known neurological deficits as determined by history and physical examination to investigate a range of responses. All the subjects were given informed consent and the protocols were approved by the East Orange Department of Veterans Affairs (VA) Medical Center International Review Board (IRB) and the University of Medicine and Dentistry of New Jersey-Newark IRB. All the subjects performed all trials in each condition of the SOT of the NeuroCom EquiTest System.

Apparatus and Procedure

We used the NeuroCom EquiTest System, which consists of a support surface and a visual surround. An individual takes part in six conditions of a SOT on the EquiTest System. Conditions 1, 2, and 3 are with the platform fixed, and conditions 4, 5, and 6 are 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 change in 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 to minimize her or his 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 three trials under each of the six conditions:

3. Eyes open, surround and platform stable.
4. Eyes closed, surround and platform stable.
5. Eyes open, sway-referenced surround.
6. Eyes open, sway-referenced platform.
7. Eyes closed, sway-referenced platform.
8. Eyes open, sway-referenced surround and platform.

The NeuroCom EquiTest System calculates ES for each trial in each condition according to

$$\mathrm{ES} = 100 \times \{12.5 - [\theta_{\max}(A) - \theta_{\max}(P)]\}/12.5\,, \quad (\mathbf{1})$$

where, $\theta_{\max}(A)$ is the maximum anterior sway angle in degrees during a trial, $\theta_{\max}(P)$ is the maximum posterior sway angle in degrees during the same trial, and 12.5 is assumed to be the limit of sway in degrees in the sagittal plane for normal stance of an individual (**Figure 1**) [20].

No movement of the subject results in a perfect score of 100. If the subject falls, 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°, e.g., 14°. In this example, the ES will be negative—although in practice, the ES is given a value of 0. The composite 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 s trials with force data sampled at 100 Hz.

To assess A-P postural stability using PSI, we consider the effort needed to maintain stability across an entire dynamic balance trial where the platform or visual environment is altered to perturb balance. For this purpose, we consider the total value of the stabilizing torque to counteract the destabilizing torque due to gravity in quiet standing. We define the PSI as the percentage ratio of the total destabilizing torque due to gravity (obtained

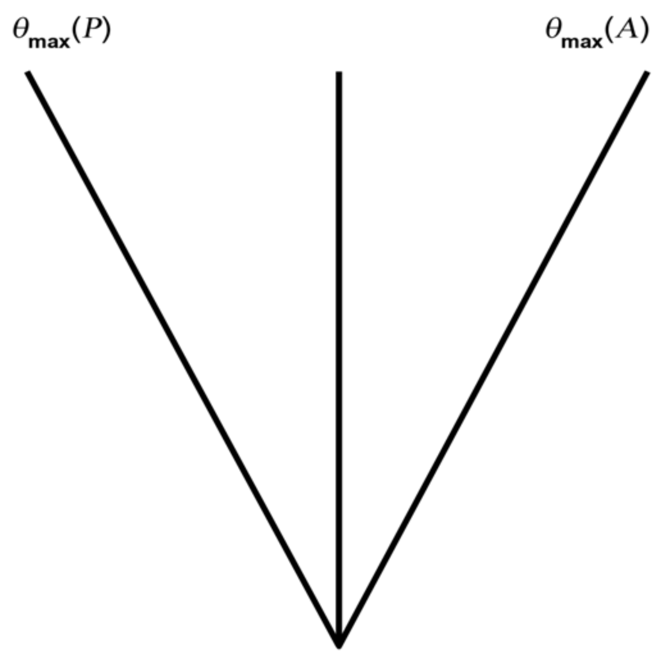

Figure 1.
Diagram representing maximum backward (posterior) $\theta_{\max}(P)$ sway and maximal forward (anterior) $\theta_{\max}(A)$ sway and upright standing as used in computing equilibrium score.

from the product of the weight, height, and sway angle—this product represents the effect of gravity) and the total stabilizing torque during quiet standing for each of the six conditions. A value of 100 indicates perfect stability in any of the six conditions. The magnitude of instability is indicated by the deviation of PSI from 100. In mathematical terms, we have

$$\text{PSI} = 100 \times (\Sigma|Mgh\theta|/\Sigma|\tau|) . \qquad (2)$$

In **Equation (2)**, M is the mass of the subject, g is the acceleration due to gravity, h is 0.55 times the height of the subject (the average distance of center of mass (COM) from the platform, based on anthropometric data), τ is the stabilizing torque at the ankle, the vertical bars indicate absolute value, Σ is the summation of the values inside the bars, and θ is the sway angle in radians [21]. In **Equation (2)**, when the numerator and the denominator are equal, the PSI is 100 percent and the subject is perfectly stable. **Equation (2)** can be used independently to calculate a PSI value for each condition. The composite PSI is derived from the same weighted average as composite ES, with the use of the raw data from the NeuroCom EquiTest System, in each condition and each trial.

The parameters involved in **Equation (2)** can be seen in **Figures 2** and **3**. These are reproduced from our earlier article on PSI [11], as a ready reference.

From our earlier article and our model [11,21], the sway angle and the torque τ at 2,000 data points are given by

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

and

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

Note that a (**Equation (4)**) is not shown in **Figure 3** since it is very small. It is the perpendicular distance from the line through the ankle and pin joints to the COM of the foot. The sampling frequency used is 100 Hz.

In **Equations (3)** and **(4)**, F_F, F_R = reaction forces measured with front and rear force transducers respectively; d = distance from force transducer to pin axis on

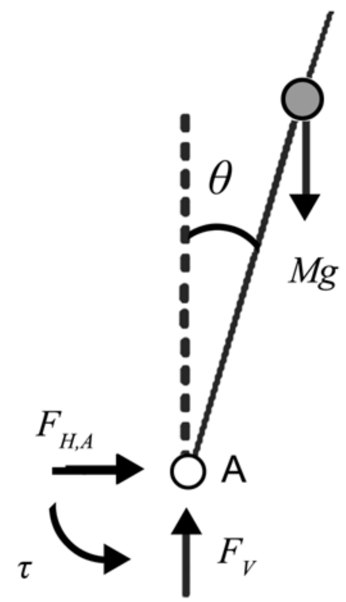

Figure 2.
Free body diagram of body (above ankle). Ankle (A) is at small open circle. M = mass of body above ankle. θ = absolute sway angle with respect to a fixed vertical reference, F_V = vertical force acting at ankle joint, $F_{H,A}$ = horizontal force acting at ankle joint, τ = torque acting at ankle joint, and g = acceleration due to gravity.

force plate; F_H = horizontal reaction force (shear force) measured with force transducer at pin joint of force plate; e = distance from horizontal force transducer to ankle joint; m = the total mass of the feet and the force plate; I = the moment of inertia about the ankle joint; and k is the gain factor, where k = 0 for test conditions 1, 2, and 3 (i.e., when the platform is fixed) and k = 1 for conditions 4, 5, and 6 (i.e., when the platform is moving). In **Equation (3)**, the last term in the denominator, i.e., $(F_F + F_R)/(k + 1)$, must be divided by 2 for a moving platform.

We have used **Equation (3)** of our two-link model (foot and body linked at the ankle, **Figure 3**) to evaluate θ and the ES, instead of using the machine-reported ES for **Figure 4**. Thus, we did not use the machine-reported ES that uses a single-link model where the foot is taken as a fixed point, i.e., ankle joint and heel coincide and the body sways like a simple inverted pendulum about this fixed point (**Figure 2**). However, the results are not affected qualitatively. Note that our two-link model reduces to the single-link model of the machine. This can be verified by taking $a = e = F_H = k = 0$ (which are ignored in a single-link model,) and total body weight = sum of the vertical forces. The details are discussed in

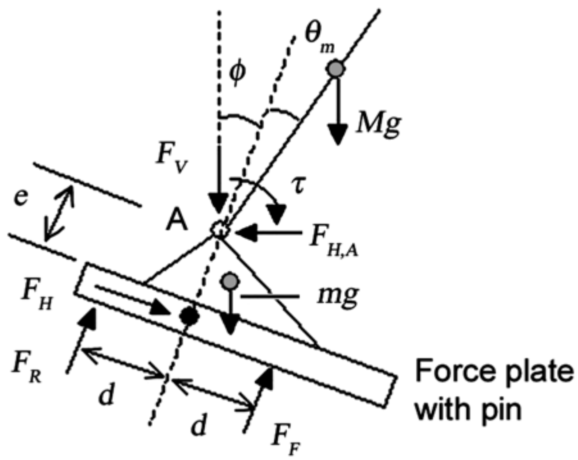

Figure 3.
Free body diagram of feet with force plate. d = distance from force transducer to pin axis on force plate, F_H = horizontal reaction force (shear force) measured with force transducer at pin joint of force plate, e = distance from horizontal force transducer to ankle (A) joint, F_V = vertical force at A joint, m = total mass of feet and force plate, M = mass of body above A joint, ϕ = rotation angle of force plate during sway-referenced motion, g = acceleration due to gravity, θ_m = measured relative sway angle with respect to line perpendicular to force plate, $F_{H,A}$ = horizontal force acting at A joint, τ = torque acting at A joint, and F_F, F_R = reaction forces measured with front and rear force transducers, respectively.

our earlier articles [11,21]. Another reason we have used **Equation (3)** of our model is because we must use the same θ for computing ES as we used to compute PSI.

RESULTS

To investigate question 1 (see "Introduction" section of this article), we plotted the mean composite ES and mean composite PSI of all 30 subjects mentioned earlier, calculated over a period of 5 s, 10 s, and 20 s (**Table 1**) and then found the percentage difference in the composite PSI and composite ES scores relative to 20 s duration. **Table 1** clearly shows that the percentage difference for composite ES is 22 percent for 10 s duration, whereas the composite PSI is only 2 percent for 10 s duration. The difference is even larger when comparing a 5 s and 20 s duration, where the percentage difference for composite ES is 61 percent for 5 s duration and the difference for composite PSI is only 9 percent for 5 s. These results for each group are also shown in the table. Therefore, if a subject falls, for example, after 10 s, we can be more confident that the composite PSI score provides a more consistent estimate of stability for the time than the composite ES. We note from **Table 1** that as the duration of the trial increases, composite ES can only decrease, since only the two most extreme data points are taken. However, for composite PSI, the results become level over time and the composite PSI may even increase, since the subject might have some initial wobbling and then stabilize. Thus, composite ES has an inherent time-dependence, whereas composite PSI has much less time-dependence.

Regarding question 2, we plotted composite ES and composite PSI versus composite ankle stiffness for the same 30 subjects. Ankle stiffness is defined as the rate of change of torque at the ankle with respect to the displacement (in radians) of the COM. Composite ankle stiffness is evaluated with the same weighted average as the composite ES and composite PSI. The results are presented in **Figure 4**. The experimental data are shown in **Table 2**. From this figure, one can see that composite PSI correlates better (R = –0.337) with composite ankle stiffness than does composite ES (R = 0.145). In addition, composite PSI decreases as composite ankle stiffness increases as one would expect, whereas composite ES increases as composite ankle stiffness increases, which is counterintuitive. We also note that the standard error of estimate (i.e., the square root of the residual variance) with respect to the regression line of the PSI data is smaller than that of the ES data: 7.0 for PSI, compared with 17.7 for ES.

Because better stability depends on lower ankle stiffness [18–19] (i.e., less rigidity at the ankle), lower ankle stiffness would be expected to be associated with higher composite PSI. Since composite PSI decreases with increasing composite ankle stiffness in **Figure 4**, this decrease suggests that composite PSI is a more valid indicator of this aspect of stability than composite ES.

DISCUSSION

The NeuroCom EquiTest System uses a single-link model in which the foot is taken as a fixed point (ankle joint and heel coincide), and the body sways about this fixed point like an inverted pendulum. In this simplified model, the stabilizing torque (τ) equals the destabilizing torque ($Mgh\theta$). This can be easily verified from **Equations (3)** and **(4)** by taking $a = e = 0$ (since the ankle joint and heel are considered a single point in a single-link

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Table 1.
Composite equilibrium score (ES) and postural stability index (PSI) for 30 subjects for sensory organization test of 5, 10, and 20 s durations are presented. Group and overall means and differences from 20 s test means are also presented.

Subject No.	Composite ES (s)			Composite PSI (s)		
	5	10	20	5	10	20
Veteran						
1	64	50	45	59	64	64
2	76	64	54	60	60	60
3	71	50	25	55	68	74
4	54	16	15	57	61	64
5	76	63	57	56	56	56
6	50	16	14	59	60	62
7	46	28	13	54	53	56
8	63	55	48	58	56	57
9	45	19	13	61	73	76
10	67	46	36	62	64	63
Group Mean	61	41	32	58	62	63
Difference	91%	27%	0%	–8%	–3%	0%
Normal						
11	64	53	46	55	58	64
12	62	43	27	61	71	71
13	70	62	56	57	63	65
14	72	57	48	54	58	58
15	66	59	42	60	72	78
16	33	24	15	57	54	54
17	68	58	52	54	55	57
18	65	57	51	60	63	58
19	78	60	49	57	72	71
20	83	78	74	55	55	56
Group Mean	66	55	46	57	62	63
Difference	44%	20%	0%	–10%	–2%	0%
Chronic Fatigue Syndrome						
21	65	39	22	58	70	69
22	71	65	61	54	57	60
23	44	34	31	65	65	61
24	71	50	38	59	74	82
25	70	54	50	56	61	59
26	72	62	56	60	61	58
27	55	39	32	51	55	54
28	35	25	14	56	62	62
29	68	65	55	57	64	66
30	37	19	15	59	65	67
Group Mean	59	45	37	58	63	64
Difference	57%	21%	0%	–10%	–1%	0%
All Mean	62	47	38	58	62	63
Difference	61%	22%	0%	–9%	–2%	0%

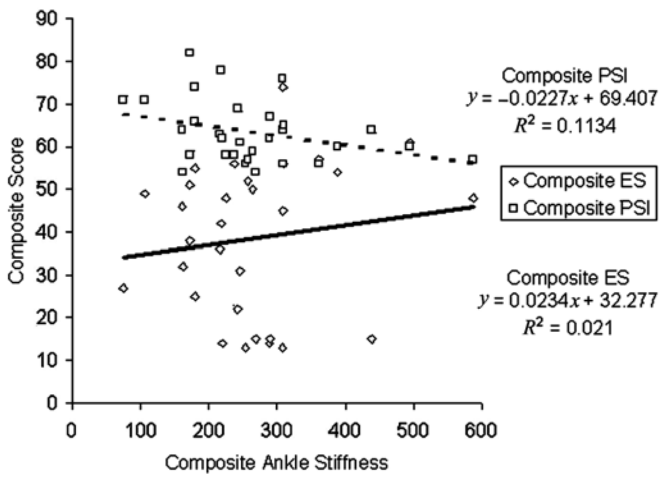

Figure 4.
Composite equilibrium score (ES), Postural Stability Index (PSI) vs. composite ankle stiffness. □ = composite PSI values while ◊ = composite ES values. Units of ankle stiffness are N·m/rad. Experimental details for are given in **Table 2**.

Table 2.
Experimental details for **Figure 4**.

Subject No.	Composite Stiffness	Composite ES	Composite PSI
1	309	45	64
2	389	54	60
3	180	25	74
4	438	15	64
5	361	57	56
6	289	14	62
7	254	13	56
8	587	48	57
9	308	13	76
10	217	36	63
11	161	46	64
12	75	27	71
13	310	56	65
14	225	48	58
15	218	42	78
16	269	15	54
17	258	52	57
18	172	51	58
19	107	49	71
20	309	74	56
21	242	22	69
22	495	61	60
23	246	31	61
24	172	38	82
25	264	50	59
26	237	56	58
27	162	32	54
28	220	14	62
29	180	55	66
30	290	15	67

ES = equilibrium score
PSI = Postural Stability Index

model), $k = 0$ (for fixed platform), $F_H = 0$ (since horizontal force is ignored in the NeuroCom EquiTest System single-link model), and $(M + m)g = F_F + F_R$ in the first two conditions. Thus, our concept of PSI as the ratio between stabilizing and destabilizing torques will always be equal to 1 in the single-link model. This concept is not so in our two-link model. With the use of the two-link model, the ankle joint and heel are separate points and the body sways about the ankle joint as occurs physiologically. Regarding ES, we have verified that if we ignore horizontal forces and rotation of the plate and use the moving average formula for computing COM displacement as was done in the EquiTest System, the computed ES in the single-link model is almost the same as the machine-reported ES. However, computed ES for our two-link model is quite different from the machine-reported or single-link model ES.

We note that our formula for a PSI explicitly includes the mass and height of the subject as well as the ankle torque. These are important facets of postural stability. ES assumes an angle of 12.5° as the limit of stability for all individuals, irrespective of mass, height, age, or sex, and is insensitive to different combinations of A-P sway. Moreover, ES only considers the two extreme values of the sway angle in a given trial, not the sway angle at each data point. Thus, only 2 out of 2,000 measurements account for a 20 s trial. On the other hand, PSI computation includes the sway angle at every data point for each trial. Thus, PSI uses all the data derived from the SOT and accounts for a greater array of biomechanical variables that affect postural stability during quiet standing than does the ES. In addition, van Emmerik et al. show that the traditional assessments focusing on the amount of postural sway to assess stability are erroneous, since very different stability patterns may have the same amount of sway [22].

We note that the torque τ at the ankle used in the definition of PSI is related to muscle strength. The range of sway of COM, i.e., $\theta_{max}(A)$ and $\theta_{max}(P)$ sway angles, is given in the definition of ES. So muscle strength has the dominant influence on PSI, while the range of sway has the dominant influence on ES.

Note also that the purpose of this article is not to compare composite ES with composite PSI quantitatively, since they convey different meanings. Rather, the main purpose is to show that PSI is a more valid measure of A-P postural stability than ES.

We determined the subject's ability to maintain balance based on our analysis using the ankle strategy. This is a limitation of our analysis. However, if the subject uses a "hip strategy" to maintain balance, instead of an "ankle strategy," this will influence both PSI and ES. PSI can then be evaluated based upon the data obtained from a three-link model that we have developed (not included in this article). In this case, torque τ and sway θ will be evaluated at the hip. The EquiTest System does not measure the necessary variables to compute these. Consequently, more sophisticated hardware will be needed. For stability maintained entirely by a "hip strategy," weight, i.e., *Mg*, in our equation for PSI, will be the weight of the participant above the hip and *h* will be the distance of the COM from the hip joint. ES will be evaluated with the use of our equation for θ, in which ground reaction forces will change in the "hip strategy" compared with the ankle strategy.

CONCLUSIONS

In this article, we have shown that PSI provides a more reasonable measure of standing A-P postural stability than ES. PSI can provide an acceptable index even if a person falls during the trial (although none of our subjects fell during the test). On average, the percentage change in PSI for a test of 10 s duration is only 2 percent of that of a 20 s test. For ES, this percentage change is 22 percent on average. In addition, ES values can only decrease with duration of the test, whereas PSI does not have this bias. This is further evidence that PSI has better reliability than ES.

We note that greater ankle stiffness indicates reduced stability, i.e., ankle stiffness is negatively correlated with stability. We have observed that composite PSI is negatively correlated with composite ankle stiffness, as expected, compared with the small positive correlation of composite ES with composite ankle stiffness. This increases our confidence in the value of composite PSI as a measure of postural stability. Furthermore, the correlation for composite PSI with composite ankle stiffness is better than the correlation for composite ES with composite ankle stiffness.

In our previous article [11], we showed that PSI can distinguish between individuals who spend most of the time at the boundary (limit of stability) or in the middle region of the sway, while these individuals can have the same ES. In addition, we showed, in that article [11], that PSI is strongly related to average sway angle, an important facet of balance. PSI was strongly and negatively correlated with average sway, as expected, while ES was weakly and positively correlated. Together with the current results, these data strongly support the use of the PSI as a measure of postural stability.

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