Postural Stability Index is a More Valid Measure of Stability Than Equilibrium Score

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Abbreviations: COM = center of mass, COP= center of pressure, ES= equilibrium score, PSI= postural stability index., SOT = sensory organization test.

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Abstract:

Researchers, therapists and physicians often use Equilibrium Score (ES) from the Sensory Organization Test (SOT), a key test in the NeuroCom 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 paper [1], we proposed a new measure of anterior/posterior (A/P) postural stability, the Postural Stability Index (PSI), which takes into account more biomechanical aspects than ES. In that paper, it was shown that PSI provides a clinically important adjunct to ES. In this paper, 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 is better related than ES to ankle stiffness, which is generally recognized as in indicator of postural stability. These results suggest that PSI is a more valid measure of A/P stability than ES.

Introduction:

Understanding postural stability and balance is important because millions of Americans experience dizziness and balance problems in their lifetimes [2]. Populations with increased occurrence of balance problems include people with Chronic Fatigue Syndrome [3-6] and the elderly [2, 7]. Our preliminary studies also suggest that people with CFS are more likely to have balance problems. 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 to diagnose balance problems early and to evaluate the effects of interventions to treat these problems.

Dynamic posturography [8, 9] 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**.** The SOT involves quiet standing, with eyes open or closed, platform and surroundings fixed or moving. The SOT results in an outcome measure called the equilibrium score (ES), based upon the maximum anterior and posterior sway angles during SOT trials, reflecting the overall coordination of these components to maintain standing posture. Currently, physicians, therapists and researchers often use the equilibrium score (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 [10, 11]. Because the SOT-based ES does not take into account some key biomechanical aspects of postural stability, such as weight, ankle moment and shear force, we proposed a new measure of anterior/posterior (A/P) postural stability, called the Postural Stability Index [1]. PSI is defined as the 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. The boundaries of stability zones were modeled using ellipses to capture the two dimensional form and orientation of the stability zones. However, in practice it is difficult for physicians to quickly identify these stability zones to assess postural stability of a patient. Alexander and colleagues [13] 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 diminish when a standing person is subjected to various types of perturbations. Shepard and colleagues [14] used this method in comparing the instability of young and elderly adults. However, quantifying angular momentum and angular impulse accurately is difficult, since it requires knowledge of motion of several body segments [15].

We believe that in a clinical setting, a single number, or a small set of numbers, 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 in view, we developed in our previous paper [1], a single measure defining postural stability, PSI, based on the physics of standing. We showed in that paper, 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, even though there are more chances to fall in the former case. 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 [16-18] 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 this paper, 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 to assess stability even if a subject falls during a trial? This contrasts with ES, where 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 [19] and Down syndrome [20]. Greater ankle stiffness correlates with poor stability in these studies. Keeping this in view, we ask: Is PSI better correlated than ES with ankle stiffness, an important aspect of postural stability?

Method

Subjects

Data from 30 subjects, 10 civilians with chronic fatigue syndrome (CFS), 10 veterans with medically unexplained symptoms, and 10 healthy people, were used to compare the composite ES computed by the NeuroCom EquiTest System and the composite PSI developed in our earlier paper [1]. Among 10 CFS subjects, in the age group of 23-55 years, 4 were male and 6 female, all of them white. Among 10 veterans in the age group of 34-78 years, 8 were male and 2 female; 5 were white, 1 black, 1 Asian and 3 of unknown race. Among 10 healthy subjects in the age group of 22-55 years, 2 were male, and 8 female; 8 were white and 2 black. The diagnostic group of individuals with CFS was chosen because these individuals have been suggested to have more balance problems than healthy individuals [3-6]. Because of this finding of balance problems in

CFS, 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 have an impact on balance. Rather these individuals have medically unexplained symptoms, so we were assessing whether they also have balance problems. A group of healthy persons with no known neurological deficits as determined by history and physical examination was also studied to investigate a range of responses. All the subjects were given informed consent and the protocols were approved by the East Orange VA Medical Center IRB and the UMDNJ-Newark IRB. All the subjects performed all trials in each condition of the SOT of the Equitest.

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 sensory organization test (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 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 in 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 calculates ES for each trial in each condition according to the formula:

$$ES = [12.5 - [\text{Theta}_{max}\,(\text{ant}) - \text{Theta}_{max}\,(\text{post})]] / 12.5 \qquad (1)$$

where, Theta_{max} (ant) is the maximum anterior sway angle in degrees during a trial; Theta_{max} (pos) is the maximum posterior sway angle in degrees during the same trial; 12.5 is assumed for a normal individual to be the limit of sway in degrees in the sagittal plane for normal stance [21]. See Fig. 1.

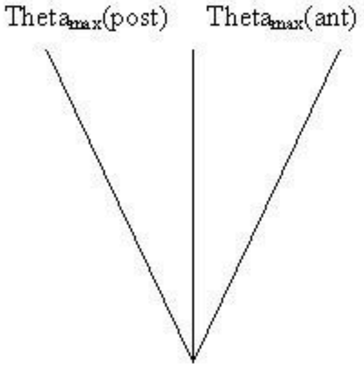
Theta$_{max}$(post)
Theta$_{max}$(ant)

Fig. 1. A schematic diagram representing maximal forward (anterior) sway and maximum backward (posterior) sway and upright standing as used in computing Equilibrium Score (ES).

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 degrees, say 14 degrees, and in that case 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 second 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 trial of dynamic balance 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 from the product of the weight, height and the sway angle, gravity’s effect) 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:

$$PSI = 100 * [\Sigma \left| Mgh\theta \right| / \Sigma \left| \tau \right|] \qquad (2)$$

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 COM from the platform, based on anthropometric data), 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 [22]). In equation (2), when the numerator and the denominator are equal, the PSI is 100%, and the subject is perfectly stable. Equation (2) can be used to independently calculate a PSI value for each condition. The composite PSI is derived by the same weighted average as composite ES, using the raw data from the EquiTest device, 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 paper on PSI [1], as a ready reference.

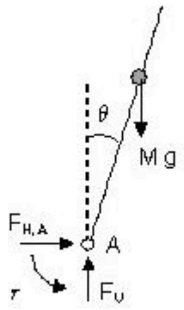
θ
Mg
$F_{H,A}$
A
τ
F_V

Figure 2. Free body diagram of body (above ankle). The ankle is at the small open circle.

Here

M is the mass of the body above the ankle.

θ is the absolute sway angle with respect to a fixed vertical reference.

F_V is the vertical force acting at the ankle joint.

$F_{H,A}$ is the horizontal force acting at the ankle joint.

τ is the torque acting at the ankle joint.

g is the acceleration due to gravity.

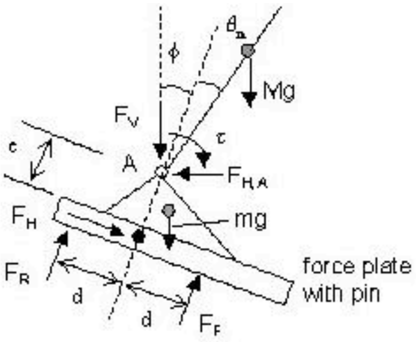
θ_a
ϕ
Mg
F_V
τ
c
A
$F_{H,A}$
F_H
mg
F_R
force plate
with pin
d
d
F_F

Figure 3. Free body diagram of feet with force plate.

Here

F_F , F_R are reaction forces measured with front and rear force transducers respectively.

d is the distance from the force transducer to the pin axis on the force plate

F_H is the horizontal reaction force (shear force) measured with force transducer at the pin joint of the force plate.

e is the distance from the horizontal force transducer to the ankle joint

F_V is the vertical force at the ankle joint..

m is the total mass of the feet and the force plate.

M is the mass of the body above the ankle joint.

ϕ is the rotation angle of the force plate during sway referenced motion..

g is the acceleration due to gravity.

θ_m is the measured relative sway angle with respect to the line perpendicular to the force plate

$F_{H,A}$ is the horizontal force acting at the ankle joint.

From our earlier paper and our model [1, 22], 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

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

Note that a (in 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 center of mass of the foot. The sampling frequency used is 100 Hz.

In equations (3) and (4), I is the moment of inertia about the ankle joint, 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), and 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, see Fig. 3), to evaluate theta and then the ES instead of using the machine reported ES for Figure 4. Thus, we did not use the machine based ES which 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, see Fig. 2. The results are, however, not affected qualitatively. It is noted that our two link model reduces to the single link model of the machine. This can be verified by taking $a = \mathrm{e} = \mathrm{F_H} = \mathrm{k} = 0$ (which are ignored in a single link model,) and total body weight = sum of the vertical forces. The details are discussed in our earlier papers [1] and [22]. Another reason for using equation (3) of our model is that, since we are using theta from equation (3) to compute PSI, we must use the same theta for computing ES.

Results:

To investigate question 1 (see Introduction), we plotted the mean composite ES and mean composite PSI of all thirty subjects mentioned above, calculated over a period of 5 seconds, 10 seconds and 20 seconds (see Table 1 for experimental results) , and then found the percentage difference in the composite PSI and composite ES scores relative to 20 seconds duration. It is clear from Table 1 that the percentage difference for composite ES is 22% for 10 seconds duration, whereas for composite PSI it is only 2% for 10 seconds duration. The difference is even larger when comparing a 5 second and 20 second duration, where the percentage difference for composite ES is 61% for 5 seconds duration and for composite PSI the difference is only 9% for 5 seconds. These results for each group also shown in the table. Therefore, if a subject falls after say, 10 seconds, we can have more confidence that the composite PSI score provides a more consistent estimate of stability for the time period 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 level off 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.

Table 1. Composite ES and PSI for 30 subjects for SOT tests of 5 sec., 10 sec. and 20 sec. durations are presented. Group and overall means and differences from the 20 sec. test means are also presented.

ID	Composite ES			Composite PSI			
	5 Sec.	10 Sec.	20 Sec.	5 Sec.	10 Sec.	20 Sec.	
1	64	50	45	59	64	64	**Veteran**
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%	
11	64	53	46	55	58	64	**Normal**
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%	
21	65	39	22	58	70	69	**CFS**
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%	

Regarding question 2, we plotted composite ES and composite PSI versus composite ankle stiffness for the same 30 subjects mentioned above. Ankle stiffness is defined as the rate of change of torque at the ankle with respect to the displacement (in radians) of the center of mass (COM). Composite ankle stiffness is evaluated using the same weighted averaging as for the composite ES and composite PSI. The results are presented in Figure 4. The experimental data are shown in Table 2. It can be seen from this figure that composite PSI correlates better (R = -.337) with composite ankle stiffness than does composite ES (R =.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 counter intuitive. 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 to 17.7 for ES.

Because better stability depends upon lower ankle stiffness [19, 20] (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, it suggests that composite PSI is a more valid indicator of this aspect of stability than composite ES.

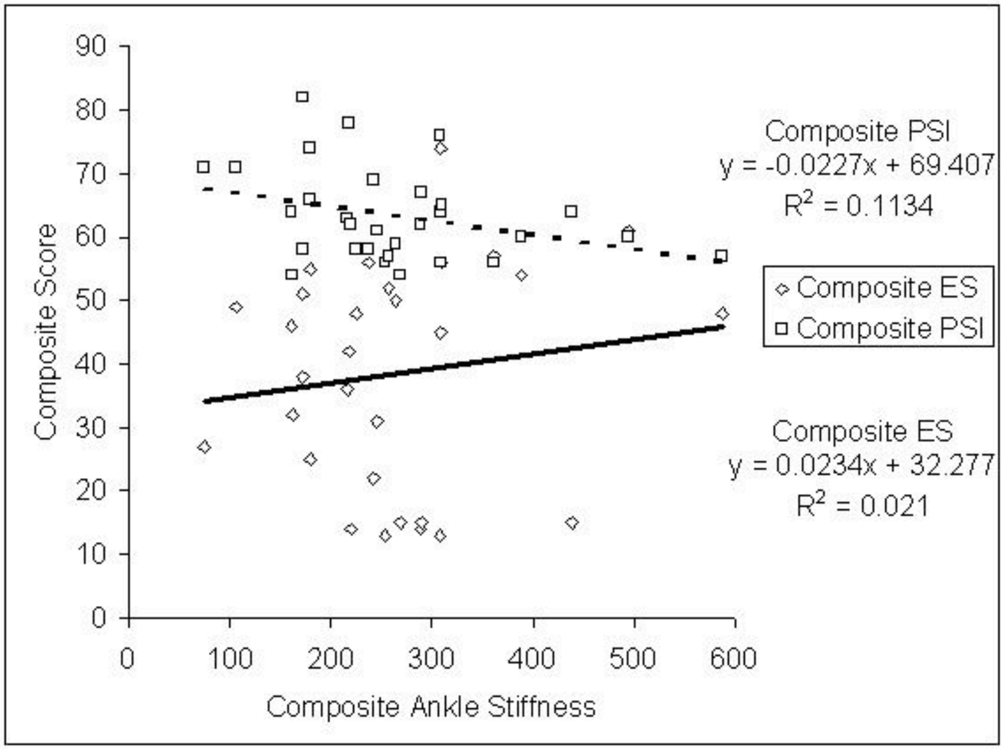
Composite Score
0
10
20
30
40
50
60
70
80
90
Composite Ankle Stiffness
0
100
200
300
400
500
600
Composite PSI
y = -0.0227x + 69.407
$R^2 = 0.1134$
◇ Composite ES
□ Composite PSI
Composite ES
y = 0.0234x + 32.277
$R^2 = 0.021$

Fig. 4 Composite ES and PSI vs. composite ankle stiffness. The solid squares represent composite PSI values while the hollow diamonds represent composite ES values. The units of ankle stiffness are N.m /rad. The experimental details for Fig. 4 are given in Table 2.

Table2. Experimental details for Figure 4.

ID	Comp Stiffness	Comp ES	Comp 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

Discussion:

The Equitest device 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 (Mghθ). This can be easily verified from equations 3 and 4 above by taking a = e = 0 (since the ankle joint and heel are considered as a single point in a single link model); k = 0 (for fixed platform); F_H = 0 (since horizontal force is ignored in the NeuroCom 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 is not the situation in our two link model. In using 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 done in the Equitest device, the computed ES in the one 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 one link model for ES.

We note that our formula for a postural stability index (PSI) includes the mass and height of the subject as well as the ankle torque explicitly. These are important facets of postural stability. 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, 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. 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 takes into account a greater array of biomechanical variables that affect postural stability during quiet standing than does the ES. Van-Emmerick, et al. [23] also show that the traditional assessments focusing on the amount of postural sway to assess stability is erroneous since very different stability patterns may have the same amount of sway.

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. maximum anterior and maximum posterior sway angle, 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 paper 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.

Our analysis is based on the subject using an “ankle strategy” to maintain balance. This is a limitation of our analysis. However, if the subject uses a “hip strategy” for maintaining balance, instead of an “ankle strategy”, this will have an influence on both PSI and ES. PSI can then be evaluated, based upon the data obtained from using a three link model we have developed (not included in this paper). In this case, torque τ and sway θ will be evaluated at the hip. The Equitest device does not measure the necessary variables to compute these. So, more sophisticated hardware will need to be used. 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 center of mass from the hip joint. ES will be evaluated by using our equation for θ, in which ground reaction forces will change in the “hip strategy” compared to the ankle strategy.

Conclusions:

In this paper, 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 test subjects fell during the test). The percentage change in PSI for a test of 10 seconds duration is only 2% of the PSI value for a test of 20 seconds on average. For ES this percentage change is 22% 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 of better reliability of PSI over ES.

We note that greater ankle stiffness is an indication of reduced stability, i.e., ankle stiffness is negatively correlated with stability. We have observed that composite PSI is negatively correlated to composite ankle stiffness, as expected, compared to 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.

It was shown in our previous paper [1] , that PSI can distinguish between individuals who spend most of the time at the boundary (limit of stability) or in the middle region, while these individuals can have the same ES. In addition, we showed in that paper [1], that PSI is strongly related to average sway angle, an important facet of balance. PSI was strongly and negatively correlated with the 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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