Relationship Among Postural Stability, Weight, Height and Moment of Inertia of Normal Adults

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Abstract

Using the definition of postural stability index (PSI) developed by the authors in their earlier work, and the experimental results on 22 normal adults employing the Neurocom Equitest device, we demonstrate in this paper, that there is little correlation among postural stability, weight, height, the product of weight and height, and moment of inertia of a subject about the ankle joint. However, we observe, that there is a slight tendency for PSI and therefore stability to decrease as the height increases.

Introduction

The influence of height on the stability of a subject in quiet standing (static posturography) has been studied by several researchers[1,2]. In these works, different definitions of stability were used. These methods have certain limitations[3,4,5]. To our knowledge, some of the variables such as height, weight, the product of height and weight and moment of inertia have not been studied in relation to stability in *dynamic posturography* (explained in the Methods section below). We have developed a new measure of postural stability, the Postural Stability Index (PSI)[6] which overcomes these and other limitations. In the current paper, we employ PSI to study the relationship of height, weight, their product, and moment of inertia to stability in dynamic posturography.

The influence of height on postural stability has been studied[1,2]. Heights in the range of 1.63-1.73 m and 1.78-1.88 m for male adults from 40 to70 years of age were found not to be correlated with postural stability for male adults[1]. The same conclusion was reported for younger adults from 18-27 years of age[2]. In both these findings, the excursion curve of the center of pressure (COP) during quiet standing for two conditions only, i.e., with eyes open and eyes closed were used in assessing stability. However, COP parameters, such as length, area, displacement, and velocity, are not indicative of instability / stability[3,4]. These variables may indicate underlying neural or sensorimotor dysfunction, but COP movements may have successfully stabilized the center of mass (COM) or center of gravity over the base of the support[5].

Some basic principles of stability in the biomechanics of postural control have been suggested by Hayes[7]. In particular, we are interested in the claims[7] that (1) stability is inversely related to the height of the center of gravity above the support and (2) that stability is proportional to weight. There is no mathematical literature supporting principles (1) and (2). The purpose of this paper is to investigate, mathematically and experimentally, the validity of these principles with regard to postural stability when stabilizing forces such as muscle torque at the ankle are taken into account in analyzing the subject under study.

We have recently developed a new measure of stability, the Postural Stability Index, PSI[6] which is based upon the concept that the ratio of destabilizing torque (due to gravity) to the stabilizing torque (due to muscles) at the ankle is one for perfect stability. The deviation of this index from unity is an indication of the instability of a subject. This measure takes into consideration the weight, height, sway and the torque at the ankle and is irrespective of age, gender, normal or diseased subject. In addition, this measure considers more of the dynamics than in quiet standing. We shall employ this measure to address the validity of principles (1) & (2) above and investigate the relationship of stability with weight, height, their product, and the moment of inertia about the ankle joint. We shall also use four more dynamic conditions in which the platform and surroundings move, with the subject having eyes closed / eyes open, as explained in the Methods section below.

Methods

Dynamic posturography[8,9] has become an important tool for understanding postural stability 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 outputs a measure called equilibrium score (ES), reflecting the overall coordination of these systems to maintain standing posture. Because the SOT-based ES does not take into account some key biomechanical aspects of postural stability, we proposed a new measure of postural stability, PSI, based on the physics of standing[6] and used this index to evaluate stability.

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 1-3 are with the platform fixed and conditions 4-6 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. 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[10].

Since PSI is a more valid measure of stability,[6,11] we use it to evaluate stability in this paper. We now explain the details of PSI.

We consider the effort needed to maintain stability across an entire set of trials of dynamic balance (see the six conditions listed above). For this purpose, we consider the total value of the stabilizing torque generated to counteract the destabilizing torque due to gravity. 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) and the total stabilizing torque for each of the six conditions. A value of 100% indicates perfect stability. The degree of instability is reflected in how much the PSI differs from 100%. In mathematical terms:

$$\begin{aligned} &\mathrm{PSI}=\sum|\mathrm{Mgh\grave{e}}|/\sum|\hat{o}| && \text{if } \sum|\mathrm{Mgh\grave{e}}| < \sum|\hat{o}| \\ &\mathrm{PSI}=\sum|\hat{o}|/\sum|\mathrm{Mgh\grave{e}}| && \text{if } \sum|\hat{o}| \leq \sum|\mathrm{Mgh\grave{e}}| \end{aligned} \qquad (1)$$

In equation (1), 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 absolute value, Σ is the summation of the values inside the bars, and $\theta(t)$ is the sway angle in radians at any time t during the test [12]. In equation (1), when the numerator and the denominator are equal, the PSI is 100%, and the subject is perfectly stable. Equation (1) can be used to independently calculate a PSI value for each condition. The composite PSI is defined 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 (2000 data points). The range of PSI is 0 to100%.

The parameters involved in equation (1) can be seen in Figures 1 and 2. These are reproduced from our earlier paper on PSI[6], as a ready reference.

(Insert Figures 1 and 2 here)

From our earlier papers and our model[6,12], the sway angle θ and the torque τ at the 2000 data points are given by:

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

and

$$\tau = (F_F - F_R)d + F_H e - mga \cos\frac{k\theta}{k+1} \tag{3}$$

Note that *a* (in equation (3)), the perpendicular distance from the line through the ankle and pin joints to the center of mass of the foot, is not shown in Figure 2 since it is very small.

In equations (2) and (3), *I* is the moment of inertia about the ankle joint, *k* is the gain factor where $k = 0$ for test conditions 1-3, (i.e., when the platform is fixed), and $k = 1$, for conditions 4-6 (i.e., when the platform is moving), and in equation (2), the last term in the denominator, i.e. $(F_F + F_R)/k+1$ must be divided by 2, for a moving platform.

Results

The correlation among composite postural stability index (PSI), height, weight, product of height and weight, and moment of inertia about the ankle joint, based upon tests performed on 22 normal subjects with height range of 1.47-1.83 m and age range of 27 to 55 years are shown in figures 3 and 4. 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 experimental details are given in table 1. From these figures, we can see that there is little correlation among these variables. However, from figure 3, we find that PSI, and therefore stability, has a slight tendency to decrease as height increases.

(Insert Figures 3 and 4 and Table 1 here)

Discussion

It appears that stability as identified by Hayes[7] relates to the amount of displacement the body experiences, when subjected to certain destabilizing forces, i.e. the lower the displacement, the greater the stability. For instance, a heavy body will experience less displacement compared to the lighter one under the same set of destabilizing forces. Therefore a heavy body is more stable by Hayes' interpretation. From this point of view, principle (2) seems to be valid. It is also evident that Hayes does not consider opposing forces (such as ankle stiffness) to counteract the destabilizing forces in the above principles. But such opposing (stabilizing) forces are inherent in the subject under study.

Stability limits of quiet standing postural control in children and adults[2] were determined for eyes open and eyes closed. Here, 'stability limits' were defined by the area beneath the feet that the subject can use to contain postural stability. This may or may not be indicative of stability / instability[3,4]. It was found that young children 4-14 years have much smaller stability limits than adults. At age 7, there is an increase in stability limits showing adult like stability. This may be the result of development of the sensory system[2].

We note that we have used anthropometric measures for the height of the center of mass from the ankle joint (.55 times the total height) and for the moment of inertia in our computations. The values taken assumed all subjects have the same weight distribution. If a subject has a different weight distribution, the results might vary.

Our analysis was done from a biomechanics perspective only. Other aspects such as neurological responses were assumed to be the same in all subjects.

Conclusions

Based on our results, we conclude that there is poor correlation of postural stability with weight, height, product of weight and height, and moment of inertia among normal adults from age 27 to 55 and of height 1.47-1.83 m. However, we observe that stability has a slight tendency to decrease as the height increases. Our result is weakly supportive of principle (1) of Hayes' review article[7], i.e. if there is any correlation between height and stability, it is quite small. However principle (2), concerning the correlation of stability with weight, is violated. Here, our result supports the principle that weight is independent of stability[1,2]. Since the stability is slightly (inversely) dependent on the height of the subject, tall people need to sway slightly less compared to shorter people to decrease their destabilizing torque due to gravity, $\Sigma \left| Mgh\theta \right|$, and maintain their stability (see equation (1)).

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Figure Captions

Figure 1. 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.

Figure 2. 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.

Figure3.

The correlation of composite PSI with weight, height and moment of inertia.

Figure 4.

The correlation of composite PSI with the product of weight and height..

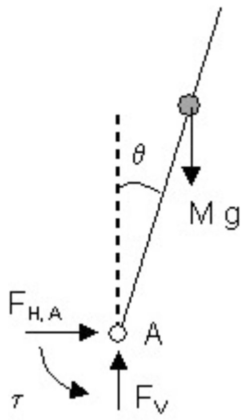

Figure 1. Free body diagram of body (above ankle). The ankle is at the small open circle.

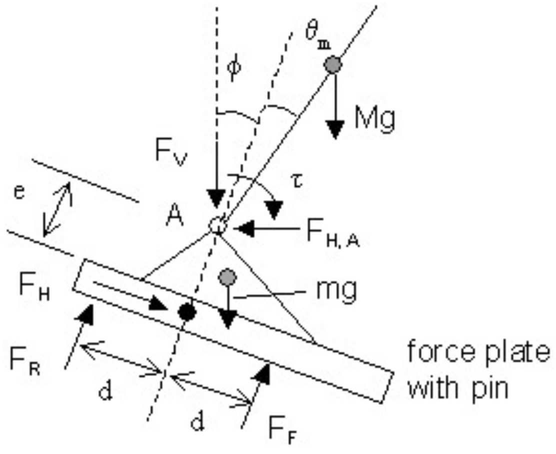

Figure 2. Free body diagram of feet with force plate.

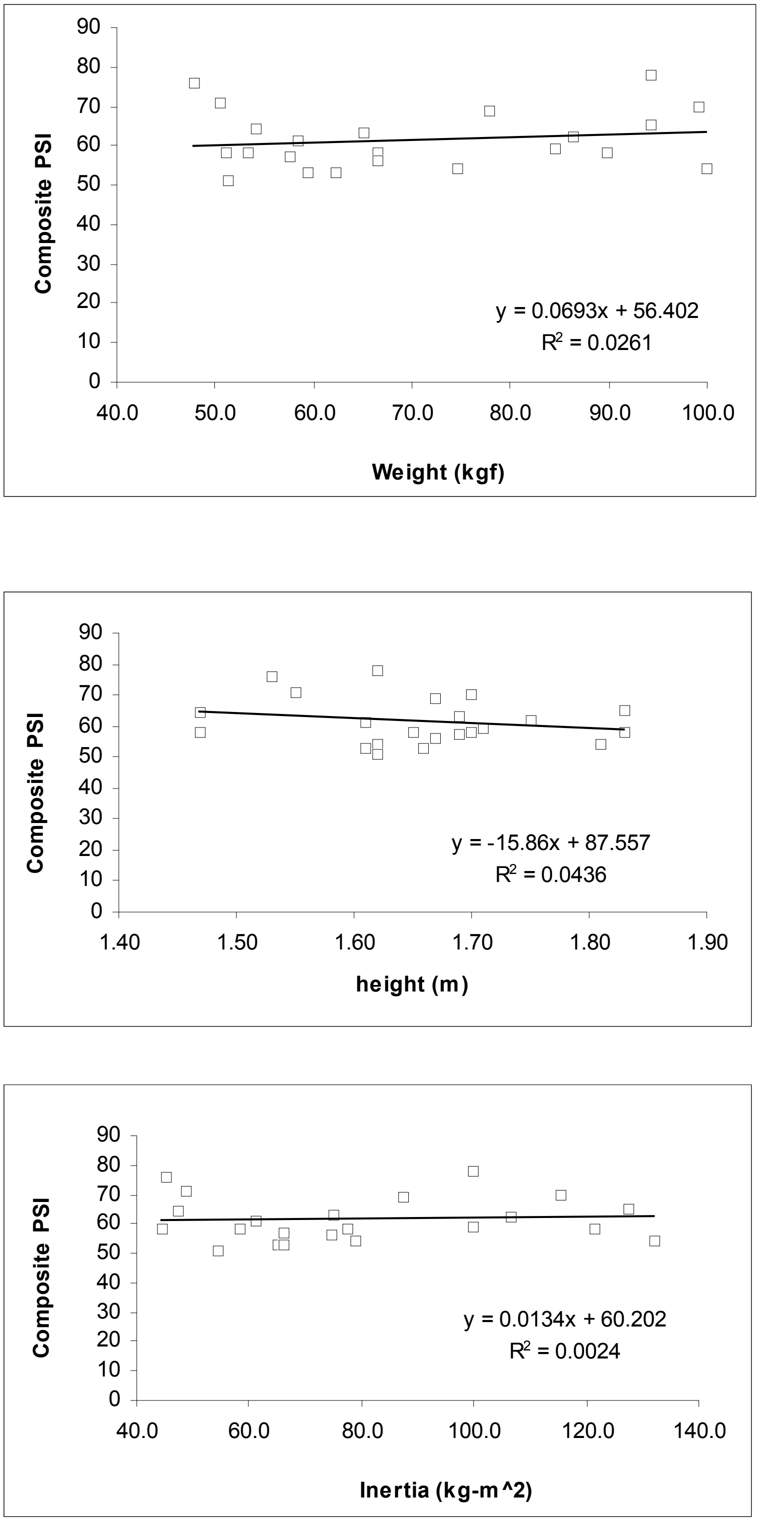

Figure 3 The correlation of composite PSI with weight, height and moment of inertia.

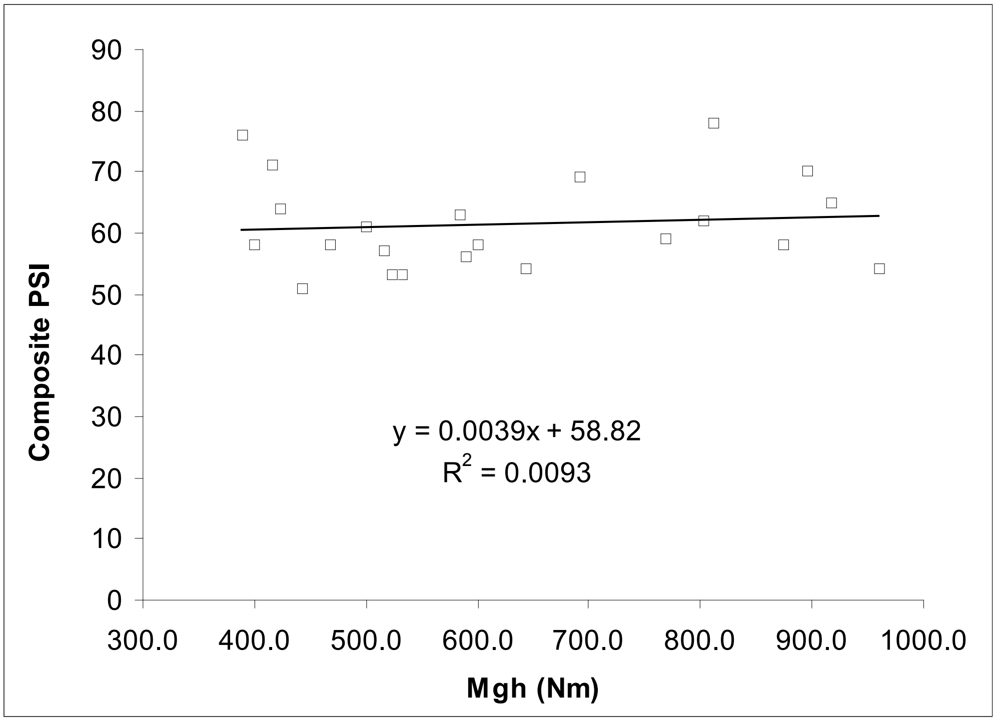

Figure 4 The correlation of composite PSI with the product of weight and height..

Table1. Experimental details for figures 3 and 4.

ID	age	H	W	Mgh	inertia	CompositePSI
1	49	1.47	54.3	424.0	47.3	64
2	28	1.83	94.3	916.9	127.5	65
3	55	1.70	66.5	601.2	77.6	58
4	27	1.62	94.3	812.1	99.9	78
5	54	1.62	74.7	643.5	79.2	54
6	52	1.69	57.6	517.3	66.4	57
7	22	1.65	53.3	467.6	58.6	58
8	23	1.55	50.5	415.7	48.9	71
9	28	1.67	66.5	590.3	74.9	56
10	40	1.61	58.5	500.5	61.2	61
11	50	1.53	47.8	389.1	45.2	76
12	26	1.61	62.3	532.9	65.2	53
13	26	1.47	51.2	400.1	44.7	58
14	23	1.62	51.4	442.8	54.5	51
15	45	1.70	99.1	895.9	115.7	70
16	42	1.66	59.5	524.6	66.2	53
17	39	1.83	89.9	874.8	121.6	58
18	39	1.69	65.1	584.6	75.0	63
19	45	1.71	84.6	769.4	99.9	59
20	42	1.81	99.9	961.3	132.2	54
21	44	1.75	86.4	803.5	106.8	62
22	49	1.67	77.9	691.2	87.7	69