Inter-machine Consistency of the Sensory Organization Test with Human Subjects and Standardized Weights

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Abstract. The Sensory Organization Test (SOT) is a well accepted and commonly used method to quantify stance stability under varying sensory conditions. However, the accuracy of each machine may vary thus hindering the comparison of results from different laboratories. The purpose of this study was to investigate the consistency of postural stability measures of the SOT conducted on two machines made in 1991 and 1997. Three postural stability measures (equilibrium score, sway area, sway velocity) were obtained using standardized static weights (20-80 kg), swaying weights (21–81 kg), and human subjects (n=10, mean age=22.2 years) on the two machines. The testing sequence was balanced between machines. The results showed good consistency between machines while using the swaying weights and while human subjects were tested. However, a significant difference between machines was found while using the static weights (p<0.05). It was concluded that the computerized postural stability measures of SOT have good inter-machine consistency with non-stationary weights and humans, but that the static weight should be added to the calibration routine to detect abnormal machine behaviors.

Key words: Consistency, Force plate, Sensory organization test.

INTERRODUCTION

Balance is a fundamental requirement of human movement. In order to maintain optimal balance, a human subject must be able to maintain stability under varying sensory environments and to shift weight peripherally to accommodate voluntary movements1, 2). An example of altered sensory environment is when a train moves away from a standing nearby subject. The standing subject may misinterpret the moving visual feedback as self-motion, thus signaling the motor system to exhibit postural muscle responses. This response may destabilize the subject. A person with good balance ability should be able to efficiently compare the irrelevant visual feedback with the accurate somatosensory and vestibular inputs. The results of the comparison should abort the unnecessary postural muscle response and insure stability. This ability to rapidly compare, weigh, and select sensory inputs to optimize postural stability is crucial for humans living in the changing world.

The Sensory Organization Test (SOT) simulates the natural sensory environment in a laboratory setting3). The SOT has been used extensively across the world to examine standing balance under varying sensory conditions in different patient populations4–8). The SOT includes six sensory
conditions, they are: (1) eyes open, (2) eyes closed, (3) sway-referenced vision, (4) sway-referenced support, (5) eyes closed and sway-referenced support, and (6) sway-referenced vision and support. In a sway-referenced vision condition, a visual enclosure surrounding the platform system is made to tilt synchronously with the spontaneous sway of the standing subject thus eliminating sway-related visual inputs. In a sway-referenced support condition, the supporting platform is made to tilt synchronously with the spontaneous sway of the standing subject thus eliminating sway-related somatosensory inputs from the ankles and feet.

The specificity and sensitivity of the SOT has been compared across five studies using the equilibrium score (ES) as the output measure. The average test of specificity was 92% in normal subjects. The sensitivity is different for various diseases, and has a range between 21% and 100%. The average sensitivity of SOT was approximately 40% across the five studies involving 836 patients. It was concluded that the ES, which based its calculation on the peak to peak sway angle, might miss the subtle changes of patients and under estimate the disorders.

The validity and reliability studies of the SOT seem more satisfactory than the sensitivity study. The 1-week test-retest reliability of SOT in non-institutionalized older adults was reported to be fair to good, again using the ES as the output measure. The intra-class coefficients (ICC) of ES from the first trial of each sensory condition were between 0.15 and 0.70, representing fair to good retest reliability. The sway-referenced support condition had the worst ICC value in comparison with other testing conditions. Meanwhile, the counts of losses of balance during the SOT showed good reliability (77%–100% agreements). The validity of the sway-referenced visual condition in eliminating sway related visual feedback, however, seems questionable. One study recorded linear and angular displacements of head motion simultaneously with the motion of the visual enclosure. The results revealed that the correlation between sagittal head translation and enclosure motion were moderately high, however, the head displacement leads motion of the visual surround by 250 ms to 452 ms on the average.

In addition to ES, two other computer-generated outcome measures are available from the SOT to quantify postural stability, they are, sway area (SA) and sway velocity (SV). While the ES is calculated from the anteroposterior peak to peak excursion of center of pressure (COP), the SA is a measure of COP excursion in a two dimensional plane. The validity between ES and SA during the SOT on a Smart Balance Master system has been tested in our laboratory. The results showed that the consistencies in which the ES and the SA discriminated among sensory conditions were high and similar (Kendall’s coefficients W=0.84 and W=0.87, respectively). Furthermore, since both ES and SA were derived from the COP data, their correlation was high (r=−0.71 to −0.94, p<0.0001) for most conditions. The only exception was the first trial of the eyes open condition (r=−0.51, p<0.02). The SV has been found to significantly differentiate between fallers and nonfallers but its reliability and validity against other measures have not been tested.

The SOT is extensively used worldwide and the issues of reliability, validity and sensitivity have been addressed in the literature. However, despite frequent comparison of results among laboratories, the reliability of the SOT between machines, i.e., the inter-machine consistency remains unclear. The reliability of the system may be affected by the accuracy of strain gauges, the signal-to-noise ratio of the electrical circuit, or the feedback delay in the sway-referenced conditions. Furthermore, the three computer-generated output measures of postural stability may demonstrate inconsistencies between machines. The purpose of this study was to investigate the inter-machine consistency of computerized output measures of postural stability during the SOT of the Smart Balance Master system using static weights, swaying weights, and healthy human subjects.

**METHODS**

**Equipment and output variables**

Two Smart Balance Master systems (NeuroCom Inc., Clackamas, Oregon USA) were used in this study. One was purchased in 1991 (machine A); the other was purchased in 1997 (machine B). The design and specifications of the two machines were the same. Each system consists of (1) a tiltable dual forceplate with four strain gauges under each corner to measure the vertical component of COP, (2) a visual movable enclosure with a computer monitor located in front of the subject, (3) 486 computer and
software system, (4) a fifth strain gauge to measure the horizontal shear force of COP. The strain gauges were calibrated and one strain gauge which read slightly out of range was removed and tested. All strain gauges were in a normal state during the experiments. The SOT consists of six sensory conditions: (1) eyes open and fixed support (EO), (2) eyes closed and fixed support (EC), (3) sway-referenced vision and fixed support (Vs), (4) eyes open and sway-referenced support (Ss), (5) eyes closed and sway-referenced support (ECSs), and (6) sway-referenced vision and support (VsSs). In the Vs condition, the visual enclosure was rotated simultaneously and proportionally with spontaneous sway of the subject, thereby minimizing the sway-related visual feedback. Under this circumstance, the visual feedback conflicted with the somatosensory and vestibular feedback. Under the Ss condition, the support surface was tilted around the ankle joint at the sagittal plane to minimize the sway-related somatosensory feedback from the ankle and foot. Under this condition, the somatosensory input conflicted with the visual and vestibular inputs. In addition, the visual enclosure and the support surface simultaneously tilted synchronously with the spontaneous body sway during the VsSs condition. Each trial of SOT was twenty seconds in duration.

Three computerized output variables were analyzed in this study, i.e., equilibrium score (ES), sway area (SA), and sway velocity (SV). ES is a quotient calculated from the actual peak to peak sway angle and the theoretical maximum sway angle to indicate postural stability. SA is a proportion of actual COP dispersion area to the theoretical limits of stability in a 360-degree plane. SV is a measure of path length divided by trial duration. These outputs are all indicators of postural stability and are not available simultaneously in machines with different versions of NeuroCom software. Machine A is equipped with software version 3.4 and is capable of outputting variables SA and SV. Machine B is equipped with software version 3.2 and is capable of outputting variables SA and ES. Thus SOT data files were analyzed on both machines in order to obtain all three types of data outputs.

Experiment A: Static weight

Standardized dead weights provided by the Center for Measurement Standards at the Industrial Technology Research Institute of the Republic of China were placed on one of the five predetermined locations on the forceplate during each trial. The five locations were center, left rear corner, left front corner, right front corner, and right rear corner. The five locations were chosen to accommodate for the potentially asymmetrical foot positions of human subjects, such as cerebral palsy children and stroke patients. Four weights (20, 40, 60 and 80 kg) were used to include the common range of human body weights. Thus data were collected with each of the 4 weights on each of the 5 locations. For each location and weight combination, 3 trials were repeated before changing to a different location or weight. The sequence of location or weight was balanced between machines. Because dead weights are not affected by changing visual conditions, data were collected under conditions EO, i.e., a fixed support surface condition, and Ss, i.e., a sway-referenced support surface condition.

Experiment B: Swaying weight

The second experiment was conducted with a 1-kg sandbag hanging from a tripod like a pendulum at 45 cm above the force plate (Fig. 1). The base of tripod formed a 40-cm equal length triangle. Weights of 20, 40, 60, and 80 kg were placed symmetrically under the tripod on the force plate to meet the minimum weight requirement of the force plate. For each trial, the sandbag was pulled...
posterior to form an angle about 45° from the perpendicular line and then released to allow rhythmical swaying motion. A thread tied to the tripod marked the end point of pull. In order to decrease the variability from manual pulls and releases, fifteen trials were repeated for each weight. Data were collected under either a fixed support surface condition or a sway-referenced support surface condition.

**Experiment C: Human subjects**

Ten college students (5 males and 5 females) volunteered for this experiment. The characteristics of subjects are listed in Table 1. All the subjects were self-reported healthy. Subjects were tested under all six sensory conditions of the SOT. Three trials were repeated under each condition as recommended by the manufacturer. The testing sequence was balanced between machines among subjects. The subject stood bare feet on the force plate and the width between feet was standardized according to their height.

**Statistical analysis**

For Experiments A and B, two-sample t-tests were used to test the inter-machine differences for variables SA, SV and ES. Multivariate analysis of variance (MANOVA) for repeated measures was used to analyze human subject data. The design was a $2 \times 2 \times 6$ (gender $\times$ machine $\times$ sensory conditions) factorial design. The multiple dependent variables were SA, SV, and ES. Tukey’s HSD procedure was used for post hoc analyses. Pearson’s correlation coefficients were calculated to test the consistency of the two machines with human subjects. The significance level was set at $p<0.05$.

**RESULTS**

The means and standard deviations of SA, SV, and ES with static weights are shown in Table 2. The data were pooled among weights and locations because the means and variability were not different among weights or locations. Significant differences were found between machines with static weights for SA [$t (31)=-6.25, p<0.001$], SV [$t (31)=-8.05, p<0.001$], and ES [$t (31)=9.49, p<0.001$]. The result of swaying weights is shown in Table 3. There was no significant difference between machines for any of the output variables, i.e., SA [$t (7)=-3.42, p<0.11$], SV [$t (7)=-0.99, p<0.35$], and ES [$t (7)=0.42, p<0.69$].

The results of healthy human subjects are shown in Table 4. MANOVA for repeated measures revealed no significant gender differences in any of the output variables, thus the data were pooled between genders in the subsequent statistical analyses. No significant machine effect was found for SA [$F (8,1)=0.39, p>0.39$] and ES [$F (8,1)=1.18, p<0.31$]. However, the SV was significantly different between machine A and machine B [$F$...
Significant condition effects were found for SA \( [F (40,5)=23.57, p<0.001] \), SV \( [F (40,5)=62.05, p<0.001] \), and ES \( [F (40,5)=44.98, p<0.001] \), indicating that postural stability varies significantly under different sensory conditions. Post hoc analyses are reported in Table 5. The SAs under EO, EC and Vs conditions were significantly smaller than the SA under the Ss condition. The SAs under ECSs and VsSs conditions was significantly larger than the SAs under all other conditions. For SV, the data were segregated into two groups. The ECSs and VsSs conditions had significantly larger SV than all other conditions. For ES, the EO and EC conditions were significantly smaller than the VS, Ss, and ECSs conditions. Furthermore, the ES in conditions Ss, ECSs, and VsSs were found to be significantly larger than the other conditions. The Pearson correlation coefficients of output variables showed significant correlations \( (r=0.66 \text{ for SA}, r=0.53 \text{ for SV}, \text{ and } r=0.69 \text{ for ES}) \) between machines \( (p<0.0001) \).

**DISCUSSION**

The results of this study showed that inter-machine consistency of the SOT was fairly good with swaying weights for ES, SV and ES. The inter-machine consistency was fairly good with human subjects for ES and SV. On the other hand, a significant difference between machines was found with static weights for ES, SV and ES. It was observed that the force plate remained perfectly still.
when static weights were placed on machine A. But when static weights were placed on machine B, the force plate was observed to wobble slightly under the sway-referenced testing condition. Correspondingly, the output variables from machine B with static weights showed large fluctuations from the ideal values. In terms of accuracy and repeatability, machine A seems to be superior than machine B. It appears that machine B has worse noise suppression characteristics. Thus the noise level of the two machines was significantly different, showing poor inter-machine consistency with static weights. Despite this large increase in the noise level of machine B, the routine calibration procedure recommended by the manufacturer did not detect any fault with machine B. Further examination of the machine is needed since the origin of excessive noise in machine B could not be ascertained by this experiment. This was, however, beyond the scope of the study.

No differences in any of the output variables were found among different weights or different locations. Thus between the weight range of 20 to 80 kg, the differing distribution of weights on the force plate did not affect the output variables investigated in this study.

This study agreed with previous studies that standing stability is similar between healthy young male and female subjects. This study also agreed with previous studies that human subjects perform differently under varying sensory conditions. Post hoc analyses revealed that the 6 testing conditions were categorized into two groups when the SV variable was used. Yet the testing conditions were categorized into 3 groups when SA and ES were used. Thus the SA and ES were better variables to discriminate the effect of testing conditions. It is further noted that the sequence of increasing values of SA, SV, and ES in our study was consistently as follows: EO, EC, Vs, Ss, ECSs, and VsSs. Previous studies revealed different results, i.e., the VsSs was sequenced prior to ECSs. The effect of age on the sequencing of testing results should be explored in the future.

The correlation analysis revealed significant correlation between two machines with all of the output variables. The better indices to obtain higher inter-machine consistency were SV and ES. Yet significant difference between machines was found with SV when the human subjects were tested. Hence, ES is suggested for use in future studies of SOT to obtain better inter-machine consistency as well as better differentiability among testing conditions.

CONCLUSIONS

The consistency of three computerized output variables between two balance machines was tested with static weights, swaying weights, and healthy human subjects. The static weight experiment revealed a significant difference between machines, showing large inter-machine variations of the noise level. The static weight protocol may be used to detect the degree of deviation of the balance machine in addition to the routine calibration procedure. Inter-machine consistency is satisfactory with swaying weights and with human subjects. In view of both better inter-machine consistency and better differentiability among testing conditions, it is recommended that the ES be selected as the balance index of the SOT.

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