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Original Article

Test-retest reliability of linear and nonlinear measures of postural stability during visual deprivation in healthy subjects

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Abstract. [Purpose] The purpose of this study is to evaluate the reliability of linear and nonlinear measures of the center of pressure (COP) during visual deprivation. [Subjects and Methods] Fifteen young adults participated in this study. COP signals were recorded in two conditions: eyes open and eyes closed. Three trials were performed in each condition with a rest period of approximately 1 min. The intraclass correlation coefficients (ICCs) and standard error of measurement (SEM) were calculated. [Results] The investigation of ICC and SEM between trials showed that the Lyapunov exponent (ICC: 0.76–0.96, SEM: 0.03) and total mean velocity (ICC: 0.71–0.95, SEM: 0.05) were more reliable and repeatable than range and area (95% confidence ellipse), while area had the least reliability (ICC: 0.49–0.77, SEM: 0.56). [Conclusion] The Lyapunov exponent can be considered an appropriate postural control index, and the evaluation of postural stability should be done by considering linear and nonlinear tools.
Key words: Test-retest reliability, Postural stability, Nonlinear measure

INTRODUCTION

Optimal postural control is an essential requirement for performing daily activities. The central nervous system must identify and selectively focus on the sensory inputs (visual, vestibular, and proprioceptive) that are providing the functionally most reliable information[1, 2]. If one or more of these systems fail, or the sensory information is not correctly processed, the risk of a fall or instability increases. As balance is the foundation for all voluntary motor skills, considerable research has been conducted to evaluate the balance performance in patients with low back pain[3–6], anterior cruciate ligament injury[7, 8], and chronic ankle instability[9, 10]. Many variables have been developed from force platform signals to quantify postural steadiness. The center of pressure (COP) is the most common and is defined as the point of application of the ground reaction forces under the feet[11]. COP displacement can be characterized as traditional linear measures. These measures include, but are not limited to, COP length in the anterior-posterior or medial-lateral direction, sway area, and mean COP velocity.

Recently, a nonlinear system approach has been used to estimate dynamic stability by analyzing the time-dependent behavior of kinematic variance of a target trajectory[12, 13]. The maximum finite-time Lyapunov exponent (λmax) is an approach to model the local stability of the system[14]. Mathematically, λmax represents the average rate of the exponential divergence of infinitesimally close trajectories (nearest neighbors) in state space, portraying how the system responds to an extremely small (local) perturbation[15]. A positive λmax indicates that the nearest neighbors will diverge over time (unstable), whereas a negative λmax represents convergent (stable) behavior.

Local dynamic stability has been used in different studies to analyze various concepts, such as trunk movements during

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Table 1. Formulae used to calculate the COP parameters

Parameter	Formula
Range AP (cm)	$\left|y_{max} - y_{min}\right|$
Range ML (cm)	$\left|x_{max} - x_{min}\right|$
Area (cm^2)	$A = 2\pi F_{0.05[z, n-z]}\sqrt{\sigma_x^z \sigma_y^z - \sigma_{xy}^z}$
	Where $\sigma_{xy} = \Sigma \dfrac{(x_1 - x)(y_1 - y)}{n}$
Total mean velocity (cm/s)	$\overline{\upsilon} = \dfrac{2}{r}\Sigma_2^r\sqrt{(x_{t+2} - x_t)^2 + (y_{t+2} - y_t)^2}$
Lyapunov exponent	$y(i) = \dfrac{2}{\Delta t}(lnd_j(i))$

AP: anterior-posterior; ML: medial-lateral

repetitive lifting loads[16], the role of walking velocity in stability[15, 17, 18], and the development of sitting postural control in infants[19].

Like any other measures, postural control measures are not perfectly reliable and are subject to measurement error from three potential sources: the instrument, observer, and variability in the biologic phenomena being measured[20, 21]. In the previous literature, the reliability of traditional linear COP measures was evaluated in different conditions[21–24]. But to the authors' knowledge, no study has determined the test–retest reliability of nonlinear postural stability measures during sensory deprivation. Therefore, the main purpose of the present study is to assess the reliability of the linear and nonlinear measures of the COP during visual privation.

SUBJECTS AND METHODS

Fifteen healthy volunteers (7 males, average ± SD 22.2 ± 0.95 years, 76.0 ± 8.7 kg, 1.77 ± 0.47 m; 8 females, average ± SD 24.0 ± 2.8 years, 62.3 ± 8.7 kg, 1.64 ± 0.73 m) participated in this study. The subjects had no cardiopulmonary disease, neurological disorder, musculoskeletal impairment, or any history of low back pain in the prior 6 months. Subjects were excluded if they had any dizziness, fatigue, any vigorous physical activity, or stress before testing. All the subjects signed an informed consent form approved by the Institutional Ethics Committee of the Tehran University of Medical Sciences.

COP data were recorded by a force platform (Bertec Corporation, Columbus, OH, USA) at a sampling frequency of 500 Hz. The data were stored on a Pentium-based PC and then exported to MATLAB for the calculation of COP parameters. Anterior-posterior and medial-lateral displacement of the COP were measured along the y-axis and x-axis, respectively.

Postural sway was assessed in two different random conditions, including (1) standing on the force platform with eyes open and (2) standing on the force platform with eyes closed.

Subjects stood quietly with their bare feet separated about pelvic-width apart and with their arms resting at their sides. In the eyes-open condition, the subjects were instructed to simply look at a wall approximately 3.5 m in front of their faces. In the eyes-closed condition, the subjects wore a blindfold to eliminate visual input.

Three trials, with a rest period of approximately 1 min, were performed for each condition, and each trial lasted for 30 seconds. The raw data were filtered with a sixth order zero-phase, low-pass Butterworth filter at 10 Hz. The linear parameters calculated from the COP data were anterior-posterior displacement, medial-lateral displacement, total mean velocity, and area (95% confidence ellipse), and the nonlinear parameter was the Lyapunov exponent. The formulae used to calculate each parameter are presented in Table1.

The calculation of the Lyapunov exponent was performed using Chaos data analyzer software. The embedding dimension is a critical parameter to calculate the Lyapunov exponent and its calculation is conducted using a global false nearest neighbor analysis[25]. The global false nearest neighbor analysis describes the minimum number of variables required to form a valid state space from a given time series. The embedded dimension is a description of the number of dimensions needed to unfold the structure of a given dynamic system in space. For consistency in the analysis, the same embedding dimension 3 was used for all files. To create an n-dimensional state-space from the 1-D Euclidean norm of the COP trajectory, the method of the delay Equation 1 was used.

(1) $y(t) = [r(t), r(t+T_d), r(t+2T_d), \ldots r(t+(n-1)\ T_d)]$,

Where y (t) is the n-dimensional state space, r (t) is the original Euclidean norm time series data, n is the number of reconstruction dimensions, and Td is a constant time delay[26].

Table 2. Descriptive data for the COP measures in different sensory conditions (open eyes and closed eyes; n=15)

	Open eyes			Closed eyes		
	Test 1 mean (SD)	Test 2 mean (SD)	Test 3 mean (SD)	Test1 mean (SD)	Test 2 mean (SD)	Test 3 mean (SD)
Range AP	1.97 (0.61)	2.00 (1.07)	1.91 (0.58)	1.91 (0.64)	2.07 (0.91)	1.82 (0.96)
Range ML	1.00 (0.39)	0.90 (0.28)	1.09 (0.47)	0.90 (0.44)	1.00 (0.57)	0.74 (0.31)
Area (95% ellipse)	0.96 (0.61)	0.95 (1.10)	0.80 (0.43)	0.82 (0.72)	0.71 (0.47)	0.63 (0.63)
Total mean velocity	0.47 (0.11)	0.53 (0.11)	0.57 (0.17)	0.56 (0.13)	0.60 (0.19)	0.53 (0.14)
Lyapunov exponent	0.12 (0.07)	0.13 (0.09)	0.13 (0.09)	1.86 (0.53)	1.80 (0.89)	2.23 (0.67)

AP: anterior-posterior; ML: medial-lateral. The units of COP measures are as follows: cm (Range), cm/s (Total mean velocity), and cm^2 (Area); λ is in an arbitrary unit (the Lyapunov exponent).

Table 3. Reliability analysis of COP measures in different sensory conditions (open eyes and closed eyes; n=15)

	Open eyes		Closed eyes	
	ICC (95% CI)	SEM	ICC (95% CI)	SEM
Range AP	0.75 (0.41–0.91)	0.38	0.78 (0.50–0.92)	0.39
Range ML	0.81 (0.55–0.93)	0.17	0.62 (0.10–0.86)	0.27
Area (95% ellipse)	0.37 (0.49–0.77)	0.56	0.73 (0.37–0.90)	0.31
Total mean velocity	0.88 (0.71–0.95)	0.05	0.68 (0.24–0.88)	0.08
Lyapunov exponent	0.90 (0.76–0.96)	0.03	0.75 (0.41–0.91)	0.35

AP: anterior-posterior; ML: medial-lateral

The Lyapunov exponent was then calculated by analyzing the exponential rate of divergence of the initially neighboring trajectories in the reconstructed state space. This was done using an algorithm, where λmax was approximated as the slope of the linear best-fit line created by Equation 2[27].

$$(2) \quad y(i) = \frac{1}{\Delta t} \langle lnd_j(i) \rangle$$

Where $\langle lnd_j(i) \rangle$ represents the average logarithm of displacement, $d_j(i)$, for all pairs of nearest neighbors, throughout a certain number of time steps (iΔt).

SPSS software version 16.0 (SPSS Inc. Headquarters, 233 S., Wacker Drive, Chicago, Illinois 60606, USA) was used to analyze all the data.

The mean of the three trials of assessing the COP parameters in each condition was used for statistical analysis to determine the reliability measures. The alpha level was set at 0.05 for all statistical analyses.

The relative reliability of the measures was assessed using the intraclass correlation coefficient (ICC)[28]. For each ICC, a 95% confidence interval (CI) was calculated to take the sampling distribution into account. Munro's classification for reliability coefficients was used to describe the degree of reliability: 0.00–0.25 (little, if any correlation), 0.26–0.49 (low correlation), 0.50–0.69 (moderate correlation), 0.70–0.89 (high correlation), and 0.90–1.00 (very high correlation)[29]. To assess absolute reliability, we used the standard error of measurement (SEM), calculated as the square root of the mean square error term derived from the analysis of variance table[30].

RESULTS

Table 2 shows the mean and SD of the COP measures for the trials, and Table 3 demonstrates the ICC, its 95% CI and SEM.

No significant differences were found between test and retest mean scores for any COP measures in the two conditions, which indicates the absence of any systematic bias (p>0.05).

In the open eyes condition, very high reliability was found for the Lyapunov exponent (ICC=0.90), high reliability was found for total mean velocity (ICC=0.88), range medial-lateral (ICC=0.81), and range anterior-posterior (ICC=0.75), and low reliability was found for the sway area (95% ellipse) (ICC=0.37).

In the closed eyes condition, high reliability was found for range anterior-posterior (ICC=0.78), the Lyapunov exponent (ICC=0.75), and the sway area (95% ellipse) (ICC=0.73), and moderate reliability was found for range medial-lateral (ICC=0.62).

DISCUSSION

In this study, the within-day test-retest reliability and repeatability of linear and nonlinear measures of a COP time series were investigated for healthy subjects (with open and closed eyes) while quietly standing.

Linear measures, such as the range and length of a path traced by the COP, can quantify the amount of movement of the COP during a specific task or the quantity of variation present in a set of values, independently of their order in the distribution. In contrast, nonlinear measures can best capture the variation in the COP regarding how motor behavior emerges in time, for which the temporal organization in the distribution of values is of interest. Nonlinear measures can provide new insights into the ways that the nervous system controls the complexity of dynamic balance[19, 31]. For example, Newell[32] used COP data from children, adults, and the elderly by measuring standing posture sway and found that children had decreased complexity and dimensionality in relation to the COP. Nonlinear analysis of COP data has also been used to examine differences in standing posture between healthy controls and patients with tardive dyskinesia, and it has found that patients exhibit decreased complexity in their sway patterns[33]. The examples from these studies and several others indicate that nonlinear analysis can reveal the richness or limits of behavioral control options[34] or describe the strategies employed for the organization of the body's degrees of freedom[19].

Our results showed that all linear parameters except the sway area in the open eyes condition presented ICC values ranging from moderate to high reliability, and the Lyapunov exponent showed very high reliability in the open eyes (0.90) and closed eyes (0.75) conditions.

The total mean velocity in the open eyes condition presented the highest ICC (0.88) value compared with all the other linear parameters, while the sway area in the open eyes condition showed the lowest ICC (0.37) value.

Depending on the COP variable, our results can be compared with other studies.

Luoto et al.[35] investigated differences of the balance performance between groups of LBP and healthy subjects. They reported that total mean velocity was the most sensitive and most reliable measure among different COP parameters. Harringe et al.[3] studied the reliability of COP measurements using test-retest design in different conditions (on hard and foam surface with eyes open and eyes closed) in young female gymnasts with low back pain or lower extremity injury. They concluded that quiet stance on foam surface with eyes closed seems to be reliable and sensitive in young female gymnasts. Brown and Mynark[36] assessed balance deficits in recreational athletes with chronic ankle instability during static and dynamic trials. The chronic ankle instability group demonstrated good reliability for the COP excursion length (ICC=0.78–0.86) and velocity (ICC=0.78−0.80) in the static and dynamic conditions. Reliability of the COP excursion area (ICC=0.29−0.51) was low. In another study, Lin et al.[37] assessed the within-day and between-day reliability of several centers of pressure-based measures of postural sway to identify whether there were age-related differences in reliability. They reported that COP mean velocity was the most reliable measure (ICC=0.91–0.95) for within-day and between-day measures in 16 older healthy adults. Salavati et al.[21] investigated the between-days reliability of COP measures in a group of people with musculoskeletal disorders, including low back pain, anterior cruciate ligament injury, and functional ankle instability. The total mean velocity (ICCs of 0.84 and 0.91 for eyes open and eyes closed, respectively) was the best parameter with respect to reliability. Li et al.[22] assessed the reliability and validity of center of pressure-based parameters for balance assessment under three conditions (eyes open, eyes closed, seated) in older adults. Results showed that mean sway velocity in the seated position had the highest reliability (ICC=0.99). Mean sway velocity and path length along the medial-lateral axis were the most reliable balance parameters (ICC=0.94–0.99) in all three conditions.

Regarding the reproducibility of the Lyapunov exponent presented here, no direct comparison can be made because the reliability of Lyapunov exponent analysis of COP data has not been explored for standing tasks.

Kyvelidou et al.[38] investigated the reliability of COP measures for assessing the development of sitting postural control in infants with or at risk of cerebral palsy. The nonlinear parameters of approximate entropy, the Lyapunov exponent, and the correlation dimension for both directions were calculated in the sitting position. Similar to the results of the present study, the Lyapunov exponent showed the highest intrasession (0.64) and intersession (0.78) ICC values in comparison with all other parameters evaluated.

In another study, Donker et al.[39] quantified COP dynamics by the largest Lyapunov exponent (local stability) during visual deprivation. They found that standing with eyes closed decreased local stability (as indexed by an increase in λmax) and increased the variability of the COP time series.

In this study, results showed that the linear and nonlinear investigation of COP data is a reliable method for evaluating postural stability during visual deprivation. The changes of linear parameters were similar to those reports in the literature, with an emphasis on total mean velocity. Regarding the nonlinear measure, the Lyapunov exponent presented a very high ICC value to quantify small changes in the variability patterns of COP data. The results of the present study can be important because future researchers can use the presented COP parameters to assess any balance control impairments and to evaluate the efficacy of treatment for these impairments.

In this study, reliability was evaluated only in young healthy subjects; further studies with greater population and common musculoskeletal or neurological disorders are required to evaluate this method. The nonlinear measure in this study was limited to the Lyapunov exponent. Using different kinds of nonlinear tools, such as approximate entropy and correlation

dimensions, are suggested as considerations for future studies. In this study, increasing task difficulty was created through visual deprivation. More challenging conditions should be established by manipulating other sensory inputs (i.e., vestibular or somatosensory) in future studies.

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