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Generalizability of center of pressure measures of quiet standing

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Abstract

Center of pressure (COP) measures are commonly used as indicators of balance and postural control. At present, there are no universally accepted standards in research investigating fluctuations in the COP with regard to the number of trials or the length of a given trial. The purpose of this study was to use the tools of Generalizability Theory (G-Theory) to investigate the reliability of COP measures of quiet standing and to establish an optimal measurement protocol. G-Theory provides a tool that allows us to break down the sources of variation, or facets, in a measurement procedure and ultimately design a protocol that provides optimal reliability. Fifteen participants completed 10 90-s trials with eyes open and closed. COP measures of anterior–posterior standard deviation (SD_{AP}), medial-lateral SD (SD_{ML}), average velocity (Vel), and 95% confidence ellipse area (Area) were calculated using the first 30, 60, and 90 s of each trial. A G-study and follow-up D-studies were performed to estimate reliability coefficients (*G*-coefficients). The results of the G-Theory analysis suggest that these COP measures reached acceptable levels of reliability ($G \geq 0.70$) with at least five 60 s trials.
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1. Introduction

1.1. Center of pressure analysis of quiet standing

One of the most common assessment tools used to examine balance is the force platform. Balance performance as assessed by these devices is most often expressed using some form of quantification of the fluctuations in the center of pressure (COP). The COP is the single point location of the ground reaction force vector [1]. It is a summary measure representing the movements of all of the body segments while an individual attempts to remain upright. COP has been used to investigate changes in postural control in a variety of healthy and special populations [2–12]. Although, measures of COP are commonly used for assessing balance, there is little standardization in data collection protocol and methods used to analyze fluctuations of the COP [2–12]. In order to compare results across laboratories and participant populations, it is important that reliable protocols and assessment techniques are used. The purpose of the current investigation is to investigate the reliability of common COP measures during quiet standing using Generalizability Theory, in order to propose optimal experimental protocols that produce acceptable levels of reliability.

1.2. Reliability and center of pressure measures

There have been few attempts to establish the reliability of COP measures and provide recommendations on both the length and number of trials that should be used when assessing balance [13,14]. Goldie et al. [13] investigated test–retest reliability using measures of COP and force over two 15 s trials. They found acceptable reliability coefficients

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for actual force measures ($r = 0.71$–0.80), but reliability of the calculated COP measures, including standard deviation in the anterior–posterior and medial-lateral directions, were low ($r = 0.11$–0.30) [13]. Le Clair and Riach [14] also investigated test–retest reliability of the same measures, but included the measure of velocity. They also considered trial length, examining durations ranging from 10 to 60 s. When determining test–retest reliability, they averaged across all trial lengths and found that all measures except vertical force provided acceptable reliability ($r > 0.80$) [14]. The researchers went further to conclude that one trial provided a reliable measure of COP and that optimum reliability was obtained at 20–30 s trial durations [14]. These studies utilized the tools of Classical Test Theory [15] when investigating the reliability of the force platform measures. These tools yield a single reliability coefficient.

In the current approach, we used Generalizability Theory (G-Theory) which yields a reliability coefficient while also providing the ability to determine the sources of variability. G-Theory is a reinterpretation of Classical Test Theory that allows one to investigate the reliability of a measure over a number of measures [16]. G-Theory also allows us to investigate the sources that might contribute to the measurement error. For example, in COP analysis of quiet standing, trial length and number of trials can be factors that influence reliability. Identifying the sources of error make this approach advantageous because it enables researchers to examine which aspects of the measurement procedure influence the reliability of the scores. For example, in a particular behavioral assessment, one could examine the variance associated with the number of judges, number of trials, and days of data collection. In G-Theory these individual sources of variability are referred to as facets [16]. Using this approach, the researcher can then identify sources of error that could possibly lead to poor reliability estimates. This information can be used by the researcher to design a better, more efficient measurement procedure to reduce error and achieve the desired reliability. Specifically, G-Theory, provides an estimate of the variance components of the selected facets, and this information can be used to design a measurement procedure that results in acceptable reliability. The current study investigates how the reliability of common COP measures is affected by the number of trials performed and the length of each trial. This paper employs the tools of Generalizability Theory to establish the reliability of the several common COP measures.

2. Methods

2.1. Participants and procedure

Fifteen healthy college-aged individuals from a major Midwestern university (7 males, 8 females; age: 19.9 ± 1.3 yr, height: 1.69 ± 0.04 m, weight: 72.2 ± 12.5 kg) participated in this study. All participants signed an informed consent form and the University's Institutional Review Board approved this study. All participants were free of orthopedic and neurological conditions. An AMTI force platform (model BP600900) was used for data collection. All data were collected at 100 Hz and exported to MATLAB (version 6.0) for calculation of parameters. Data were filtered using a fourth order Butterworth, zero-phase low-pass filter at 5 Hz.

All participants completed 10 90 s trials with eyes open followed by 10 90 s trials with eyes closed. Participants were barefoot and instructed to stand quietly with arms at their side and to look at a picture placed 5 m in front at eye level. Rest periods of 30–60 s were given between trials as necessary.

2.2. Measurements

Parameters were calculated for trial lengths of 30, 60, and 90 s. The 30 s trial length was calculated using the first 30 s of the 90 s trial, the 60 s trial was calculated using the first 60 s of the 90 s trial, and the 90 s trial was calculated using the entire trial. These trial lengths were used because they are representative of the majority of trial lengths used when collecting quiet standing data [5,13,14]. Parameters used during this study were drawn from Prieto et al. [5]. Each parameter is briefly described below.

2.2.1. Standard deviation of center of pressure

Standard deviation of the COP provides a measure of the variation in the distribution of the COP position. The standard deviation of the COP was measured, from a zero-mean adjusted central position, separately for the anterior–posterior (AP) and medial-lateral (ML) COP data using the following equations:

$$\mathrm{SD_{AP}} = \left[\frac{\sum_{n=1}^{N}\left(x_{\mathrm{AP}(n)} - \bar{x}_{\mathrm{AP}}\right)^2}{N}\right]^{1/2} \quad (1)$$

$$\mathrm{SD_{ML}} = \left[\frac{\sum_{n=1}^{N}\left(x_{\mathrm{ML}(n)} - \bar{x}_{\mathrm{ML}}\right)^2}{N}\right]^{1/2}. \quad (2)$$

In these equations x_{AP} and x_{ML} represent the position of the COP in the AP and ML direction, respectively, and $\bar{x}_{\mathrm{AP}}$ and $\bar{x}_{\mathrm{ML}}$represent the zero-mean adjusted central position of the COP in the AP and ML direction. N is the total number of data points for the given trial length. It is assumed the N is large enough that $N \approx N - 1$.

2.2.2. Velocity

The average velocity of the COP was calculated by taking the total distance traveled and dividing it by the time of the trial (T):

$$\mathrm{Vel} = \frac{\sum_{n=1}^{N-1}\left[\left(x_{\mathrm{AP}(n+1)} - x_{\mathrm{AP}(n)}\right)^2 + \left(x_{\mathrm{ML}(n+1)} - x_{\mathrm{ML}(n)}\right)^2\right]^{1/2}}{T}. \quad (3)$$

2.2.3. 95% Confidence ellipse area

The 95% confidence ellipse area is a measure of the area that the COP traverses. It is determined by taking the radius of the major and minor axes and then fitting an ellipse that would include 95% of the points:

$$\text{Area} = \pi ab \tag{4}$$

where $a = [3.00(\text{SD}_{\text{AP}}^2 + \text{SD}_{\text{ML}}^2 + D)]^{1/2}$ for the major axis, $b = [3.00(\text{SD}_{\text{AP}}^2 + \text{SD}_{\text{ML}}^2 - D)]^{1/2}$ for the minor axis, $D = [(\text{SD}_{\text{AP}}^2 + \text{SD}_{\text{ML}}^2) - 4(\text{SD}_{\text{AP}}^2\text{SD}_{\text{ML}}^2 - \text{SD}_{\text{AP ML}}^2)]^{1/2}$, and

$$\text{SD}_{\text{AP ML}} = \left(\sum_{n=1}^{N} x_{\text{AP}(n)} x_{\text{ML}(n)}\right)/N.$$

In determining the major and minor axis, 3.00 represents the F statistic at a 95% confidence level ($F_{0.05[2,n-2]}$) for a bivariate distribution with n data points, where n is significantly large ($n > 120$) [5]. $\text{SD}_{\text{AP ML}}$ is the covariance.

2.3. Data analysis

The calculated parameters were exported to a specialized Generalizability analysis program (GENOVA, version 2.2, CASMA, Iowa City). A Generalizability analysis was conducted to determine the effect of (a) individual participant characteristics, (b) number of trials (1–10) used for analysis, and (c) length of trial or sampling length at 30, 60 and 90 s. A fully crossed 15(participant) × 10(number of trials) × 3(length of trials) random effects repeated-measures ANOVA design was used. The Generalizability analysis was performed on both eyes open and closed trials.

2.4. Generalizability Theory

Generalizability Theory (G-Theory) goes beyond the Intra-class Correlation Coefficient (ICC) by examining the error variances using analysis of variance procedures [16]. In fact, the ICC can be considered a special case of G-Theory. In G-Theory, there are two types of studies: one identifies the contribution of the facets to the total error by estimating the variance components of the facets (Generalizability study); and the other examines various designs of measurement procedures to select the appropriate model to use in data collection as a function of acceptable reliability (Decision study). A more detailed description of this theory and technique are presented in Shavelson and Webb [16].

2.5. Generalizability study

The facets, or potential sources of error, identified in this study were participants (P), number of trials (T), and length of trials (L). Facets may be considered fixed or random depending on the study's design, purpose, and variable used. For our study, we only sampled a few number of trials and lengths of trials out of many possible values; therefore, we considered the facets random. A repeated-measures ANOVA was then performed to provide the mean square values for the facets and interactions. The interactions in this study were participant by number of trials ($P \times T$), participant by length of trial ($P \times L$), number of trials by length of trial ($T \times L$), and the participant by number of trials by length of trial combined with the residual error ($P \times T \times L$, e). Mean square error values from the repeated-measures ANOVA were used to calculate the variance component of each facet and interaction [16]. The relative contributions of each variance component to the overall measurement error were then calculated by summing the variance components for all facets and interactions for a given trial length and condition, and then dividing the individual facet and interaction variance components by the total. This results in a percentage of the variance for each of the facets and interaction (P; T; L; $P \times T$; $P \times L$; $T \times L$; and $P \times T \times L$, e), which is an indication of how much of the measurement error can be attributed to that facet or interaction. The information obtained in the G-study was then used in Decision studies to determine the most effective measurement protocol.

2.6. Decision studies

After the G-study, a series of Decision studies (D-studies) were completed. These enable the researcher to examine many measurement designs for efficiency and practicality. The reliability coefficient produced in the D-study is the G-coefficient (G). This coefficient is based on the design parameters [16]. This means, if a researcher identified a facet in the G-study as a major source of error, such as the number of trials, then that facet could be altered in the measurement model to reduce the variance component. The G-coefficient is a norm referenced reliability estimate which is used to quantify how well a participant's observed scores correspond to the universe of scores and can be considered equivalent to the reliability coefficient (r) in Classical Test Theory [16]. The G-coefficient is represented as

$$G = \frac{\sigma_P^2}{\sigma_P^2 + \sigma_{\text{Rel}}^2} \tag{5}$$

where σ_P^2 is the variance of the participants, and σ_{Rel}^2 is the relative error variance component, i.e., the variance due to interaction between the object of measurement (participants) and the other facets. A G-coefficient value of 0.8 or above is desirable, with a value of 0.7–0.79 considered acceptable [16].

3. Results

Descriptive results of the AP standard deviation, ML standard deviation, velocity, and 95% confidence ellipse area, based on 10 eyes open (EO) or eyes closed (EC)

Table 1
G-coefficients for eyes open trials

Trial	SD_{AP}			SD_{ML}			Vel			Area		
	30	60	90	30	60	90	30	60	90	30	60	90
1	0.30	0.42	0.48	0.32	0.42	0.47	0.64	0.67	0.68	0.33	0.44	0.50
2	0.43	0.56	0.62	0.44	0.55	0.61	0.77	0.80	0.81	0.44	0.57	0.63
3	0.50	0.63	0.69	0.49	0.62	0.67	0.83	0.85	0.86	0.49	0.63	0.69
4	0.55	0.68	0.74	0.53	0.65	0.71	0.86	0.88	0.89	0.53	0.66	0.72
5	0.58	0.71	0.76	0.55	0.68	0.74	0.88	0.90	0.91	0.55	0.69	0.75
6	0.60	0.73	0.78	0.57	0.70	0.75	0.90	0.92	0.92	0.57	0.70	0.76
7	0.62	0.75	0.80	0.58	0.71	0.77	0.91	0.93	0.93	0.58	0.71	0.78
8	0.63	0.76	0.81	0.59	0.72	0.78	0.92	0.93	0.94	0.59	0.72	0.78
9	0.65	0.77	0.82	0.60	0.73	0.79	0.92	0.94	0.94	0.60	0.73	0.79
10	0.65	0.78	0.83	0.61	0.74	0.79	0.93	0.94	0.95	0.60	0.74	0.80

G-coefficients for each COP measure are based on inclusion of data from 1 to 10 trials and 30 s, 60 s, or 90 s trial lengths.

trials—each sampled for 30 s, 60 s, or 90 s intervals, are available via electronic addendum. The descriptive results of this study are consistent with the results of previous studies [5]. G-study results for each COP measure are also available via electronic addendum and are summarized below. Results of the G-study are provided as a percentage of overall variance that can be contributed to each individual facet.

3.1. Number of trials facet

The number of trials did not contribute substantially to the overall variance in any of the selected measures. The relative variance contribution for the number of trials facet (T) ranged from 0% to 1.23% of the overall variance for any of the COP measures and visual conditions studied. The percentage of variance contributed to the interaction of participants and number of trials ($P \times T$) ranged from 13.54% (SD_{AP}, EC) to 39.76% (SD_{AP}, EO). The interaction with participant contributed considerably more to the relative variance. This indicates a greater variance within a participant from trial to trial.

3.2. Length of trial facet

The length of trial contributed slightly more to the overall variance than the number of trials. The relative variance contribution for the length of trial facet (L) ranged from 1.9% (Vel, EC) to 7.55% (SD_{AP}, EC). The interaction with participant attributed slightly more to the relative variance in the measures. The percentage of variance attributed to the interaction of participants and length of trial ($P \times L$) ranged from 0.97% (Vel, EO) to 15.44% (SD_{ML}, EC; Area, EC).

3.3. Residual error variance

A large portion of the variance for each measure and condition can be attributed to the interaction of all of the facets and the residual error ($P \times L \times T$, e). The residual facet ($P \times L \times T$, e) accounts for the interaction of all the facets, and error attributed to unidentified facets. The relative variance attributed to the residual error ranged from 7.34% (Area, EO) to 41.67% (SD_{AP}, EC).

3.4. Decision studies

Tables 1 and 2 present the *G*-coefficients for each COP measure by number and length of trial. The 95% confidence ellipse measure during EO trials reached acceptable levels of reliability ($G \geq 0.70$) based on four trials at lengths of 90 s ($G = 0.72$) or six trials at 60 s ($G = 0.70$). The confidence ellipse did not have *G*-coefficients above 0.70 for 30 s trial lengths. This measure with eyes closed showed better *G*-

Table 2
G-coefficients for eyes closed trials

Trial	SD_{AP}			SD_{ML}			Vel			Area		
	30	60	90	30	60	90	30	60	90	30	60	90
1	0.41	0.44	0.46	0.42	0.51	0.54	0.65	0.68	0.69	0.45	0.52	0.55
2	0.57	0.61	0.63	0.58	0.66	0.70	0.79	0.81	0.82	0.61	0.67	0.70
3	0.66	0.70	0.71	0.66	0.74	0.77	0.84	0.86	0.87	0.68	0.75	0.77
4	0.72	0.75	0.77	0.71	0.78	0.81	0.87	0.89	0.90	0.73	0.79	0.81
5	0.76	0.79	0.80	0.74	0.81	0.84	0.89	0.91	0.92	0.76	0.82	0.84
6	0.78	0.82	0.83	0.77	0.83	0.86	0.91	0.92	0.93	0.78	0.84	0.86
7	0.81	0.84	0.85	0.79	0.85	0.87	0.92	0.93	0.94	0.80	0.85	0.87
8	0.82	0.85	0.86	0.80	0.86	0.88	0.93	0.94	0.94	0.81	0.87	0.88
9	0.84	0.87	0.88	0.81	0.87	0.89	0.93	0.94	0.95	0.82	0.88	0.89
10	0.85	0.88	0.89	0.82	0.88	0.90	0.94	0.95	0.95	0.83	0.88	0.90

G-coefficients for each COP measure are based on inclusion of data from 1 to 10 trials and 30 s, 60 s, or 90 s trial lengths.

coefficients (Table 2), reaching an acceptable level based on four 30 s trials ($G = 0.73$) or three 60 s trials ($G = 0.75$). Similar to the 95% confidence ellipse area, the measures of COP standard deviation also showed improved reliability during the eyes closed condition. Anterior–posterior standard deviation (SD_{AP}) with eyes closed reached acceptable reliability levels based on four 30 s trials ($G = 0.71$) or three 60 s trials ($G = 0.70$). Whereas, SD_{AP} with eyes open reached an acceptable reliability after five 60 s trials ($G = 0.71$). The 30 s trial length did not produce the acceptable level of reliability for the eyes open condition. Similarly, medial-lateral standard deviation (SD_{ML}) with eyes closed reached an acceptable level of reliability after four 30 s trials ($G = 0.72$) or three 60 s trials ($G = 0.70$). SD_{ML} with eyes open did not reach an acceptable level of reliability until six 60 s trials. Of all measurements included in this study, velocity reached acceptable reliability with the least number of trials. COP velocity with EO or EC had *G*-coefficient values of 0.77 and 0.79, respectively, based on two trials at 30 s trial length.

4. Discussion

Traditional measures of COP using a force platform continue to be a part of the analysis of quiet standing. These measures are simple to compute and interpret. As long as these measures continue to be used, every attempt should be made to establish the most reliable measurement techniques. At present there is not wide spread agreement on the length of trial and number of trials that should be used when collecting data during quiet stance. The purpose of this study was to examine the reliability of common COP measures used during force platform analysis of quiet standing.

Determining the optimal trial length depends on several factors including the population studied and desired measures. Results from the G-study indicate that the trial length did not contribute substantially to the overall variance. However, to reach an acceptable level of reliability, longer trial lengths were needed for several measures. All measures during the eyes closed condition produced acceptable reliability when the trial length was only 30 s (Table 2). Using shorter trial lengths, however, necessitates increasing the number of trials to reach satisfactory levels of reliability during data collection.

The eyes open condition presents more of a problem for establishing a reliable measure. During the eyes open condition, only the velocity measure attained acceptable reliability with a trial length of 30 s. Commonly used measures of standard deviation of the COP in the AP and ML directions and 95% confidence ellipse area did not achieve acceptable levels of reliability unless the trial length was 60 s. The trend of improved reliability at fewer trials and shorter trial durations can be attributed to the *G*-coefficient formula (Eq. (5)). The relative error variance term calculates the error attributable to the object of measurement (participants) and its interactions with the other identified facets. If the variance attributable to the interactions with the object of measurement is reduced, the relative error variance term will also be reduced, and in turn the *G*-coefficient will be increased. This is the case with the results of the current study and provides a possible explanation for the need for more trials at longer durations with eyes open.

Some researchers have argued that only the first trial of data collection should be used due to a learning response in relation to multiple trials even with simple tasks such as quiet standing [17]. It has also been reported that a single trial can provide reliable measures [14]. Using Generalizability Theory, the results from our investigation, however, suggest that multiple trials are necessary to attain COP measurements that accurately represent the universe of scores. Through D-studies, we found that the number of trials needed to produce reliable measures is related to the length of trials that are being collected and the measure being used. As expected, the results of this investigation indicate that longer trials generally provide a more reliable measure. A review of the literature indicates that trial lengths are often only 15–30 s with one to three trials of data being collected [5,13,14]. Depending on the measurement of interest, based on our results, this approach is not sufficient to attain reliable results.

A few notes are warranted with regard to this study. Our results were obtained with young, healthy adults. Assessments of reliability might vary significantly in populations not considered in this study (e.g., elderly, Parkinson's), where conducting five 60 s trials might be too demanding for the participants to complete. Furthermore, in this study, we derived the 30 and 60 s trial data from a 90 s trial. We used this technique to reduce the possibility of variance from another facet, i.e., multiple test days where only 30 s, 60 s, or 90 s trials were recorded. By deriving the trial data from a single trial, we acknowledge it is likely that these data are correlated and not independent: however, repeated-measures design and the use of G-Theory do not require uncorrelated independent data [15,16]. For trial lengths longer than 90 s, the G-study results provided in Tables 3–6 in the electronic addendum can be used to perform additional D-studies to assess optimal trial lengths and numbers for these trials. The possible effect of subject fatigue during these longer trials should be considered, however, as fatigue may result in significant measurement variability.

In summary, based on the results of this study and acceptable levels of reliability ($G \geq 0.7$), it is suggested that researchers employ trial lengths of 60 s and no less than five trials be used when utilizing the measurements of COP investigated in this study. This is a compromise across all of the measurements included in this study. This combination of trial number and length produces acceptable reliability for the majority of measures and conditions investigated. For those situations that did not quite reach the acceptable reliability level (SD_{ML} EO; $G = 0.68$ and Area EO; $G = 0.69$), results indicate that reliability is extremely close to the acceptable range and increasing the number of trials

does not result in large gains in reliability. Generalizability Theory provides researchers with an alternative to the Classical Test Theory when investigating reliability of measurements. Generalizability Theory is a simple yet powerful tool that can aid researchers in designing optimal measurement techniques.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gaitpost.2006.03.004.

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