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Generalizability of Stabilogram Diffusion Analysis of center of pressure measures

Richard J. Doyle [a,b], Brian G. Ragan [c], Karthikeyan Rajendran [d], Karl S. Rosengren [a,e], Elizabeth T. Hsiao-Wecksler [f,*]

[a] Department of Kinesiology and Community Health, University of Illinois at Urbana-Champaign, USA
[b] College of Medicine, University of Illinois, Chicago, USA
[c] Department of Health, Physical Education & Leisure Services, University of Northern Iowa, USA
[d] Department of General Engineering, UIUC, USA
[e] Department of Psychology, UIUC, USA
[f] Department of Mechanical Science and Engineering, 124 Mechanical Engineering Building, MC-244, 1206 West Green Street, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA

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Abstract

Quiet standing balance and postural control are often assessed by drawing information from center of pressure (COP) data collected with a force platform. Efforts to better understand the underlying processes involved in postural control have lead to methods that examine the dynamic or stochastic characteristics of the COP. One method that has recently gained popularity is Stabilogram Diffusion Analysis (SDA). There is, however, a lack of standardization in the methodology of data collection for this approach, i.e., how many trials to include and how long to sample a trial. The purpose of this study was to use the tools of Generalizability Theory (G-Theory) to investigate the reliability of SDA 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 young, healthy participants completed ten 90-s trials: first with eyes open and then eyes closed. Common measures of SDA were calculated using the first 30, 60 and 90 s of each trial. G-Theory through a Generalizability Study (G-study) and follow-up Decision Studies (D-studies) were performed to estimate reliability coefficients (*G*-coefficients). The fully crossed facets included were participants (P), length of trials (L) and number of trials (T). Results of this study suggest that at least five 60 s trials should be used when using the selected measures of SDA. These guidelines address acceptable reliability and the gains achieved by adding trials or increasing trial length.

Keywords: Postural control; Balance; Posturography; Quiet standing; Reliability

1. Introduction

1.1. Center of pressure analysis of quiet standing

Understanding the control processes functioning during quiet standing has lead to numerous techniques of data collection and analysis. In terms of data collection and interpretation, the force platform has surfaced as the preferred tool for assessment. The force platform output is usually reported as some quantification of the center of pressure (COP). Typically summary measures, such as standard deviation, sway velocity, or swept area are used to quantify the COP profile [1]. Although these type of measures are the most frequently reported, many researchers also include measurements that address the dynamic nature of COP motion. Stabilogram Diffusion Analysis (SDA) has emerged as a common technique for this specific purpose. SDA uses the tools of statistical mechanics to extract more meaningful physiological information from the COP profile [2]. This type of analysis produces several measures that describe the stochastic and deterministic nature of the COP

* Corresponding author. Tel.: +1 217 333 3415; fax: +1 217 244 6534.
E-mail address: ethw@uiuc.edu (E.T. Hsiao-Wecksler).

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profile. Numerous studies have used measures of SDA as an indication of postural control, e.g., [3–8], however little information about the reliability of SDA has been reported [2,9]. The purpose of the current study was to investigate more rigorously the reliability of SDA measures during quiet standing using Generalizability Theory (G-Theory) [10,11], in order to propose optimal experimental protocols that produce acceptable levels of reliability.

1.2. Stabilogram Diffusion Analysis

SDA assumes that the COP during quiet stance can be modeled as a system of coupled, correlated random walks [2]. SDA provides several measures that quantify the stochastic behavior of the COP profile and these measures are intended to provide information on the underlying control processes at work during quiet standing. The *diffusion coefficient* (D) is an average measure of the stochastic activity of a random walker and can be thought of as an indicator of the relative stability of the system. The *scaling exponent* (H) provides an indication if the motion of a particle (i.e., COP) is more or less likely to continue moving in the same direction that it is currently moving. If the squared distance between two points on the COP profile is plotted against the time interval that they are separated by, it becomes apparent that there are at least two distinct regions on the plot (a short-term region, which tends to be below 1–2 s, and a long-term region of larger time intervals). This transition point is referred to as the critical point. It is quantified by the *critical point coordinates*—the critical time interval (CT) and critical value (CV). The critical point has been suggested to give an indication of when postural control changes from a primarily open-loop to a primarily closed-loop control process [2]. Diffusion coefficients and scaling exponents can be determined for both the short- and long-term regions of the plot. For a detailed review see Ref. [2]. It should be acknowledged that alternative methods of investigating the dynamic nature of the COP profile exist (e.g., [12–14]). We focused our investigation on the reliability of the measures calculated using the SDA approach proposed by Collins and De Luca [2].

Studies that use SDA as the primary analysis technique have employed a variety of methods to collect data. In particular, the number of trials used in past research has ranged from 1 to 10 trials and the individual trials have varied from 30 to 90 s in length [2,3,15]. In addition to the inconsistent methodology employed in different studies, relatively little reliability information has been reported [2,9]. Collins and De Luca [2] reported the Intra-class Correlation Coefficients (ICC) on participants ($n = 10$) that completed 30 trials at 30 s of length with eyes open. ICC values were calculated on three scores; one from the first 10 trials, one from the second 10 trials, and one from the final 10 trials. They indicated that this system of summing over multiple trials to calculate a single score was employed because studies that investigate diffusion type processes typically use either a relatively long time series or a relatively large number of smaller time series. In their study, the reliability of diffusion coefficients, scaling exponents, and critical time and distance values were all found to be fair to excellent, ranging from 0.46 to 0.92. The lone exception was for the critical time value in the medial–lateral direction, which produced poor reliability ($r = 0.04$). Schiffman et al. [9] calculated ICC values, but only for the scaling exponent. These researchers examined the effect of repeated testing after a 7-day period. They reported fair to excellent reliability ($r = 0.49$–0.84) on all values except for the medial–lateral long-term values ($r = 0.18$). Both of these studies utilized Classical Test Theory [16] when investigating the reliability of the SDA. This approach yields a single overall measure of reliability and does not provide any information about the source of variability.

1.3. Generalizability Theory

Generalizability Theory is a statistical technique intended to provide researchers with the tools to investigate measurement design and reliability. Cronbach et al. originally introduced the theory to address the weaknesses of Classical Test Theory [17]. In G-Theory, and for that matter Classical Test Theory, observed scores are composed of the true score (T) and an error component (E). In Classical Test Theory, E is singular and undifferentiated. In other words anything that contributes to the difference between the observed score and the true score is lumped into this single term. The strength of G-Theory is partially due its ability to untangle this error term. Potential sources of variance, or facets, are identified and investigated individually through a series of analysis of variance (ANOVA) procedures. Specifically G-Theory permits us to identify potential sources of variance, manipulate those sources, and design a measurement protocol that satisfies our established level of reliability. The purpose of this study was to use the tools of G-Theory to investigate the effect of the number of trials and length of these trials on the reliability of SDA.

2. Methods

2.1. Participants and procedure

Fifteen healthy college-aged individuals from a large midwestern university (7 male, 8 female; age: 19.9 ± 1.3 years, height: 1.69 ± 0.04 m, weight: 72.2 ± 12.5 kg) completed this study[1]. (This sample size provides similar variances as previous reliability assessments [2], suggesting that the sample is representative of the study group.) The University's Institutional Review Board for Human Studies approved this study and all participants were required to sign an informed consent form prior to participation in this study. Participants were screened for orthopedic and

[1] This dataset has been used previously for an investigation into reliability of traditional measurements of COP [1].

neurological conditions that would interfere with data collection. All trials were collected at 100 Hz on an AMTI force platform (model BP600900, Watertown, MA). Data were exported to MATLAB (version 6.0) for calculation of SDA parameters. Participants completed twenty 90 s trials; the first 10 with eyes open followed by 10 with eyes closed. Participants were barefoot and instructed to stand quietly with arms at their side. Participants were asked to focus on a picture placed 5 m in front of them at eye level. Rest periods of up to 60 s were given between trials as necessary.

2.2. SDA measurements

Trials were divided to extract 30, 60, and 90 s trials for each individual trial completed. The first portion of each individual trial was used for the trials shorter than 90 s (i.e., 30 s trial was first 30 s of 90 s trial, etc.). These trial lengths were selected because they represent typical trial lengths used in SDA studies [2–4]. Measurements were calculated separately for anterior–posterior, medial–lateral, and radial directions (for detailed methodology see Ref. [2]). The *diffusion coefficient* (D) is a measure of the average stochastic activity that is present in a moving particle (i.e., COP) [2]. D is one half of the slope of a resultant linear–linear plot of the mean square COP distance ($\langle \Delta j^2 \rangle$) as a function of the time interval between assessment points (Δt), where Δj represents the distance in the AP, ML, or radial direction for a given Δt. The *scaling or Hurst exponent* (H) describes the relationship between successive COP locations at increasing time intervals. H is one half of the slope of a resultant log–log plot of $\langle \Delta j^2 \rangle$ as a function of Δt. Slopes were determined using the method of least squares [2]. The point of intersection between the short- and long-term regions of the linear–linear plot is the critical point C [2]. The coordinates for the critical point (CT, CV) provide the measures of the *critical time interval*, i.e., $CT = \Delta t_c$, and *critical value*, $CV = \langle \Delta j^2 \rangle_c$. SDA parameters were calculated based on the algorithm and MATLAB code by Collins and Stamp [18].

2.3. Data analysis

SDA parameters for the 30, 60, and 90 s trials were exported to a specialized Generalizability analysis program (GENOVA, version 2.2, CASMA, Iowa City). Generalizability analysis was conducted to determine the effect of: (a) individual participant characteristics, (b) number of trials included (1–10) for analysis, and (c) length of trial (30, 60, 90 s). The number of trials included in this study is a product of the measurement technique. All trials collected were included in the calculation of SDA parameters as the number of trials increased. In other words, two trials represents the score using all of the data from the first two trials, three trials represents the score using all of the data from the first three trials, and so on. This method was employed because it is assumed that diffusion type analyses benefit from increased data [2]. A fully crossed 15 (participant) × 10 (number of trials) × 3 (length of trials) random effects repeated-measures ANOVA design was used and Generalizability analysis was performed separately for the eyes open and eyes closed trials.

2.4. Generalizability Theory

In order to derive more useful information on designing a reliable measurement protocol, we employed the techniques of Generalizability Theory. G-Theory is often thought of as a liberalization of Classical Test Theory that uses the applications of analysis of variance procedures to investigate measurement reliability [11]. G-Theory analysis is completed through a series of studies: first a Generalizability Study (G-study) that determines the contribution of individual facets and facet interactions contribution to the measurement variance, and then a series of Decision Studies (D-studies) which use the results of the G-study to design a measurement protocol that reaches a desired reliability level.

2.5. Generalizability Study

In the current study, the facets identified as potential sources of variance were participants (P), number of trials (T), and length of trials (L). A repeated-measures ANOVA was then performed to provide the expected mean square values for the facets (P, T, and L) and interactions (P × T; P × L; T × L; P × T × L, e). The term, ''e'', in the final interaction represents error that can be attributed to unidentified facets that may not have been included in the present study, for example participant physical or psychological characteristics and environmental factors. The residual facet (P × L × T, e) accounts for the interaction of all of the facets and this error. Mean square error values from the repeated-measures ANOVA were used to represent the variance component of each facet and interaction [10,11]. Variance component values are summed, then each is divided by the total to give a percentage of overall variance that can be contributed to that facet or interaction. Information obtained in the G-study was then used in Decision Studies to determine the measurement protocol that reached a desired reliability level.

2.6. Decision Studies

The purpose of the D-study is to use the information gained from the G-study on the variance components to design a measurement protocol that minimizes error and maximizes reliability [10]. D-studies manipulate the identified facets providing feedback on the reliability of different measurement designs in the form of the G-coefficient (G). The G-coefficient is an analogue to the reliability coefficient (r) of the Classical Test Theory [10,11]. G-coefficient values of 0.8 or higher are desired with 0.7–0.79 considered acceptable [16].

3. Results

Descriptive results for SDA parameters in the anterior–posterior, medial–lateral, and radial direction, based on 10 eyes open (EO) or eyes closed (EC) trials—each sampled for 30 s, 60 s, or 90 s intervals, are summarized in Tables 1–3. The descriptive results of this study are comparable with results of previous studies [12,19]. Detailed G-study results for each SDA measure are available via electronic addendum, but are summarized below.

3.1. Generalizability Study

G-study results give an indication of how much each of the identified facets contributes to the overall variance observed in actual measurements. The number of trials (T) contributed relatively little to the overall variance in any of

Table 1
Mean (standard deviation) diffusion coefficients [mm^2/s] for 10 trials at given sampling times and visual conditions

Variable	Eyes open			Eyes closed		
	30 s	60 s	90 s	30 s	60 s	90 s
$D_{S,AP}$	8.68 (3.24)	7.86 (2.89)	7.73 (3.08)	15.71 (6.72)	13.55 (5.73)	12.81 (5.60)
$D_{L,AP}$	1.87 (1.66)	1.75 (1.23)	1.49 (1.043)	1.31 (1.01)	1.27 (0.89)	1.29 (1.13)
$D_{S,ML}$	2.37 (1.05)	2.02 (0.83)	1.94 (0.86)	2.80 (1.47)	2.51 (1.34)	2.39 (1.32)
$D_{L,ML}$	0.23 (0.20)	0.21 (0.20)	0.20 (0.18)	0.25 (0.22)	0.28 (0.30)	0.27 (0.25)
$D_{S,R}$	11.00 (3.91)	9.87 (3.40)	9.65 (3.73)	18.48 (7.54)	16.03 (6.61)	15.19 (6.49)
$D_{L,R}$	2.10 (1.75)	1.97 (1.75)	1.69 (1.30)	1.58 (1.13)	1.56 (1.04)	1.60 (1.30)

S and L: short- and long-term region; AP, ML, and R: anterior–posterior, medial–lateral, and radial directions, respectively.

Table 2
Mean (standard deviation) scaling exponents for 10 trials at given sampling times and visual conditions

Variable	Eyes open			Eyes closed		
	30 s	60 s	90 s	30 s	60 s	90 s
$H_{S,AP}$	0.81 (0.04)	0.83 (0.04)	0.85 (0.04)	0.86 (0.04)	0.88 (0.4)	0.90 (0.03)
$H_{L,AP}$	0.25 (0.10)	0.26 (0.08)	0.24 (0.08)	0.15 (0.07)	0.15 (0.06)	0.15 (0.05)
$H_{S,ML}$	0.78 (0.06)	0.80 (0.06)	0.82 (0.06)	0.79 (0.04)	0.81 (0.04)	0.82 (0.05)
$H_{L,ML}$	0.18 (0.09)	0.20 (0.08)	0.20 (0.08)	0.18 (0.09)	0.21 (0.08)	0.22 (0.07)
$H_{S,R}$	0.80 (0.03)	0.82 (0.03)	0.84 (0.04)	0.84 (0.04)	0.87 (0.03)	0.88 (0.03)
$H_{L,R}$	0.24 (0.09)	0.25 (0.08)	0.23 (0.08)	0.15 (0.07)	0.16 (0.06)	0.16 (0.05)

S and L: short- and long-term region; AP, ML, and R: anterior–posterior, medial–lateral, and radial directions, respectively.

the selected measures. The variance contribution for T ranged from 0% to 12.3% of the overall variance for the SDA measures and visual conditions. The interaction between participants and trials (P × T) contributed considerably more than the number of trials to the relative variance. The percentage of variance contributed to the interaction P × T ranged from 3.8% to 31.3%. These results indicate that variance was greater within the individual participant from trial to trial when compared to the variance across participants from trial to trial. The length of trial (L) facet contributed slightly more to the overall variance than the number of trials facet (0–27.6%). The interaction with participant (P × L) contributed a similar amount to the relative variance in the measures (1.3–25.6%). For all measures and conditions included, the majority of the variance was attributable to differences in the participant. Relative variance attributed to participant ranged from 32.2.4% to 88.4%. In contrast, a relatively small portion of the variance for all measures (1.4–26.1%) was attributable to the residual facet (P × L × T, e).

3.2. Decision Studies

Figs. 1–3 present the *G*-coefficients for each SDA measure and visual condition by number and length of trial. Diffusion coefficients for all conditions tested reached acceptable ($G \geq 0.70$) reliability by the second trial at 30 s length of trial, with the majority of measures exceeding this level within a single trial (Fig. 1). Scaling exponents in the medial–lateral direction reached acceptable levels of reliability for 30 s trial lengths within one to three trials (Fig. 2). Scaling exponents in the anterior–posterior direction did not reach acceptable reliability levels until trial seven for eyes open and trial eight for the eyes closed condition at 30 s trial lengths (Fig. 2). Scaling exponent measures in the radial direction reached acceptable levels for a 60 s trial length within five trials for eyes-open conditions and three trials for eyes-closed conditions. All critical point coordinate measures displayed acceptable levels of reliability within one to four trials at 30 s trial lengths (Fig. 3).

Table 3
Mean (standard deviation) critical point coordinates, critical time interval [s] and critical value [mm^2], for 10 trials at given sampling times and visual conditions

Variable	Eyes open			Eyes closed		
	30 s	60 s	90 s	30 s	60 s	90 s
CT_{AP}	1.09 (0.32)	1.14 (0.38)	1.09 (0.32)	1.11 (0.34)	1.15 (0.34)	1.21 (0.44)
CV_{AP}	13.55 (6.41)	13.40 (7.08)	12.85 (7.59)	24.00 (12.26)	22.20 (10.03)	23.34 (15.30)
CT_{ML}	1.06 (0.21)	1.07 (0.19)	1.06 (0.18)	1.09 (0.24)	1.09 (0.20)	1.09 (0.20)
CV_{ML}	3.18 (2.01)	2.62 (1.67)	2.52 (1.76)	4.27 (3.97)	3.56 (2.82)	3.32 (2.65)
CT_R	1.02 (0.24)	1.05 (0.28)	1.01 (0.18)	1.11 (0.37)	1.12 (0.35)	1.15 (0.36)
CV_R	16.13 (7.13)	15.03 (6.84)	14.58 (7.17)	27.65 (12.94)	25.26 (11.22)	25.37 (12.68)

AP, ML, and R: anterior–posterior, medial–lateral, and radial directions, respectively.

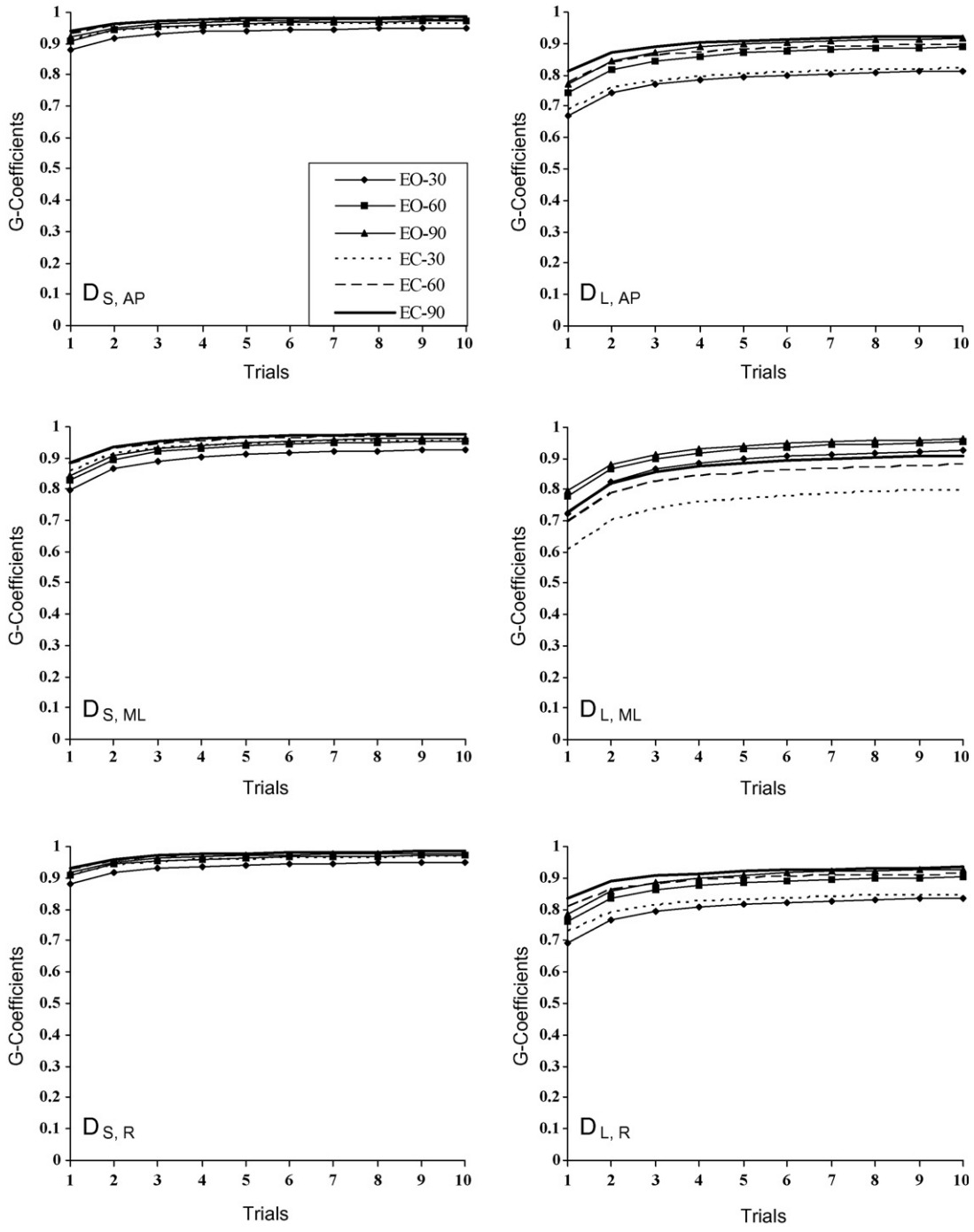

Fig. 1. *G*-coefficients for diffusion coefficients *D*. S and L: short- and long-term region; AP, ML, and R: anterior–posterior, medial–lateral, and radial directions, respectively.

4. Discussion

Force platform analysis of quiet standing offers a non-invasive, low-impact option to investigate postural control. There is relatively little consistency in methodology employed and measurements chosen for COP analysis when using a force platform [1]. SDA offers information on the dynamic nature of the COP profile and can be used as a supplement to the summary COP measurements. There is little information about the reliability of this measurement technique in terms of the optimal number and sampling length of the trials [2,9]. The purpose of this study was to thoroughly investigate the reliability of SDA measures using the techniques of Generalizability Theory in order to provide experimental design recommendations.

One of the strengths of G-Theory is the ability to identify potential sources of variability (facets) and determine their relative contribution to the overall variance

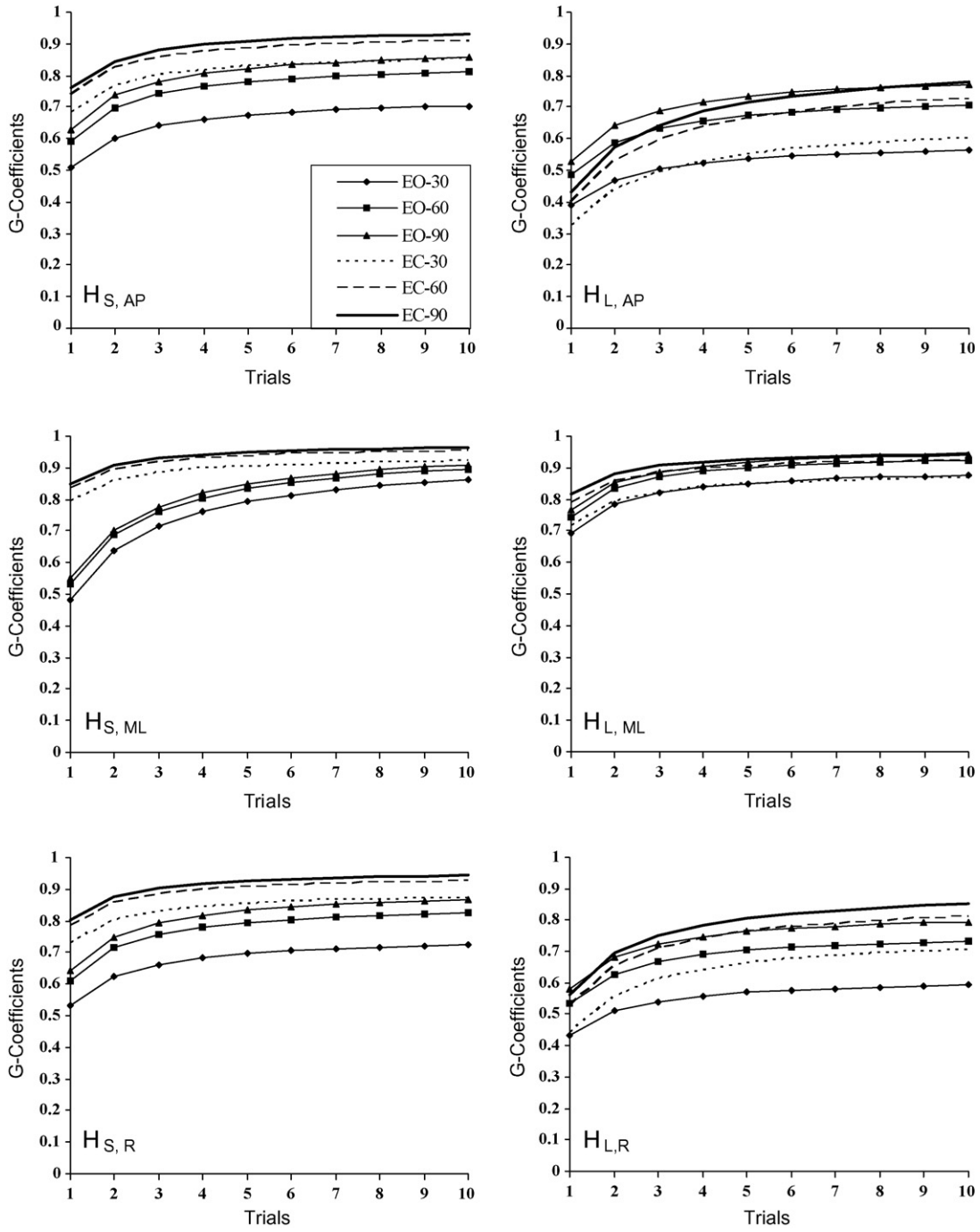

Fig. 2. *G*-coefficients for scaling exponents *H*. S and L: short- and long-term region; AP, ML, and R: anterior–posterior, medial–lateral, and radial directions, respectively.

of the measurement. The facets identified as potential sources of variance in this investigation were number of trials (T) and length of trial (L). A number of conclusions can be drawn from the G-study used to determine variance. First, across all measures the number of trials did not contribute much to the overall variance (range = 0–12.3%). We can conclude that adding trials once an acceptable level of reliability is achieved does not significantly reduce variability, since this facet does not contribute much to the variance. The length of trial contributed slightly more to the overall variance (range = 0–27.6%) when compared to the number of trials facet. In other words, the relative impact of increasing the number of trials to improve reliability is lower than increasing the length of trials. The participant (P) facet was found to be the largest contributor to variance. This finding indicates that the majority of the variance in the measurements included in this investigation are primarily due to differences between participants.

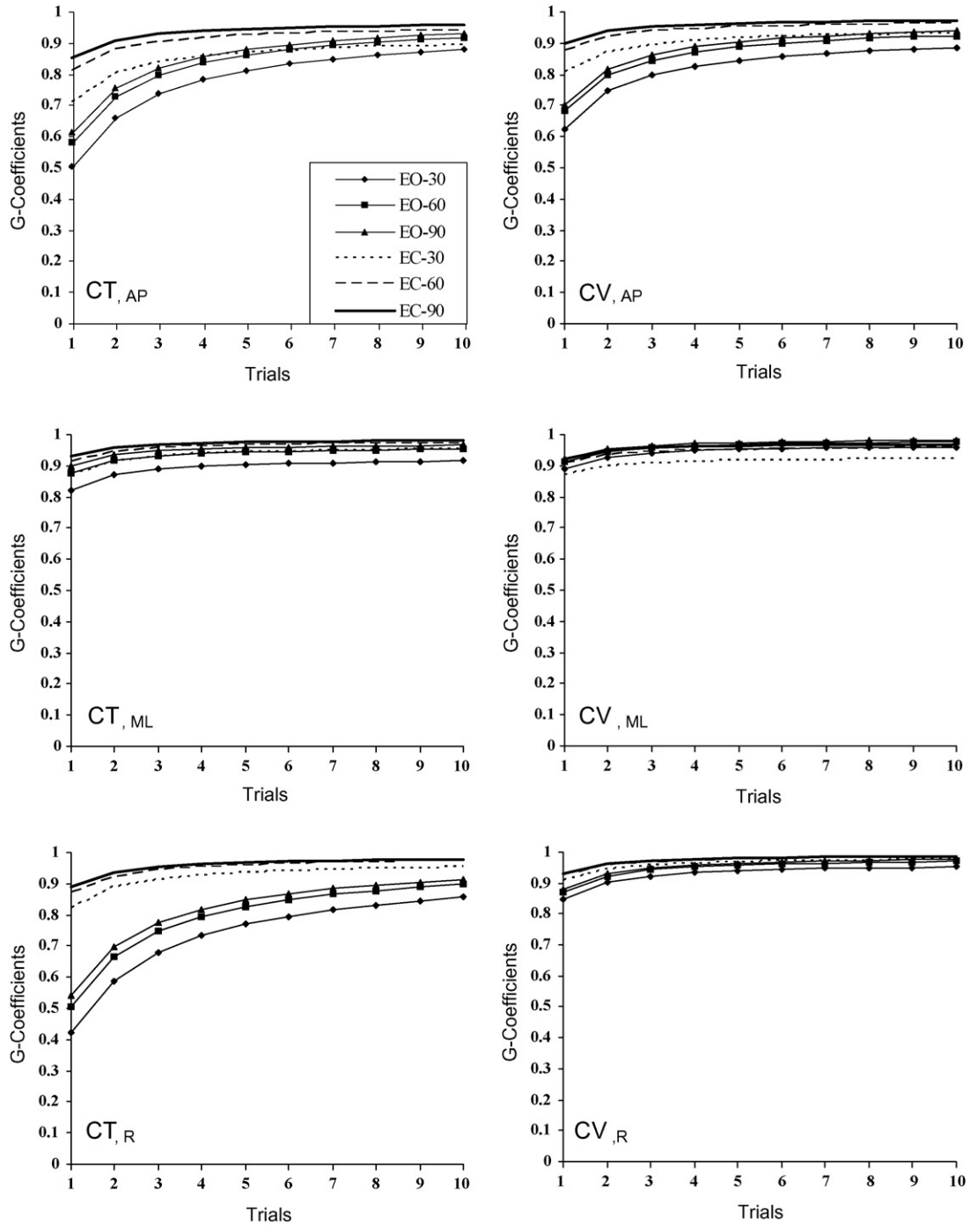

Fig. 3. *G*-coefficients for critical point coordinates—critical time interval (CT) and critical value (CV). AP, ML, and R: anterior–posterior, medial–lateral, and radial directions, respectively.

Data from the G-study were used to establish a reliable measurement technique through the D-studies. Depending on the measure of interest to the researcher, we can draw some interesting conclusions from the D-studies. The diffusion coefficient for all conditions reached acceptable reliability ($G \geq 0.7$) with only two trials at 30 s. This result suggests that if a researcher is interested in only examining the diffusion coefficients, which provide information about the stochastic nature of the COP profile and the relative stability of the system, then the amount of data collection could be significantly reduced. The reliability for the scaling exponent was less consistent. In order achieve an acceptable level of reliability in all directions at least eight trials at 60 s in length trials are necessary. The critical point coordinates reached acceptable levels of reliability that were comparable with the diffusion coefficient results.

Acceptable reliability was achieved within four trials at 30 s trial lengths.

The results of this investigation were obtained with young, healthy adults and assessments of reliability may vary significantly in populations not considered in this study (e.g., elderly, Parkinson's). 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 other facets, e.g., potential fatigue or behavioral issues (i.e., boredom and reduced motivation). 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 [10]. The purpose of this study was to investigate how the number of trials and length of trial affected the reliability of SDA measures. Further investigations in other populations and with separate trials for separate lengths should be performed to verify the results of the present study.

This study did not find a single trial length or number of trials that should be universally employed for all SDA measures. However, based on the results of this study and the goal of producing reliable measurement techniques, it is suggested that researchers employ trial lengths of 60 s and no less than five trials when assessing diffusion coefficient, scaling exponent and critical point measurements of SDA. This represents 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. Some of the measures of SDA did not meet the acceptable level of reliability with this standard. However, by inspecting the graphs of *G*-coefficients (Figs. 1–3) it becomes apparent that the majority of improvements in reliability are accomplished by or before the fifth trial. Furthermore, it can be concluded that increasing the length of the trial improves reliability more so than increasing the number of trials. In a previous study, we propose a similar standard of at least five trials at 60 s lengths when examining more traditional COP measures, such as sway velocity, standard deviation about the mean, and swept area [1].

We intend the results of this study to be used at the discretion of the researcher when designing a study utilizing the measurements of SDA. Ultimately a compromise between a feasible data collection period and acceptable reliability level will be determined by the investigator. 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.

Conflicts of interest

None of the authors has a potential conflict of interest (e.g., consultancies, stock ownership, equity interests, patent-licensing arrangements) related to the manuscript or the work it describes.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gaitpost.2007.03.013.

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