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Sampling duration effects on centre of pressure descriptive measures

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ABSTRACT

The different measures used to characterize postural sway are sensitive to variations in sampling duration, yet there remains marked variability and a lack of consistency in this temporal parameter when compared between studies. We investigated the effect of sampling duration on 22 commonly used frequency and time domain measures and stabilogram diffusion coefficients. Participants stood quietly on a forceplate during two 600 s standing trials with eyes open and eyes closed. The results clearly show that the amplitudes of the descriptive measures are sensitive to sampling duration. Only measures related to the amount of sway were sensitive for eyes open versus eyes closed conditions. In addition to sample duration, the filter settings, sampling frequency and fitting windows should be standardized since they also affect the magnitude of the descriptive measures. Without such standards, the inability to accurately compare between studies will persist.

1. Introduction

Although force plate derived centre of pressure (COP) measures of postural sway have been useful in helping to screen for abnormal balance control, little success has been achieved in using static posturography as a tool for discriminating and/or diagnosing specific disease-related balance characteristics during quiet stance [1]. One potential limitation of posturography is the lack of standardization of testing protocol and measurement parameters for force plate derived COP measures during quiet stance. For example, there is little consistency among previous studies regarding the types of descriptive measures (DMs) used to quantify COP behaviour or the length of time used to sample COP, which likely contributes to the conflicting results reported for even the simple manipulation of vision on postural control (see Table 1). As a result there remains little, if any, common grounds from which comparisons between studies can be made in hopes to establish a concrete understanding of the characteristics of normal healthy postural control, let alone pathological implications.

The need for standards within the field of static posturography was recognized almost three decades ago in a report presented at the International Symposium of Posturography in Kyoto in 1981 [2]. The report featured a number of recommendations for standards in collection, measurement and presentation of posturographic data and called upon the need for future research to better understand the factors that may influence the results of posturographic measurement in hopes to validate the norms set out by the report (3). Sampling duration, one of the key factors highlighted in the Kyoto report, has been the focus of a number of recent investigations which have validated previous concerns. For example, studies have shown that the magnitudes of various COP summary measures in the time and frequency domains are significantly influenced by sampling duration [3,4].

Although these studies have provided important insight into the potentially confounding effect of sampling duration on COP measures, the investigations were limited to sample durations of less than 120 s, which may not be sufficient to capture the very low frequency, and unique characteristics of postural sway observed during more extended periods of quiet stance [5]. Furthermore, the effect of sample duration has only been examined on a few COP summary measures under normal sensory conditions, which may not be generalizable to other DMs or conditions used commonly within the field.

Studies have also demonstrated that the reliability of COP summary measures in both the time and frequency domains are susceptible to the effects of sample duration [3,6–10]. To ensure reliable DMs, averaging together a number of shorter trials whose net duration exceeds 300 s has been proposed as an effective alternative to collecting a single long standing trial. Although considered an effective approach to generate reliable COP summary measures, this process has not yet been validated to ensure the precision of a respective DM.

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Table 1
Overview of studies on the effect of visual condition on postural sway during unperturbed standing, which used the same descriptive measures we analyzed. Shown are the descriptive measures used to quantify the effect of vision, and the sampling duration of each study. See Table 2 and the supplemental material for the acronyms of each DM.

Citation	Descriptive measures	Sampling duration	Results of visual condition
Carpenter et al. [3]	RDIST, MPF	120 s	$RDIST_{A-P} >$ in EC $MPF_{M-L} <$ in EC
Kim et al. [14]	MVEL MPF	75 s	$MPF_{A-P} >$ in EC
Kunkel et al. [15]	RDIST, MVEL	62 and 30 s	$RDIST_{A-P,\ M-L}$ and $MVEL_{A-P,\ M-L} >$ in EC
Asakawa et al. [16]	RDIST	60 s	RDIST > in EC
Laufer et al. [17]	MPF, RDIST, MVEL	60 s	MPF_{A-P}, $RDIST_{A-P}$ and MVEL > in EC
Paulus et al.[18]	RDIST	60 s	RDIST > in EC
Prieto et al. [11]	MDIST, RDIST, MVEL, MFREQ, POWER, CFREQ, FREQD	30 s	$RDIST_{A-P} >$ in EC
Vuillerme et al. [19]	MVEL	10 s	no effect

Therefore, the first aim of the study was to examine the effects of sampling duration on a wide variety of COP measures recorded from quiet standing trials whose duration far exceeds those used in previous experiments. We hypothesized that increased sampling duration would significantly influence all descriptive measures in both the time and frequency domains. The second aim of the study was to determine whether the effects of vision on postural control are dependent upon sampling duration. We hypothesized that the effects of vision on postural control would be consistent across sampling durations. The third aim of the study was to determine whether the accuracy of DMs calculated from an entire 600 s trial would be different from the average of 10 continuous 60 s taken from the same 600 s standing trial. We hypothesized that DMs calculated from the average of 60 s trials would be significantly different those calculated from a single 600 s trial.

2. Methods

2.1. Participants

10 university students (5 males and 5 females, age 23–31 years) volunteered for the study. Participants were free from neurological or orthopedic disorders as verified by self-report. All participants provided informed consent as outlined by the University of British Columbia Ethics Committee.

2.2. Procedure

Each participant stood quietly on a forceplate with their feet positioned comfortably within a square defined by dimensions equal to their foot length. The feet were traced on the forceplate to ensure consistent foot positioning between standing trials. The participants were instructed to stand quietly with their arms hanging at their sides and head in a normal forward-facing position, with eyes closed (EC) or with eyes open (EO) and focused on a stationary target located at eye level, approximately 2 m away. Participants performed a 600 s standing trial for each visual condition, separated by a seated rest period (>4 min), to minimize any effects due to fatigue. The order of presentation for EO and EC trials was counter-balanced across subjects to minimize potential order effects.

2.3. Data analysis

Ground reaction forces and moments in three planes were sampled at 20 Hz and converted to a digital signal via a 16 bit A/D converter. Continuous displacement of COP was calculated offline for each individual 600 s record, and then divided into 10 intervals, starting from 60 s and increasing in length by increments of 60 s (i.e. 0–60, 0–120, 0–180. . ., 0–600 s). For each interval, DMs were calculated in the anterior–posterior (AP) direction (see Table 2 and Supplemental Material for specific details). The time domain and frequency domain measures were adopted from Prietto et al. [11]. The stabilogram diffusion measures were calculated following the methods of Collins and De Luca [12]. Note that the frequency domain measures were calculated for two frequency ranges: (1) from 0.15 Hz to 5 Hz as in reference [11] and (2) from $1/T$ to 5 Hz as in reference [3], where T is the sampling duration. With the latter method the lowest detectable frequency becomes smaller when the total sampling duration increases.

Table 2
ANOVA results for effects of sampling duration and vision on all COP dependent measures. Please note that "N" denotes non-significant ANOVA results.

Dependent measure	Acronym	Main effect (sample duration)	Interaction (sample duration × vision)	Time to stability (s)	Direction to stability
Frequency domain					
50% Power frequency[a]	P50	N	N	N/A	N/A
95% Power frequency[a]	P95	N	N	N/A	N/A
Centroid frequency[a]	CFREQ	$p = 0.002$	N	120	↓
Frequency dispersion[a]	FREQD	$p = 0.000$	N	N/A	↓
Mean power frequency[a]	MPF	N	N	N/A	N/A
Total power	POWER	N	N	N/A	N/A
50% Power frequency[b]	P50B	$p = 0.000$	N	180	↓
95% Power frequency[b]	P95B	$p = 0.000$	N	240	↓
Centroid frequency[b]	CFREQb	$p = 0.000$	N	420	↓
Frequency dispersion[b]	FREQDb	$p = 0.000$	N	240	↑
Mean power frequency[b]	MPFb	$p = 0.000$	N	240	↓
Time domain					
Diffusion coefficient short term region	DS	N	N	N/A	N/A
Diffusion coefficient long term region	DL	N	N	N/A	N/A
Scaling exponent short term region	HS	N	N	N/A	N/A
Scaling exponent long term region	HL	N	N	N/A	N/A
Critical point square displacement coordinate	CRITX	N	N	60	N/A
Critical point time interval coordinate	CRITDT	N	N	60	N/A
Mean velocity	MVEL	N	N	60	N/A
Mean frequency (rotational frequency)	MFREQ1	$p = 0.000$	N	180	↓
Mean frequency (sinusodal frequency)	MFREQ2	$p = 0.000$	N	180	↓
Mean distance	MDIST	$p = 0.000$	$p = 0.001$	N/A (EO); 300 (EC)	↑ EC
Standard deviation	RDIST	$p = 0.000$	$p = 0.001$	N/A (EO); 360 (EC)	↑ EC

[a] Denotes spectral measures that were calculated with a fixed low frequency bound of 0.15 Hz.
[b] Denotes spectral measures calculated with a lower bound that varies with sample duration (T) as $=1/T$.

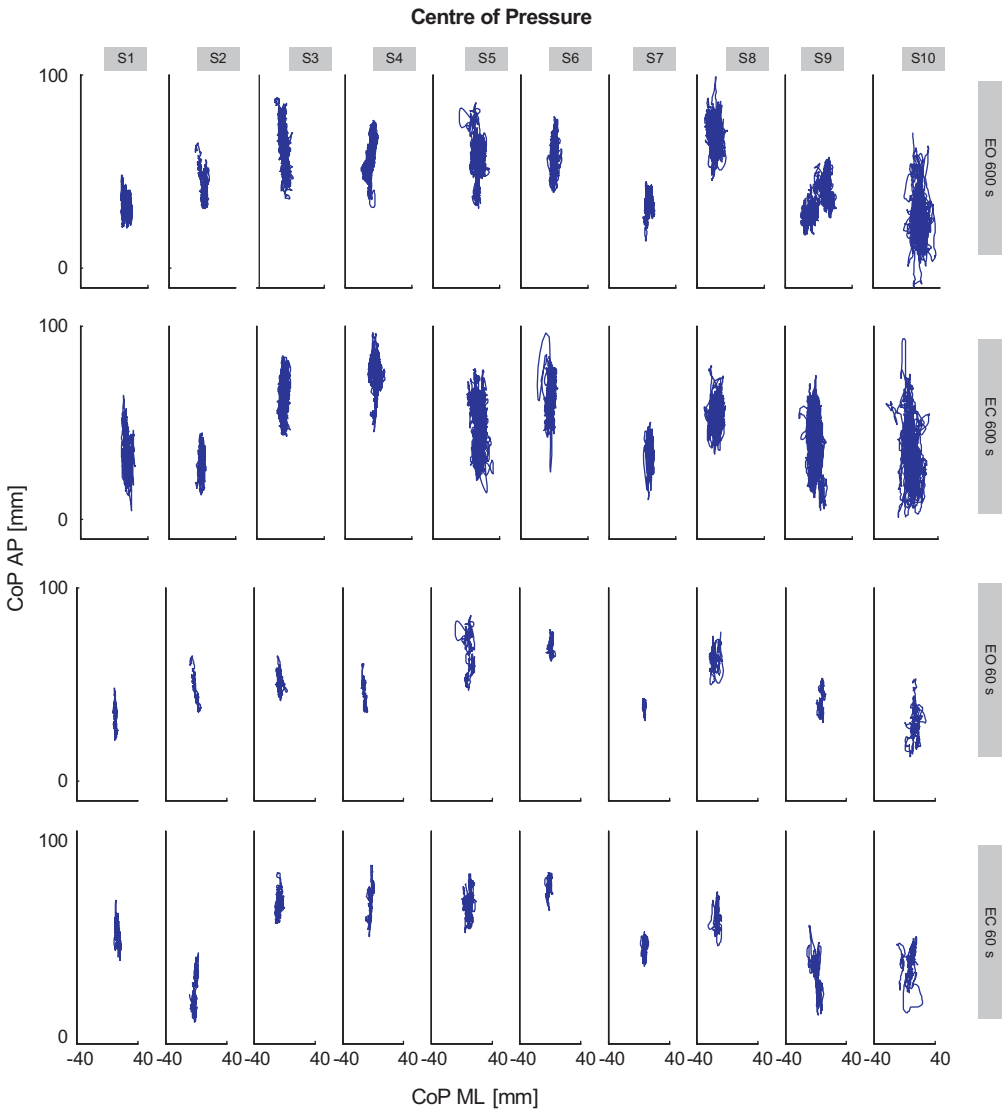

Fig. 1. Centre of pressure data of 10 healthy subjects recorded for 600 s (upper two rows) and 60 s (lower two rows) for eyes open (first and third row) and eyes closed (second and fourth row).

2.4. Statistical analysis

To address aims #1 and #2, each DM was analyzed using a two-way repeated measures ANOVA with sampling duration and vision as the independent variables. Helmert contrasts were used to determine the point in time at which the effects of sample duration were no longer significant (plateau). Helmert contrasts compare each successive time, with the average of all remaining time periods. In cases where significant interaction effects were observed, Helmert contrasts were performed separately for EO and EC conditions, and paired *t*-tests were used to compare EO and EC data at 60 s and 600 s. To address aim#3, paired *t*-tests were performed between the average of 10 consecutive data segments of 60 s and the entire 600 s trial for each DM for EO trials only. For both the ANOVAs and paired *t*-tests, family-wise error was set at 0.05 and was corrected for multiple comparisons using a Bonferroni adjustment (adjusted *p*-level = 0.0022).

3. Results

As shown in Fig. 1, the range of COP movements is noticeably larger when recorded over a 600 s compared to 60 s sampling duration. Furthermore, differences between EC and EO become obvious only when considering the entire 600 s sample. Significant effects of sampling duration were observed for certain time and frequency domain measures (Table 2). In the time domain, MFREQ1, MFREQ2 were significantly influenced by a main effect of sampling duration, with durations of at least 180 s required to reach stability. The effect of sampling duration for RDIST and MDIST was dependent on vision (Fig. 2). Post hoc analyses revealed that during EO trials, RDIST and MDIST were not significantly different when calculated from sample durations longer than 60 s. However, during EC trials, RDIST and MDIST required samples of at least 360 s and 300 s, respectively, to reach stable measures (Fig. 2).

Main effects of sampling duration were also observed for all of the frequency domain measures in which the lowest bound of the frequency window decreased with increasing sampling duration. Post hoc tests revealed that stability was achieved at 180 s for P50b, 240 s for P95b, MPFb and FREQDb, and 420 s for CFREQb (Fig. 2). Main effects of sampling duration were observed for only a few of the frequency domain measures with a fixed frequency window (Table 2). As shown in Fig. 2, stability was achieved at 120 s for CFREQ and 300 s for FREQD. In contrast, measures of MPF, P50 and P95 were not significantly influenced by sampling duration. Moreover, there were no significant effects of sampling duration on any of the group means stabilogram diffusion parameters. However, more detailed analysis of the stabilogram diffusion plots revealed that for sample duration shorter than about 180 s, the estimated slope coefficients (Ds, Dl, and HL) showed atypical values, occasionally resulting in negative estimates of the critical coordinates (critx and critdt). These unrealistic

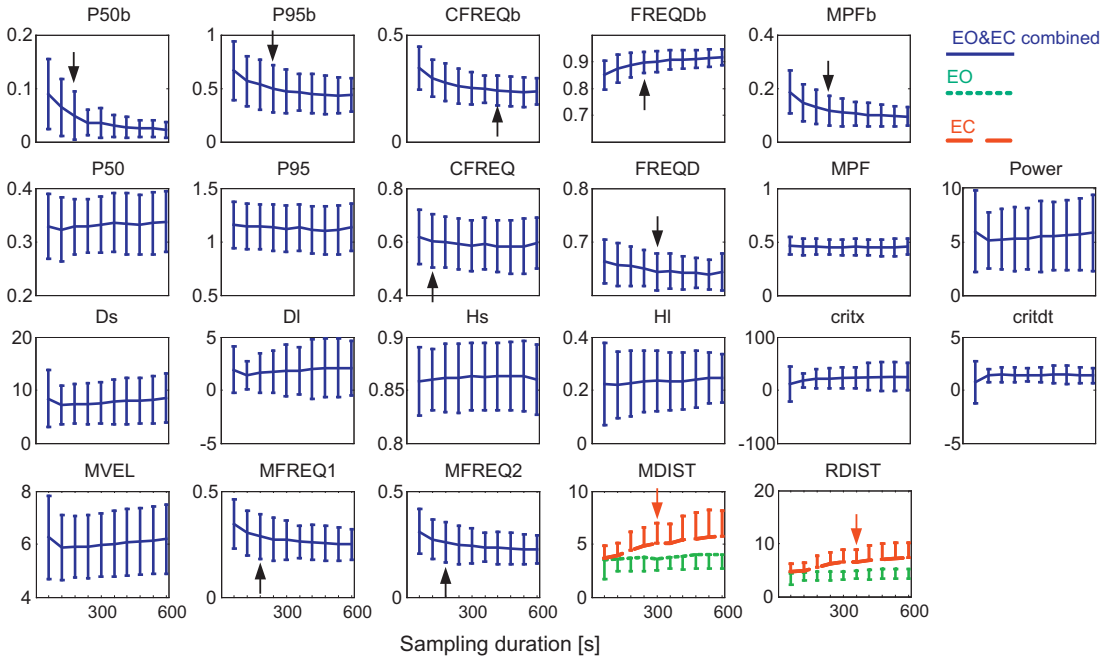

Fig. 2. Group means (and standard deviation bars) of the estimated descriptive measures as a function of sampling duration (always beginning at time 0). Results of the visual conditions were grouped in cases when no significant interaction effect between sampling duration and visual conditions was found (solid blue lines). For the cases in which a significant interaction effect was found the results are shown for eyes closed (red dashed lines) and eyes open (green dotted lines). For the descriptive measures for which we found a significant main effect of sampling duration the Helmert contrasts are denoted by the arrows. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.).

values increased the variance and therefore decreased the likelihood of detecting significant effects of sample duration.

Comparisons between the average of 10 consecutive data segments of 60 s with the entire 600 s trial (Fig. 3) revealed that the 600 s samples had decreased frequency related measures (P50b, P95b, CFREQb, FREQDb, MPFb, MFREQ1, and MFREQ2), and increased time domain measures (RDIST, MVEL, and MDIST) compared to the mean of 10 × 60 s segments (all p-values <0.002), despite the fact that the measures are derived from the same total number of data points.

4. Discussion

The primary goals of our study were to examine the effects of sampling duration on a wide variety of COP descriptive measures over extended periods of time and to determine whether the effects of vision on postural control are dependent upon sampling duration. The results confirmed prior recommendations to sample COP measures for at least 60 s to ensure stable standard deviation measures of COP displacements (RDIST) for quiet standing trials when vision is available [3]. With vision removed, however, much

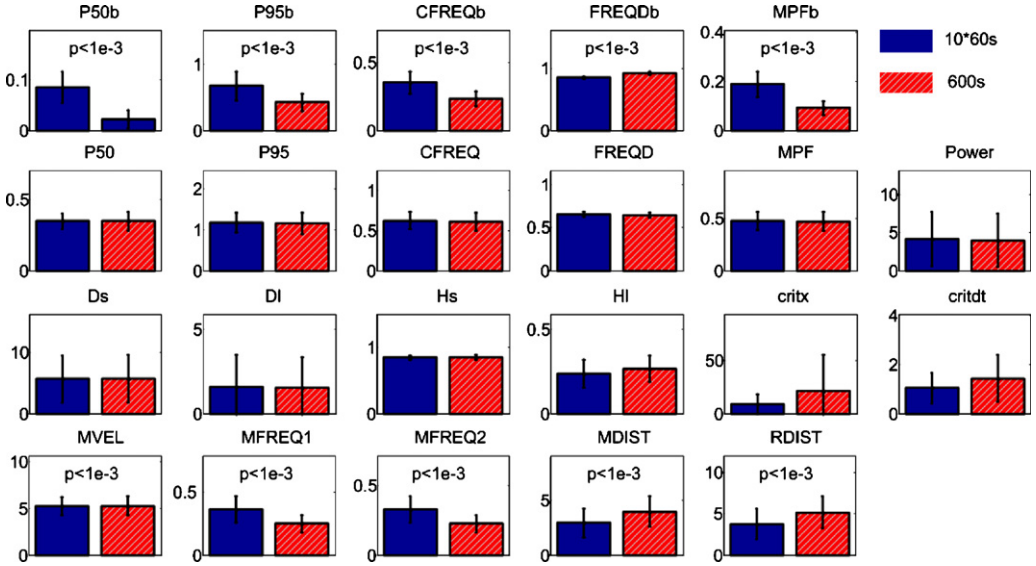

Fig. 3. Comparison of the average of 10 data segments of 60 s (blue solid bars) with the unsegmented data trials of 600 s (red shaded bars). Shown are mean and standard deviations of the descriptive measures of the AP centre of pressure averaged across subjects for the eyes open condition. When the p values of the paired t-test are shown significant differences were detected between the 10 × 60 s segments and the 600 s trial. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.).

longer sample durations are required to achieve a stable RDIST measure, suggesting that eye closure introduces larger amplitude displacements in the COP signal that span, or only emerge after, long periods of stance (Figs. 1 and 2). Previous observations for MPFb values however, were not consistent with the current findings. While Carpenter et al. [3] observed significant decreases in the magnitude of MPFb as sample duration increased up to 60 s, the current study found that similar measures must be sampled for at least 240 s before stable outcome measures are achieved. Differences in the time to stability for MPFb found between this study and that of previous work is likely due to the emergence of unique characteristics of sway seen only during extended standing [5], and a reduction in the proportional impact of the transient elements of the COP signal which are found only during the first 20 s of a standing trial [13]. In the latter case, although the transient components of the signal is kept constant across each of the sample durations used in the current study, its relative contribution to the overall signal will be far greater in studies that examined sample durations less than 120 s [3,4].

The changes seen in RDIST and MDIST with increased sampling duration were mirrored by most other DMs in the time domain (MFREQ1 and MFREQ2) and frequency domain based on variable frequency windows (P50b, P95b, CFREQb, MPFb, and FREQDb). The susceptibility of these DMs to sampling duration can be attributed to the large amplitude, but very slow fluctuations that dominate the COP signal. For example, in a 120 s sample, over 95% of the power is found in frequencies below 0.5 Hz [3] and even lower frequencies may be present in longer duration COP signals. Therefore, by measuring longer, more of these low frequency components are 'seen' and taken into account in the analysis. However, since these slow fluctuations are very small and insignificant in the body sway velocity, the related measure (MVEL) is much less sensitive to sample duration.

The sensitivity to sample duration is reduced if frequency measures are based on a fixed versus a variable (time-dependent) frequency window. Although stable, the accuracy of these measures is sacrificed when using relatively short window lengths for the same reasons that the lowest sway frequency components are ignored when the sample duration decreases. The lowest bounds of detectable frequencies are sensitive to both the sampling duration and to the length of the fixed frequency window. Therefore, adjustments made to either durations would result in an under representation of all the frequency components inherent to COP signals. Specifically, as both sampling duration decreases and as the length of the fixed frequency windows deviate from the total sampling duration, the relative strength of signals located higher within the frequency spectrum of continuous sway would be over-estimated.

Similarly, it is likely that stabilogram diffusion coefficients are also insensitive to changes in sample duration because the measures are based on changes in time (delta T), which has a fixed upper bound of 10 s. Again, while this makes these measures stable with respect to shorter stance trials, it suggests that other characteristics within the COP signal that have longer time courses, may not be reflected in the stabilogram diffusion co-efficients, potentially ignoring relevant components of the COP.

One possible criticism of our current findings is the potential for measures derived from longer sample durations to be confounded by the effects of fatigue [12]. In order to account for this potential confounding effect of fatigue, we repeated our analysis on the same data, but in the reverse order, with incrementally longer sample durations beginning at 600 s, and extending backwards in time. The results (see Supplementary Figure) clearly demonstrate that the same effect of increased sampling duration can be observed independent of the direction in which the signal was analyzed, suggesting that fatigue has little effect on our overall findings.

4.1. Effectiveness of averaging shorter trials

While the reliability of a DM calculated from a shorter duration sample may improve by averaging over multiple trials [6–9], our results clearly demonstrate that measures derived from the average of 10×60 s segments remain significantly different from measures derived from the entire unsegmented 600 s sample. This result is not surprising considering that each measure from the time domain, or frequency domain (using a variable frequency window), will consistently fail to capture the largest amplitude, low frequency components of a COP signal, ensuring that the average of these individual trials will consistently under- or over-estimate the true value of the COP signal, respectively.

4.2. Recommendations for sample duration

The natural question that arises is how long should one sample to have an accurate and reliable measure of COP? The simple answer to this question is that: it depends on (a) the type of DM used and (b) the sensory condition under which stance is being studied. Based on the current results, it appears that previous recommendations of a standardized sample duration of at least 60 s still holds for measures in time domain including RDIST and MDIST as long as vision is available. DMs based on fixed frequency windows, and measures of stabilogram diffusion co-efficients, also provide stable measures from samples of at least 60 s in both eyes open or eyes closed conditions. Therefore, these measures may be better suited for comparisons between groups or individuals who are unable to stand for long periods of time. However, in such cases, experimenters must realize that they may only be capturing the higher frequency components of the COP signal and may miss important information typically found within the lower frequency bands.

In contrast, if time domain measures are to be used to compare the effects of vision then the previous recommendation of 60 s needs to be extended to 300 s (MDIST) or 360 s (RDIST), to ensure that the largest amplitude COP components are reflected in the DM. Likewise, if the aim of a study requires an accurate assessment of all frequency components within a COP signal, then sampling duration needs to be extended to 180 s, 240 s or 420 s depending on the DM to capture the lowest frequency components of the COP signal.

4.3. Clinical implications

The lack of diagnostic and discriminatory ability of posturography in the past may have been due to the confounding effects of sampling duration. To overcome this confounding effect of sample duration it is necessary that patient groups do perform clinical and experimental standing trials for the same length of time as controls in order to provide accurate comparisons.

To compare different studies from different labs a standard for sampling duration is also essential, and this sampling duration should be as long as acceptable for a wide range of patient populations. Interestingly, we found that DMs related to velocity or frequency domain DMs with a fixed frequency window were less influenced by sample duration. When differences are expected to be manifested mainly at higher frequencies – e.g. tremor in PD – these DMs will be the most sensitive to discriminate patients from controls, and to discriminate between treatment conditions. Since the DMs are also highly sensitive to how the data is filtered, frequency windows used for the frequency domain measures (this study), and time intervals to fit the stabilogram diffusion coefficients, should also be standardized. When the scientific community agrees on standards in methodological practices, only then can data finally be compiled in an effort to build reference

databases that could ultimately be used to understand the fundamental aspects of human balance and the ways in which to limit the prevalence of falls.

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Conflict of interest

None.

Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gaitpost.2011.02.025.

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