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Postural sway parameters in seated balancing; their reliability and relationship with balancing performance

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ABSTRACT

This study investigated a representative set of 39 parameters characterizing center of pressure movements (sway) in seated balancing, with the aims to determine test–retest reliability, to clarify the interrelations between these parameters, and to determine which parameters were related to balance loss in seated balancing. 331 subjects volunteered to perform three 30-s seated balancing trials in a single session. Ten subjects lost balance on all three trials, 34 lost balance on one or two trials. The test–retest reliability of postural sway parameters was poor with all intra-class correlations below 0.7 and below 0.4 for 9 parameters. Sway parameters were strongly intercorrelated and many parameters thus provide little added value. Parameters that had no intercorrelations above 0.7 comprised three conventional summary statistics of center of pressure (CoP) movements and 3 parameters reflecting the temporal structure of the CoP trajectories. None of the parameters was related with balance loss in univariate analyses, while multivariate models revealed that higher sway velocity and a lower short-term diffusion coefficient were related with less balance loss. This indicates that a multivariate assessment of CoP trajectories is necessary to characterize balancing performance.

1. Introduction

Control over the trunk is important for postural stability, because of its high mass [1] and its height above the ground. Measurements in stance provides only limited information on trunk control, since postural adjustments can be accomplished with responses at the ankle, knee, hip and trunk joints independently, or combined [2–4]. In sitting, trunk control can be studied without the influence of lower extremity responses. Several studies have used an unstable seat to this end in healthy subjects [5–9] and in patient groups [10–17]. In this paradigm, subjects are instructed to sit on an unstable seat, dynamically balancing by trunk movement only (Fig. 1) while the seat angle or center of pressure (CoP) under the seat is traced.

Parameters characterizing seated sway consisted of conventional summary statistics of angle or CoP position and velocity and additional parameters derived from studies on standing postural sway. A wide range of postural sway parameters has been introduced [18–25]. To select parameters for further studies a range of these parameters were compared. First reliability was tested, to be able to select parameters that can be estimated with sufficient statistical precision from a limited number of measurements. Second, since a high degree of correlation between different postural sway parameters in standing has been reported [21,26], correlations between parameters were calculated, to test which parameters provide independent information. Finally, it was determined which of the parameters are related to performance in the task, i.e. to the ability to maintain balance.

2. Methods

The subjects for this study were participants in the Amsterdam Growth and Health Longitudinal Study (AGAHLS) an observational, longitudinal study on 698 subjects started in 1976 [27]. The goal of the AGAHLS was to describe the longitudinal relations between growth, health, and lifestyle in a representative sample of the Dutch population. The AGAHLS was approved by the Medical Ethical Committee of the VU University Medical Center in Amsterdam, Netherlands. The most recent measurement took place in 2006. A random selection of 331 of the participants performed the seated balancing test in this year (Table 1).

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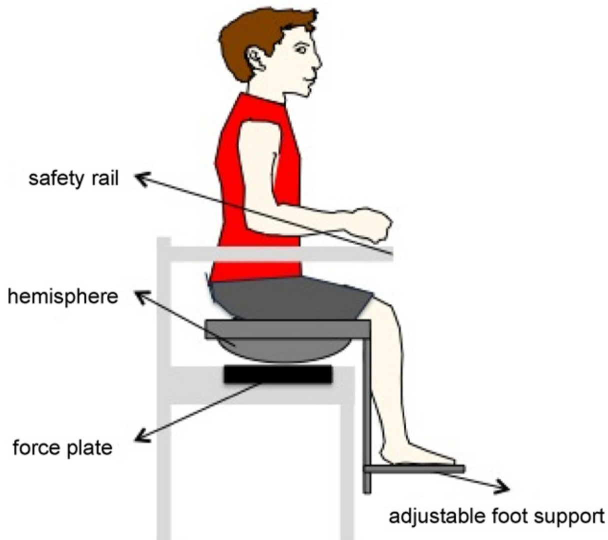

Fig. 1. Schematic overview of the unstable seat.

Table 1
Subject characteristics, mean (SD).

Gender	53% Female, 47% male
Age	42 (0.73) yrs
Height	1.77 (0.09) m
Sitting height	0.91 (0.04) m
Body mass	77.3 (13.7) kg

Trunk control was measured using a seat resting on an aluminum hemisphere (39 cm radius), creating instability in the frontal and sagittal planes, unless corrected by active balancing of the subject (Fig. 1, [17]). The seat was placed on a custom-made force plate that was sampled at 50 samples/s. A leg and foot support were attached to the seat to prevent influence of leg movements. The footplate was adjusted to support the feet with the knees and hips at 90-degrees angles. A rail was built around the seat for safety. Participants were instructed to sit as quietly as possible, holding their hands above the rail as illustrated in Fig. 1. This posture limited compensatory arm movements and allowed them to grab the rail rapidly, when loosing balance. The participants wore a bracelet, connected to a low-voltage battery. Touching the rail closed a circuit, such that a pulse was generated and recorded on the system for force measurements. Two minutes of practice were given before data collection. Three trials of 30 s were performed with 30 s rest between trials.

Data analysis was performed using Matlab R2007a (Mathworks, Natick MA, USA). The first 5 s of each trial were discarded to avoid non-stationarity related to the start of the measurement. Data were analyzed only when no contact with the safety rail had been detected. CoP trajectories were calculated and referenced to the mean CoP position.

The following parameters were calculated to express the deviation of the CoP from its average position: the range of the CoP in x (fore-aft) and y (left–right) directions (RANGEx and RANGEy), the root mean square value of the CoP in x and y directions (RMSx and RMSy), the mean distance of the CoP to its origin (meanD), the area of an ellipse that encompassed 95% of the CoP distribution (AREA) [21], as well as the long and short radius of this ellipse (radMAX, radMIN).

To characterize CoP velocity, the average and the standard deviation of the CoP velocity were calculated (meanV and sdV).

A hybrid velocity/deviation parameter (V/D) was calculated as [21]:

$$\mathrm{V/D} = \frac{\mathrm{meanV}}{2\pi\ \mathrm{meanD}} \tag{1}$$

In the frequency domain, the mean power frequencies of the distance to the origin (MPFr) and of the CoP movements in x and y directions (MPFx and MPFy) were calculated as well as the 80th percentile frequencies (FP80r, FP80x and FP80y) [23]. These parameters were obtained through Fourier transformation of the CoP trajectories with a Welch method using 500-points windows with 450 samples overlap.

The normalized path (npath) was calculated as the average of the derivative with respect to time of the CoP trajectory normalized to unit variance [25].

Diffusion plots were generated by plotting the mean square CoP displacement versus increasing time intervals (up to 10 s) [18]. These plots have two regions, separated by a period over which the slope of the plot changes considerably. The following parameters were extracted from these plots: diffusion coefficients, i.e. half the linear slope fitted to the short-term and long-term regions (Ds and Dl), scaling exponents, i.e. the slopes fitted to the regions after log–log transformation of the diffusion plot (Hs and Hl), and the critical point (CP), i.e. the point separating the two regions. The short-term region was defined by fitting a line to the diffusion plot over windows of increasing size starting from 0 to 0.1 s until the goodness of fit decreased below $r = 0.995$. The long-term region was defined as ranging from the end of the short-term region to 10 s. The CP was defined as the x-coordinate of the intersection of the two fitted lines.

In addition, detrended fluctuation analysis was used to quantify persistence of the CoP movements [28,29]. This analysis was performed on motion in the x and y directions separately. In order to estimate the Hurst exponent, the CoP trajectory was first integrated and subsequently divided into non-overlapping intervals ranging from 10 to 125 samples. Within each interval, the time series was linearly detrended to remove trivial correlations and the root mean square of the residual was calculated. The Hurst exponent (DFAH) is the slope to the log–log representation of the root mean square residual as a function of interval size.

Sway density analysis was performed according to Baratto et al. [23] using matlab functions provided by this group. In short, for each time instant the number of consecutive samples of the CoP that fell inside a circle of a 2.5 mm radius were determined. The resulting sway density curve (SDC) was low-pass filtered (4th order Butterworth, cut-off frequency 2.5 Hz) and the following parameters were extracted: numMAX, i.e. the mean number of SDC peaks per second, meaNDUR, i.e. the mean time between consecutive SDC peaks, sdDUR, i.e. the standard deviation of times between consecutive peaks, meanDIST, i.e. the mean of the spatial distance between consecutive SDC peaks, sdDIST, i.e. the standard deviation of the spatial distance between consecutive peaks, meanPEAKS, i.e. the mean duration of the SDC peaks, sdPEAKS, i.e. the standard deviation of the duration of the SDC peaks.

Recurrence analysis [22] was applied to the CoP trajectories using a matlab toolbox developed by Marwan et al. [30]. From the 2-dimensional CoP data, state space reconstructions were made by delay embedding (3 times 2 dimensions, delay time 0.6 s). Next, data points that are neighbors (within 1 mm from each other) in state space were identified. The recurrence in a time series can be represented graphically through the recurrence plot in which each data point on the x-axis is plotted against each other data point on the y-axis and recurrent points are identified. From this plot, the percentage of recurrent data points (%RECUR), the percentage determinism (%DET), the mean diagonal length (DIAG), and the entropy (recENTR) were calculated.

Additionally entropy was quantified using the sample entropy (sampENTR) of the time series of the distance of the CoP to the origin normalized to unit variance [29,31]. The sample entropy was calculated from the probability that a signal of length N repeated itself within a tolerance range 0.04 for 3 points, provided that it already repeated itself for 2 points, without allowing self-matches.

Finally, divergence of the CoP state space trajectories was quantified using finite-time Lyapunov exponents [32]. CoP state space trajectories were reconstructed as above. Subsequently, Euclidean distances between neighboring trajectories in state space were calculated as a function of time and averaged the over all original nearest neighbor pairs to obtain the average logarithmic rate of divergence. Divergence curves were calculated over windows of 10 s. The slope of the resulting divergence curves provides an estimate of the maximum finite-time Lyapunov exponent [33]. Slopes were estimated over two intervals: 0–0.08/MPFr (LyapunovS) and 0.5/MPFr to 10 s (LyapunovL).

Test–retest reliability of each of the sway parameters was assessed by the intra-class correlation (ICC). Due to balance losses, repeated trials were available for 315 subjects. In view of the varying number (2–3) of available trials among these subjects, the $ICC_{1,2}$ was calculated, using a random selection of two trials for those subjects that completed three trials. Sway parameters were considered sufficiently reliable when ICC >0.4.

For subsequent analyses, results of repeated trials were averaged within subjects. To assess the interrelationships between the sway parameters Pearson's coefficients of correlation between all parameters were calculated.

Based on the ICC and the interrelationships, sway parameters were selected as independent variables for logistic regression with balance loss during one of the trials as the dependent variable. On the first step, only variables with an ICC below 0.4 were excluded, since for further analysis the average of the trials was used. Subsequently, the minimally sized set of parameters that contained no intercorrelations of 0.7 or higher was iteratively determined and used for further analysis. Backward conditional (p to remove = 0.10) logistic regression analysis was used to determine the relationship between the selected parameters and balance loss.

3. Results

Ten subjects lost balance on all three trials and thus had to be discarded for further analysis. Reliability of most parameters was low to moderate, with ICCs ranging from −0.01 to 0.70 (Table 1).

The sway parameters showed strong intercorrelations (Table 2). Of the parameters with sufficient reliability, Hs appeared to contain unique information, while meanV and sdPEAKS were highly correlated to only a single other parameter. Not surprisingly, the parameters describing the deviation of the CoP were highly correlated. These variables were also correlated to V/D, to npath, to the outcomes of the recurrence analysis, and to

Table 2
Descriptives (mean, standard deviation (SD) and coefficient of variation (COV)) and intra-class correlations (ICC) of postural sway parameters and correlations between sway parameters retained for further analysis to all other parameters.

	Descriptives			Reliability		Pearson's correlations					
	Unit	Mean	SD	COV (%)	ICC	meanV	meanD	MPFr	Ds	Hs	sdPEAKS
meanV	cm/s	2.378	0.340	14	0.68	1	0.28	0.29	0.66	0.04	−0.34
sdV	cm/s	1.165	0.320	28	0.44	**0.73**	0.40	0.12	**0.82**	0.30	−0.45
RANGEx	cm/s	2.615	0.739	28	0.46	0.38	**0.87**	−0.52	**0.72**	0.54	−0.45
RANGEy	cm/s	2.691	0.791	29	0.49	0.37	**0.89**	−0.54	0.61	0.42	−0.46
RMSx	cm/s	0.545	0.171	31	0.49	0.27	**0.92**	−0.61	0.60	0.50	−0.40
RMSy	cm/s	0.565	0.184	33	0.51	0.28	**0.94**	−0.64	0.51	0.38	−0.41
meanD	cm/s	0.705	0.214	30	0.59	0.28	1	−0.67	0.56	0.44	−0.42
AREA	cm^2	3.824	2.297	60	0.55	0.34	**0.96**	−0.57	0.59	0.43	−0.42
radMAX	cm	0.662	0.207	31	0.55	0.25	**0.98**	−0.69	0.51	0.40	−0.36
radMIN	cm	0.440	0.121	28	0.59	0.39	**0.90**	−0.50	0.69	0.52	−0.53
V/D	Hz	0.590	0.169	29	0.64	0.21	**−0.81**	**0.86**	−0.29	−0.50	0.33
MPFr	Hz	0.491	0.137	28	0.41	0.29	−0.67	1	−0.05	−0.25	0.09
MPFx	Hz	0.346	0.112	32	0.42	0.30	−0.54	**0.78**	0.03	−0.20	0.11
MPFy	Hz	0.327	0.098	30	0.49	0.26	−0.63	**0.83**	−0.02	−0.19	0.09
FP80r	Hz	0.604	0.179	30	0.32	0.32	−0.54	**0.91**	0.13	−0.04	−0.08
FP80x	Hz	0.423	0.137	32	0.39	0.34	−0.41	**0.71**	0.24	0.06	−0.07
FP80y	Hz	0.404	0.127	32	0.44	0.27	−0.54	**0.76**	0.09	−0.06	−0.03
npath	Hz	4.816	1.338	28	0.66	0.19		**0.85**	−0.33	−0.54	0.36
Ds	cm^2/s	0.225	0.127	56	0.52	0.66	0.56	−0.05	1	0.61	−0.54
Dl	cm^2/s	0.026	0.031	121	0.03	0.07	0.69	−0.49	0.21	0.23	−0.14
Hs		0.707	0.050	7	0.51	0.04	0.44	−0.25	0.61	1	−0.46
HL		0.164	0.104	63	0.09	−0.19	0.37	−0.45	−0.15	0.01	0.16
CP	s	1.034	0.476	46	0.32	−0.19	0.36	−0.50	−0.14	−0.01	−0.04
DFAHx		1.340	0.109	8	0.50	−0.32	0.44	**−0.71**	−0.22	−0.02	0.03
DFAHy		1.368	0.108	8	0.52	−0.28	0.54	**−0.74**	−0.08	0.14	0.00
numMAX	Hz	1.656	0.071	4	0.08	−0.07	−0.36	0.24	−0.16	−0.24	0.09
meanDUR	s	0.603	0.027	5	0.09	0.11	0.39	−0.25	0.21	0.27	−0.10
sdDUR	s	0.228	0.026	11	0.03	−0.07	0.19	−0.27	−0.04	0.10	−0.02
meanDIST	cm	6.421	2.072	32	0.63	0.63	0.68	−0.16		0.62	−0.65
sdDIST	cm	4.701	1.190	25	0.44	0.52	0.70	−0.29	**0.85**	0.65	−0.54
meanPEAKS	s	0.743	0.201	27	0.52	−0.53	−0.50	0.03	**−0.74**	−0.55	**0.90**
sdPEAKS	s	0.401	0.145	36	0.59	−0.34	−0.42	0.09	−0.54	−0.46	1
%RECUR	%	0.001	0.001	62	0.56	−0.21	**0.82**	**−0.81**	0.17	0.35	−0.12
%DET	%	0.605	0.192	32	0.70	−0.07	**0.80**	**−0.72**	0.49	0.60	−0.43
DIAG	cm	3.366	1.025	30	0.53	−0.05	**0.85**	−0.66	0.46	0.54	−0.38
ENTRrec		1.357	0.516	38	0.67	−0.07	**0.83**	**−0.72**	0.48	0.57	−0.39
SAMPENTR		1.257	0.283	23	0.62	0.04	**−0.83**	**0.74**	−0.49	−0.56	0.39
LyapunovS	Hz	5.961	2.570	43	0.48	0.31	−0.52	**0.82**	0.15	0.00	−0.08
LyapunovL	Hz	−0.004	0.029	820	0.03	−0.02	0.06	−0.13	0.02	0.03	0.11

Parameters in bold were not included in regression analysis because of colinearity shaded paramaters were not included in regression analysis because of low reliability.

Table 3
Regression coefficients (B) and their standard errors (S.E.) and associated p-values obtained in univariate and multivariate backward conditional logistic regression analyses with balance loss as the dependent variable.

		B	S.E.	p-Value
Univariate	meanV	−0.37	0.56	0.51
	meanD	0.78	0.81	0.33
	MPFr	−0.84	1.27	0.51
	Ds	1.90	1.24	0.13
	Hs	7.08	3.80	0.06
	sdPEAKS	0.42	1.21	0.73
Multivariate	meanV	−1.83	0.80	**0.02**
p = 0.02	Ds	5.13	1.93	**0.01**
	Constant	0.97	1.56	0.54

Values in bold indicate significance.

sampENTR. Frequency parameters were highly interrrelated and were correlated to the parameters that describe persistence and divergence. In addition, high correlations of frequency measures with entropy measures and recurrence analysis outcomes were found. Finally, Ds and a number of parameters of the sway density analysis were highly correlated.

Based on the test–retest reliability 9 of the 39 parameters were excluded from further analyses (Table 2). From the remaining set, meanV, meanD, MPFr, Ds, Hs and sdPEAKS were retained for further analysis, as the minimally sized set of parameters containing no intercorrelations above 0.7. Thirty-four (out of 321) subjects lost balance on one or two trials. To test the relationship with balance loss of the sway parameters retained, the results of these subjects obtained during the trials that were successfully completed were contrasted to those of the 287 subjects that did not loose balance. Only low meanV and high Ds were significantly related to balance loss (Table 3). None of the sway parameters showed a relationship with balance loss in univariate analyses.

4. Discussion

The test–retest reliability and the interrelations of a set of 39 parameters describing the movements of the CoP obtained from three 30-s seated balancing trials were determined. Reliability was overall rather low, with ICCs below 0.7. In addition, many parameters were highly correlated; each thus provides only limited unique information. After exclusion of parameters with low reliability (ICC <0.4), we determined the smallest set of parameters without high intercorrelations ($r > 0.7$). The resulting set of 6 parameters was compared between subjects that did and did not loose balance in one or two trials. In univariate analyses, none of the parameters was related to balance loss, while multivariate analysis revealed that balance loss was more common in subjects with a relatively low mean CoP velocity and a high short-term diffusion coefficient.

A previous study reported coefficients of correlation between test and retest values of a number of parameters [5]. However, correlations were calculated between data sets comprising tests performed under varying conditions and are therefore not interpretable in terms of test–retest reliability. The poor reliability of the sway parameters in the present study can in part be explained by the short trial duration (30 s), since better results were obtained with trials of 60 s [8]. To increase reliability it thus seems advisable to increase trial duration. However, with a longer trial duration fatigue may develop during the trial. We therefore prefer the use of averaged results over multiple short trials. The reliability was especially poor for Hl and LyapunovL. Also the high between-subject variance of these parameters suggests that reliable estimation of these parameters requires longer trials. The ICC is highly sensitive to between-subject variance. Some of the parameters had a low between-subject variance as was evident from the coefficients of variation. This may be related to the subject group's homogeneity with respect to age and the exclusion of individuals with overt musculoskeletal or neurological disorders.

Strong intercorrelations between parameters were found. Principal component analysis on the set of parameters with sufficient reliability revealed that only 4 modes with eigenvalues higher than 1 accounted for over 87% of the variance in the data set. Instead of using the resulting factor scores, we preferred to use the original parameters as these allow more straightforward interpretation than the factor scores. Choosing a minimum-sized data set without intercorrelations over 0.7, six parameters were retained. Three of these parameters, meanV, meanD and MPFr, provide conventional summary statistics on the velocity, deviation and frequency content of the CoP.

Other parameters determined in the present study, were introduced to provide insight in the temporal structure of the CoP trajectory that is not represented in conventional summary statistics. The present results however suggest that for seated balancing most of these provide limited additional information. However, the short-term diffusion coefficient (Ds) and the Hurst exponent (Hs) obtained from the stabilogram diffusion analysis, and the standard deviation of the duration of the peaks in sway density curve (sdPEAKS) were not strongly correlated to the three conventional summary statistics mentioned above. Ds and Hs characterize the displacements of the CoP over short intervals. Ds quantifies the magnitude of these displacements, whereas Hs indicates their persistence. In the present data, the confidence interval of Hs was above 0.5 indicating that displacement over short time intervals is persistent, i.e. it grows faster than in random motion. The short-term region of the diffusion plot was, because of this persistence, interpreted as signifying open-loop control of the motion of the body's center of mass [18] that would be corrected towards a fixed point at longer time-scales. However, others have suggested that the short-term displacements reflect closed-loop, corrective movements towards an open-loop controlled trajectory [34]. High values of Ds could thus signify large amplitude feedforward motions, or large amplitude corrective movements. Both would suggest reduced performance or increased task difficulty.

The parameter sdPEAKS quantifies the variability of the duration of the peaks in the sway density curve. It should be noted that this parameter was highly correlated ($r = 0.90$) to the mean duration of the peaks (meanPEAKS). The latter parameter reflects how long the CoP dwells within areas with a 2.5 mm radius. High dwell times may reflect the extent to which a subject is successful in temporarily approximating static equilibrium.

None of the variables was related to balance loss in univariate analyses. In contrast, Pérennou et al. [13] found a relationship between the variance of the seat angle and balance loss in stroke patients. Possibly this disparity can be explained by the fact that the task was likely relatively easy for the healthy subjects in the present study. In the present study, a multivariate analysis showed meanV and Ds to be related to balance loss. This suggests that the probability of balance loss is determined multi-factorially, which can be understood on the basis of these particular variables. When high velocity coincides with large amplitude (high Ds), persistent movements, this can easily lead to balance loss. On the other hand a high CoP velocity would appear to be beneficial when it occurs in small amplitude movements, that is at a high frequency.

It has been argued that sway parameters obtained from unperturbed balance control cannot distinguish between properties of the balance control system and the mechanical properties of the controlled system [35]. Indeed, many of the parameters were significantly though only weakly ($r < 0.6$) correlated to body mass and sitting height. It appears reasonable to assume that task performance depends on both the controller and controlled system through their effect on sway, as reflected in the parameters studied. Therefore, no correction for anthropometrical characteristics was applied in the analyses.

In conclusion, test–retest reliability of postural sway parameters obtained from 30-s seated balancing tests, is poor. Therefore, averaging of outcomes of multiple trials is recommended. Sway parameters are strongly interrelated and many parameters thus provide little added value. Nevertheless, a minimum-sized set of independent parameters contained both conventional summary statistics of CoP movements and parameters reflecting the temporal structure of the CoP trajectories. Balance loss could not be related to any single variable, while multivariate models revealed that low velocity and large short-term diffusion CoP movements are related with balance loss. This indicates that multivariate assessment of CoP trajectories is necessary to characterize balancing performance.

Conflict of interest

None.

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