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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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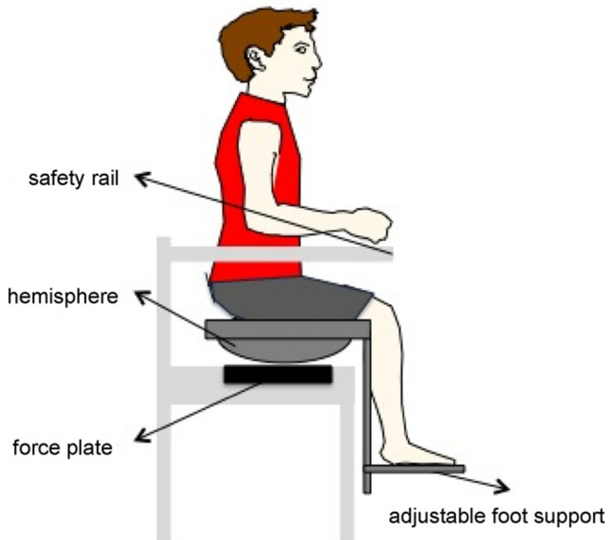

Fig. 1. Schematic overview of the unstable seat.

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]:

$$\mathrm{V/D} = \frac{\mathrm{meanV}}{2\pi\ \mathrm{meanD}} \quad (1)$$

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.