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RESEARCH ARTICLE

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Movement sway: changes in postural sway during voluntary shifts of the center of pressure

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Abstract We introduce a method for quantification of movement sway—spontaneous migrations of the center of pressure (COP) during its voluntary shifts. Subjects stood on a force platform or on a board with a narrow support surface ("unstable board") and performed voluntary cyclic shifts of the COP at different frequencies. Movement sway was typically higher than postural sway; sway in the mediolateral direction was particularly increased. Movement sway showed a drop with the frequency of voluntary COP shifts. During standing on the unstable board, postural sway increased while movement sway decreased. The effects of task parameters were stronger on the sway component in the direction of the voluntary COP shift than in the orthogonal direction. We interpret changes in movement sway with task parameters as partly resulting from modulation of the search function of sway during voluntary COP shifts.

Keywords Posture · Sway · Instability · Variability · Human

Introduction

Postural sway as spontaneous shifts of the center of pressure (COP) during quiet standing has been commonly investigated in both basic and applied studies of postural control (Gurfinkel 1973; Johansson and Magnusson 1991; Horak et al. 1997). Studies of postural sway have formed the experimental basis of several theories of postural stabilization (Winter et al. 1998; Gatev et al. 1999; Collins and DeLuca 1993; Zatsiorsky and Duarte 1999, 2000). Increased postural sway may be a cause of loss of balance in healthy humans in unstable conditions (Aruin et al. 1998; Duarte and Zatsiorsky 2002) as well as in patients with neurological disorders (Horak et al. 1989).

Many everyday human activities, such as making a step or standing up from the chair, involve voluntary shifts of the COP. These shifts occur against the background of postural sway. Within the current study, we assume that voluntary shifts of the COP and the background postural sway are independent processes: The former is timed to an internal command to initiate an action associated with a change in the COP, while the timing of the latter is independent of such a command. Within this scheme, voluntary COP shifts may be expected to show sway-related errors that can interfere with the voluntary action. Furthermore, we view COP shifts (and resulting shifts of the center of mass) as performance variables controlled by the central nervous system (CNS) using a set of internal control variables, such as postulated in the equilibrium-point (EP) hypothesis of motor control (Feldman 1986; Latash 1993; Feldman and Levin 1995).

It is generally unknown how postural sway affects voluntary shifts of the COP. Most studies of COP shifts associated with voluntary movements (Bardy et al. 1999; Alexandrov et al. 2001) describe average patterns of such shifts and pay little attention to spontaneous COP migration occurring on the background of the required action.

Sway has been viewed as a consequence of noisy processes within the human neuromotor system, as a reflection of an active search process (Collins and De Luca 1993; Gatev et al. 1999; Riccio and McDonald 1998), and as an output of a control process of stabilization of an unstable structure, the human body (Baratto

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et al. 2002). In all three cases, sway can be expected to change with parameters of a voluntary action. It is unknown how sway changes when a task requires voluntary shift of the COP rather than keeping it within an area of support.

The main goal of this study has been to introduce a procedure for quantitative assessment of sway associated with voluntary shifts of the COP; we address this phenomenon as "movement sway." The method was applied to compute several sway characteristics across conditions that differed in the required frequency of voluntary COP shifts, in the direction of the COP shifts, in conditions of postural stability, and in the availability of visual information. We hypothesize that voluntary shifts of the COP are indeed associated with sway, which can be higher than postural sway and show dependences on such task parameters as speed of the voluntary COP shift, postural stability, and availability of visual information.

Materials and methods

Subjects

Five female and five male young healthy volunteers took part in the study. Their age ranged from 22 to 34 years, their average height was 1.71 (±SD 0.06) m, and their average weight was 68 (±SD 11) kg. The subjects gave informed consent according to the procedures approved by the Internal Review Board of the University of Sao Paulo.

Apparatus

During the experiments, the subject stood on a wooden board placed on top of an AMTI OR6-WP-1000 force platform. The platform was used to record time patterns of the three components of the force (Fx, Fy, Fz) and three components of the moment (Mx, My, Mz); x, y, and z are the anterior-posterior, medial-lateral, and vertical directions, respectively. The subjects viewed the monitor located approximately 1 m from the subject at the eye level as illustrated in Fig. 1. The monitor provided visual feedback on the actual COP displacements, which were computed by $COPx = (-h \cdot Fx - My)/Fz$ and $COPy = (-h \cdot Fy + Mx)/Fz$, where h is the height of the board over the force plate (h=4.1 cm). Note that using this type of feedback makes COP the main performance variable whose time pattern the subjects were supposed to reproduce. A standard auditory metronome was used to pace the subject.

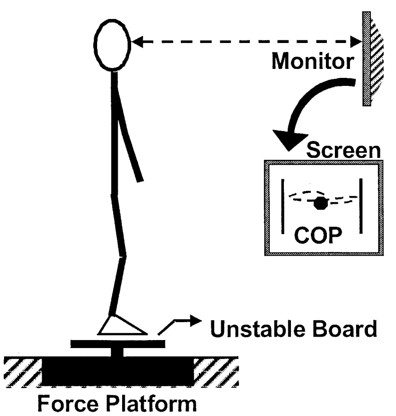

Fig. 1 Illustration of the experimental setup

The visual feedback of the COP position was implemented by a special code written in LabView software (LabView 6.1, National Instruments Co.) that acquired the force plate signals at a sampling frequency of 100 Hz. The force plate data acquisition was performed using a standard personal computer with a 16-bit A/D board (model PCI 6431, National Instruments Co.).

Procedure

Prior to the experiment, each subject was required to select comfortable positions of the feet on the board such that the feet were parallel, and the distance between the feet was approximately 0.3 m (comfortable for all subjects). These positions were marked and reproduced across trials. Between trials, the subjects were allowed to rest, walk or sit, as they preferred, and fatigue was never an issue.

Each subject performed 30 trials: one amplitude of voluntary COP shift (6 cm) vs. two directions of the COP shift (anterior-posterior, AP, and mediolateral, ML) vs. three postural conditions (open eyes, OE, closed eyes, CE, and while standing on the unstable board, UB) vs. six frequencies of the voluntary COP shift (0.0—quiet stance, 0.5, 0.75, 1.0, 1.25, and 1.5 Hz), which were presented in a pseudo-random (balanced) order. Each trial started with the subject standing on the board and looking at the monitor. The monitor showed two red lines oriented either vertically (for trials with voluntary ML COP shifts) or horizontally (for trials with voluntary AP COP shifts). COP displacement in the AP direction was translated into vertical displacement of the signal on the monitor (forward–up), while COP displacement in the ML direction was translated into lateral displacements of the signal on the monitor. The distance between the lines always corresponded to the COP shift of 6 cm. The monitor also showed the subject a cursor corresponding to the instantaneous position of the COP in the required direction.

The metronome was turned on, and the subject was required to move the cursor between the two lines such that at each metronome beat the cursor touched one of the red lines and reversed its movement; hence, COP shifts were at half of the frequency of the metronome. There were no explicit accuracy constraints. After 10 s, the monitor was turned off, while the metronome was on, and the subject was required to continue the same action for another 35 s.

Each subject performed one trial per condition. Four major factors were manipulated:

Frequency. The following metronome frequencies were used: 0 (quiet stance), 1 Hz, 1.5 Hz, 2 Hz, 2.5 Hz, and 3 Hz corresponding to the following frequencies of the COP shifts: quiet stance, 0.5 Hz, 0.75 Hz, 1 Hz, 1.25 Hz, and 1.5 Hz.

Direction. The subjects were asked to produce COP oscillations either in the AP or in the ML direction.

Vision. The subjects performed the task with their eyes open or they were required to close their eyes when the monitor feedback was switched off.

Stability. The board was either resting on four large supporting units placed under the corners of the board (stable standing) or it rested on a long (0.6 m) and narrow (0.06 m) rectangular beam ("unstable board"). The beam was fixed to the bottom of the board and made contact with the force platform (Fig. 1). The beam could be oriented either in a sagittal plane (ML instability) or in a frontal plane (AP instability, illustrated in Fig. 1). Note that in unstable conditions, tasks were apparently limited to voluntary shifts of the COP along the long dimension of the board.

Data processing

Prior to the main stages of data processing, all the data were filtered with a 4th-order 10-Hz low-pass zero-lag Butterworth filter. The last 30 s of each trial was analyzed, which included only data collected with the eyes closed. The data were processed offline using the MatLab software package.

Analysis of quiet stance

Since postural sway is a non-stationary process, prior to analysis, each time series was detrended by subtracting from the raw data a straight line fit computed using the least squares method. COP shifts in the AP and ML directions were analyzed separately. For each COP trajectory, the following variables were calculated:

1. The area of excursion (E-area) calculated using principal component analysis (PCA), which determined the area of ellipses containing 85.35% of the data;
2. Root mean square (RMS) values of the deviation from the mean;
3. Mean velocity (*V,* equivalent to the so-called "sway-path" normalized by the trial duration).

The power spectral density (PSD) of the detrended data was estimated using Welch's averaged periodogram method (Matlab Signal Processing Toolbox, The MathWorks, Inc., 1996) with the resolution of 0.1 Hz.

The frequency (f_{80}) corresponding to 80% of the total power of the signal during quiet stance was defined for each condition. The area under the PSD curve was computed between zero and f_{80}.

The method of movement sway analysis

The method of movement sway analysis is based on an assumption that voluntary shift of the COP and postural sway are independent processes, the former being timed to the required voluntary action, while the timing of the latter is independent of the action. This assumption can be compared to those made commonly in studies of interactions between involuntary (e.g., tremors) and voluntary actions, which have been viewed as two interacting independent processes sharing a common physiological and biomechanical plant (Elble and Koller 1990; Elble et al. 1994; Vaillancourt and Newell 2000a, 2000b). The method is also reminiscent of the commonly used technique of extraction of an evoked potential from the background changes of an electrophysiological signal. Data processing of each trial with voluntary COP shifts involved the following stages.

1. Two time series were analyzed for each trial corresponding to COP shifts in the AP and ML directions. Analysis was identical for the two time series. Peaks and valleys of the COP signal were detected for a time series (Fig. 2A). Trajectories connecting two consecutive points, one peak point and one valley point, were considered "unitary movements" (UMs). All the ascending UMs (UM_{UP}) were aligned by their valley points and averaged ($UM_{UP.AV}$). All the descending UMs (UM_{DOWN}) were aligned by their peak points and averaged ($UM_{DOWN.AV}$).
2. The purpose of the next steps was to eliminate the voluntary pattern of COP shift from each trial and to minimize possible effects of voluntary corrections on the COP profile. A number of models of movement and force trajectories assume that motor actions are scaled with two centrally defined parameters, one related to planned movement time (*T*) and the other related to planned movement amplitude (*A*) (Enoka 1983; Hogan 1984; Gottlieb et al. 1989; Gutman and Gottlieb 1992). Based on these ideas, the following procedure was performed. For each UM (half cycle of the COP shift), its amplitude and time were defined. The corresponding average time profile ($UM_{UP.AV}$ or $UM_{DOWN.AV}$) was scaled to match its amplitude and time to those of the UM (Fig. 2B). The initial points of the UM and of the scaled UM_{AV} were aligned (note that the final points were also aligned by the procedure). Then, the scaled UM_{AV} was subtracted, point-by-point, from the UM. Each UM of a trial was corrected using this procedure. The residuals (ΔUM_i) formed a new time series (ΔCOP(t)). Note that, within this time series, the peak and valley points of COP(t) were all reduced to zero.

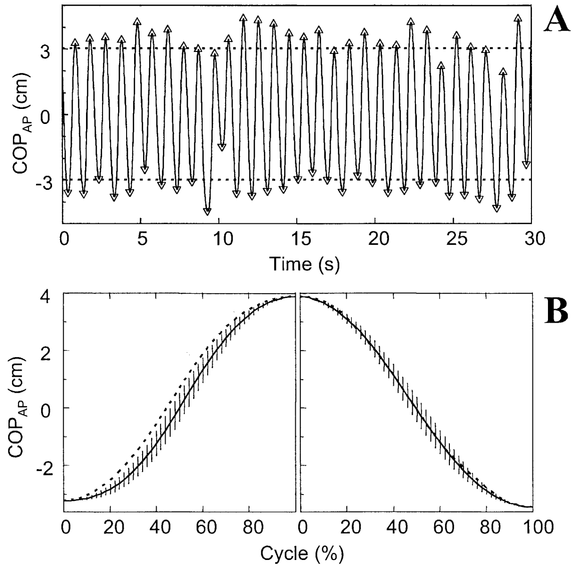

Fig. 2 **A** An exemplary trial of voluntary sway in the AP direction (1 Hz, eyes open). The targets corresponding to COP shift of 6 cm are shown by *dashed lines* and the identified peaks and valleys are shown as *up and down triangles*, respectively. **B** Average ascending and descending unitary movements (UMs, *solid lines*) with standard error bars for the trial above scaled to particular ascending and descending UMs (*dashed lines*) selected from the trial in **A**

This procedure eliminates possible effects of voluntary corrections on the COP trajectory *across* consecutive COP half-cycles. Time profiles ΔCOP(t) can show spontaneous COP shifts *within* each half-cycle and possible voluntary corrections of the COP trajectory occurring within a half-cycle. All our subjects performed smooth COP movements, and there were no obvious signs of corrections within short time intervals that could be restricted to one half-cycle of the COP shift, particularly for COP shifts at relatively high frequencies (1 Hz and over).

Figure 3 shows representative examples of time profiles of the voluntary COP shift in the AP direction (panel A), of the corrected COP trajectory (ΔCOP(t), thin trace in panel B), and of the COP time profile during quiet standing (COP_{ST}(t), bold trace in panel B). Note that the two curves in panel B refer to two different trials and are presented solely for comparison of the amplitudes and the structures of the curves. The subject was standing with open eyes, without instability. Voluntary COP shift was performed at 1 Hz.

3. To further reduce the possibility of voluntary corrections that could occur within each half-cycle, the following procedure was performed. The power spectral density (PSD) analysis was run on each ΔCOP(t) time series and on COP(t) for each trial with quiet stance, for AP and ML components of sway separately. The total power of ΔCOP(t) for each trial with voluntary COP shifts was computed within the range of frequencies from zero to f_{80} (Fig. 4A). This index ($IPSD_{80}$) was used to characterize ΔCOP(t) within a frequency range characteristic of the typical frequencies of postural sway during quiet stance. Note that the

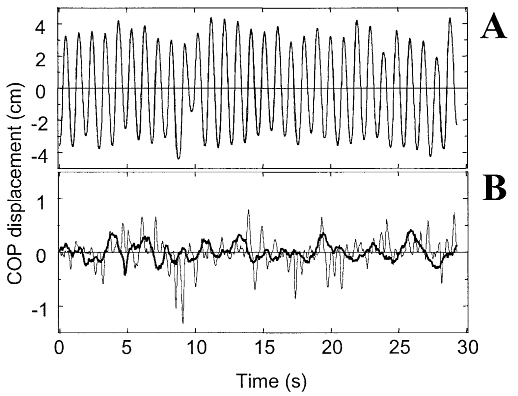

Fig. 3 **A** Exemplary time series of the voluntary COP shifts in the AP direction (1 Hz, eyes open) and the time series of the scaled average unitary movements (UMs; the two lines are superimposed and can hardly be distinguished). **B** The corrected COP trajectory (ΔCOP(t), *thin line*) and the COP time series during quiet standing (*thick line*). The curves show data before filtering at f_{80}

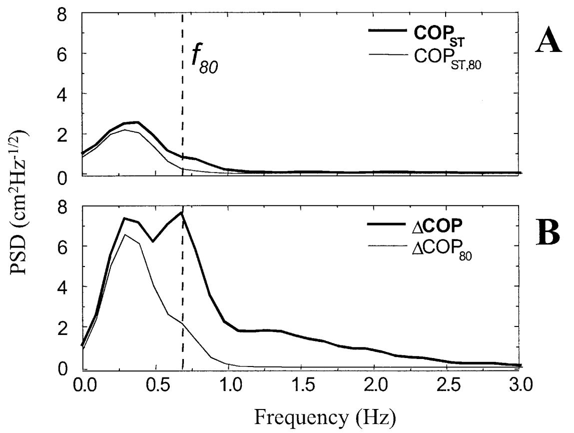

Fig. 4 **A** Representative power spectral density (*PSD*) plots of a COP time series during quiet standing with closed eyes before the low-pass filtering at the f_{80} cutoff frequency (COP_{ST}, *thick line*) and after the filtering ($COP_{ST,80}$, *thin line*). **B** Similar plots for ΔCOP of a time series during voluntary COP shift at 1 Hz with closed eyes: before filtering (ΔCOP, *thick line*) and after filtering (ΔCOP_{80}, *thin line*)

previous procedure (point 2) eliminated possible effects of voluntary corrections that lasted over half-a-cycle (for the slowest movement, at 0.5 Hz, the duration of half-cycle was 1 s corresponding to the frequency of 1 Hz). The current step eliminated all "quick corrections" that could occur within a half-cycle by introducing a low frequency cut-off, f_{80}. For illustrative purposes, the PSD function for a representative ΔCOP(t) series is shown in Fig. 4B prior to and after low-pass filtering at f_{80} with a 4th-order Butterworth filter. The subject performed the task with closed eyes, without instability. Such analysis was used to estimate the average velocity (V_{80}) and RMS of the COP (RMS_{80}).

For comparisons across conditions and across subjects, two types of normalization were performed. First, each index ($IPSD_{80}$, V_{80}, and RMS_{80}) was divided by an index computed for the same subject during quiet stance in a condition matched by other factors (such as Vision and Stability). Second, each index was divided by an index computed during quiet standing without instability and with open eyes. Results obtained after these two types of normalization showed qualitatively similar patterns. Therefore, we will further present mostly findings normalized with respect to indices computed during quiet standing in matched conditions.

Statistical methods

Repeated measures analysis of variance (ANOVA) was run with factors Frequency (five levels), Condition (three levels, stable/open eyes, stable/closed eyes, unstable/open eyes), and Direction (two levels, AP and ML). Full design was not implemented because most subjects could not stand in unstable conditions with closed eyes. For every comparison, data points that were more than 3 SDs away from the mean (across subjects) were identified. If a subject had more than two such outliers, his/her data were not used in that particular comparison (reflected in the DOFs presented in the text). Data for at least eight subjects were used in each comparison.

Results

Characteristics of the quiet stance

Typical illustrations of COP trajectories during quiet stance tasks are shown in Fig. 5. Characteristics of the quiet stance (RMS, *V*, E-area, and f_{80}), across subjects, are shown in Table 1. Note that Table 1 presents the data computed before filtering at f_{80}. The data presented in Table 1, such as RMS, are sensitive to the signal processing, in particular to the detrending procedure, and to the duration of the sample, 30 s in our data (Duarte and Zatsiorsky 2000, 2002; Carpenter et al. 2001). For example, our RMS values in the AP direction (0.33±0.13 cm) are similar to those reported by some authors (Schieppatti et al. 1994; Zatsiorsky and Duarte 1999; Carpenter et al. 2001), but are below values reported in some other studies (e.g., Baratto et al. 2002). Analysis of the effects of closing eyes and standing on the unstable board was performed using a three-way repeated-measures ANOVA (factors Vision, Stability, and Direction, described in "Materials and methods").

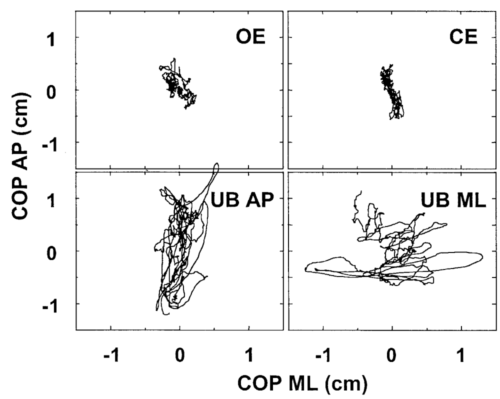

Fig. 5 Representative examples of COP trajectories during quiet standing with open eyes (*OE*), closed eyes (*CE*), instability in the AP direction (*UB AP*), and instability in the ML direction (*UB ML*)

Table 1 Characteristics of postural sway during quiet stance. Means and standard error across subjects are shown. Conditions: open eyes (*OE*), closed eyes (*CE*), instability in the AP direction (*UB AP*), and instability in the ML direction (*UB ML*)

		OE	CE	UB AP	UB ML
RMS (cm)	ap	0.33±0.13	0.34±0.1	0.50±0.19	0.44±0.20
	ml	0.14±0.07	0.12±0.04	0.18±0.09	0.32±0.11
V (cm/s)	ap	0.67±0.14	0.82±0.25	1.24±0.34	0.73±0.20
	ml	0.31±0.07	0.33±0.07	0.46±0.13	0.70±0.29
f_{80} (Hz)	ap	0.64±0.30	0.73±0.33	0.87±0.25	0.44±0.19
	ml	0.62±0.21	0.69±0.10	0.78±0.30	0.86±0.30
E-area (cm^2)	–	0.48±0.33	0.49±0.30	0.99±0.58	1.67±1.10

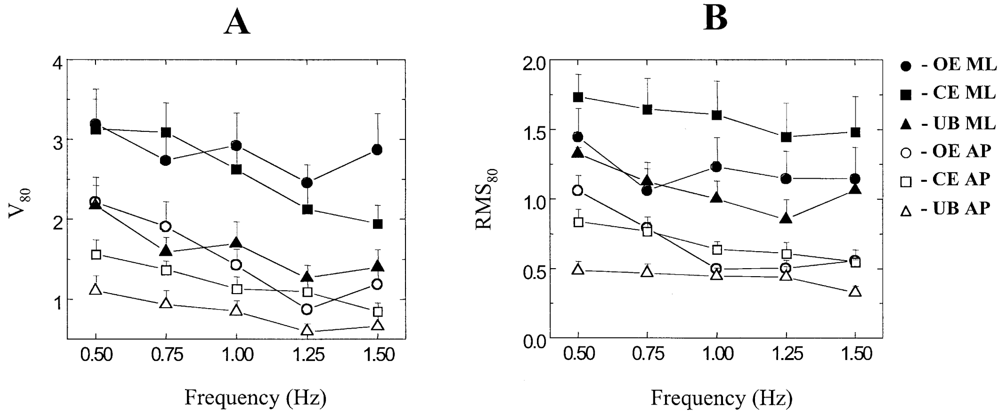

Fig. 6 Values of V_{80} **(A)** and RMS_{80} **(B)** computed for ΔCOP(t) in the direction of the voluntary COP shift for different conditions averaged across subjects (with standard error bars) normalized by the values obtained in each subject during quiet stance trials under matched conditions (*filled symbols* are for COP_{ML}, *open symbols* are for COP_{AP}, *circles* open eyes, *squares* closed eyes, *triangles* standing on the unstable platform)

Standing with closed eyes had relatively small effects on all computed indices; no effects reached the level of statistical significance. In contrast, standing on the unstable board had many significant effects. In particular, it resulted in significantly higher RMS for COP(t) in the ML direction (p<0.001 for comparisons with both open and closed eyes conditions without instability). Effects of instability on RMS in the ML direction were significantly larger than on RMS in the AP direction (p<0.001). E-area increased in both AP and ML unstable conditions, as compared to either OE or CE conditions during standing without instability (p<0.001). E-area was larger during standing with ML instability than with AP instability (p<0.05). Average velocity of the COP time series (V) increased with instability, in particular for the COP time series in the direction of the instability, i.e., for COP_{ML} for the ML instability and for COP_{AP} for the AP instability (p<0.001). Minor effects have been observed on the value of f_{80}. The only significant effect was an increase in f_{80} for the COP_{AP} during standing in AP-unstable conditions as compared to either standing with open eyes without instability or standing with instability in the ML direction (p<0.05).

Characteristics of movement sway

We analyzed characteristics of sway separately for the AP and ML directions. Besides, subjects were asked to produce voluntary shifts of the COP also either in the AP or in the ML direction. In this section, we described separately findings related to sway in the direction of voluntary COP shift (i.e., AP sway for the voluntary COP_{AP} shift and ML sway for the voluntary COP_{ML} shift), and those related to sway orthogonal to the direction of voluntary COP shift (i.e., ML sway for the voluntary COP_{AP} shift and AP sway for the voluntary COP_{ML} shift).

Movement sway in the direction of voluntary COP shift

During voluntary shifts of the COP, subjects tended to show higher sway in the direction of the voluntary COP shift as compared to postural sway during quiet stance. This tendency was particularly pronounced during voluntary COP_{ML} shifts. One unexpected finding was the smaller indices of sway during voluntary COP shifts while standing on the unstable board. Higher movement sway was observed during COP shifts at lower frequencies.

Two panels of Fig. 6 illustrate changes in two commonly used measures of sway, average velocity (V_{80}, panel A), and root mean square (RMS_{80}, panel B)

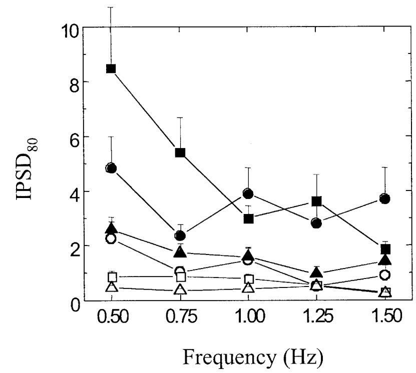

Fig. 7 Values of integrated power spectral density, $IPSD_{80}$, computed for $\Delta COP(t)$ in the direction of the voluntary COP shift for different conditions averaged across subjects (with standard error bars) normalized by the values obtained in each subject during quiet stance trials under matched conditions. Symbols and abbreviations are as in Fig. 6

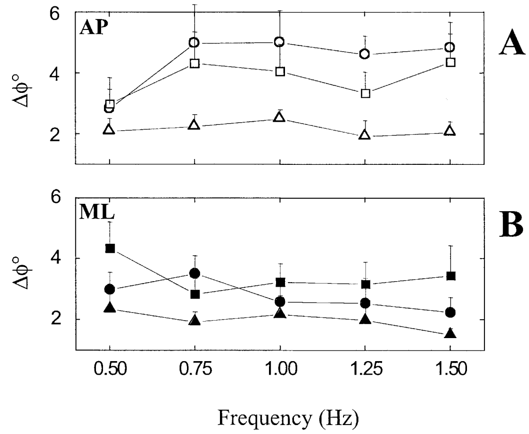

Fig. 8 Absolute angular deviation ($\Delta\varphi$) of the main axis of the PCA ellipse from the required direction of sway as a function of the frequency of the voluntary COP shift averaged across subjects (with standard error bars) for the AP **(A)** and ML **(B)** directions. Symbols and abbreviations are as in Fig. 6

computed for the $\Delta COP(t)$ time series after low-pass filtering at a frequency (f_{80}) corresponding to 80% of the power of the sway during quiet stance (see "Materials and methods"). The data were averaged across subjects and normalized by indices observed in matched conditions during quiet standing.

The index of average velocity of $\Delta COP(t)$, V_{80} (Fig. 6A), showed values significantly above unity (i.e., significantly higher than those observed in matched conditions during quiet stance), for both directions of COP shift and for all conditions with the exception of COP_{AP} in unstable conditions (open triangles in Fig. 6A). The values of V_{80} for COP_{ML} (filled symbols) were significantly higher than for COP_{AP} (open symbols). For both directions of COP shift, there was a decrease in V_{80} with an increase in the frequency of the COP shift. Significantly smaller V_{80} values were obtained in unstable conditions as compared to the other two conditions. These results were confirmed by main effects of all three factors, Condition (OE, CE, UB), Direction (AP and ML), and Frequency (0.5, 0.75, 1, 1.25, and 1.5 Hz) in a three-way ANOVA ($F_{(2,14)}$=41.4, p<0.001; $F_{(1,7)}$=16.6, p<0.005; and $F_{(4,28)}$=16.5, p<0.001, correspondingly) without significant two-way interactions.

RMS_{80} (Fig. 6B) showed patterns similar to those described for V_{80}. Three-way ANOVA showed main effects of each of the three factors, Condition, Direction, and Frequency ($F_{(2,16)}$=9.44, p<0.005; $F_{(1,8)}$=23.0, p<0.005; and $F_{(4,32)}$=10.4, p<0.001, correspondingly). In particular, values significantly above unity were observed for voluntary COP_{ML} shifts (filled symbols), while voluntary COP_{AP} shifts were associated with values under unity (open symbols). Indices for COP_{ML} shifts were significantly higher than those for COP_{AP} shifts. In unstable conditions (triangles), RMS_{80} was significantly smaller than during standing with open eyes without instability. There was a significant increase in RMS_{80} at lower frequencies of voluntary COP shift.

Figure 7 shows the magnitudes of the index of integrated power spectral density ($IPSD_{80}$, see "Materials and methods") for different conditions averaged across subjects (with standard error bars). Values above unity represent increased sway during voluntary COP shifts. The following general findings for the $IPSD_{80}$ index are similar to those observed for the RMS_{80} and V_{80} indices. Three-way ANOVA showed main effects of each of the three factors, Condition, Direction, and Frequency ($F_{(2,14)}$=5.45, p<0.05; $F_{(1,7)}$=12.2, p<0.05; and $F_{(4,28)}$= 6.58, p<0.001, correspondingly). It confirmed that $IPSD_{80}$ was higher for COP_{ML} as compared to COP_{AP}. $IPSD_{80}$ was smaller during unstable standing (UB). It decreased with an increase in the frequency of the voluntary COP shift. This tendency was stronger for the COP_{ML} supported by a significant Direction × Frequency interaction (p<0.05).

Movement sway orthogonal to the direction of voluntary COP shift

The subjects were rather accurate in maintaining the required direction of the voluntary COP shifts. To assess the average direction of the voluntary COP shift in each trial, principal component analysis (PCA) was run on all the data points, an ellipse was fitted to the data to include 85% of all the data points, and the direction of the main axis of the ellipse was defined (Duarte and Zatsiorsky 2002). Figure 8 shows the dependences between the absolute angular deviation ($\Delta\phi$) of the main axis of the ellipse from the required direction of sway and the frequency of the voluntary COP shift (f_{COP}). The data averaged across subjects are shown with standard error bars for the AP (Fig. 8A) and ML (Fig. 8B) directions of the sway and for the three main conditions (open eyes, closed eyes, and unstable). The highest average value of

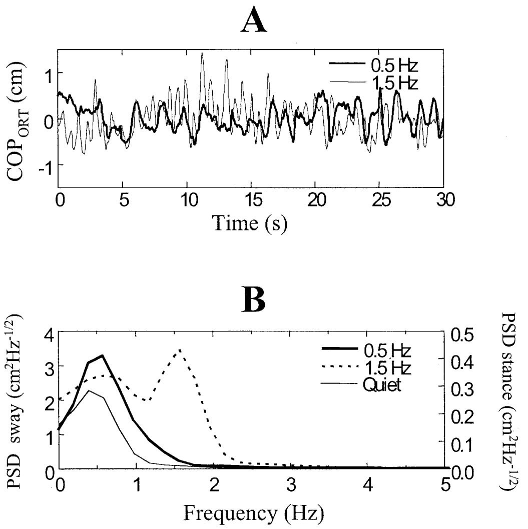

Fig. 9 Representative examples of time series of the orthogonal component of the COP shift (*COP_{ORT}*) for voluntary COP shift at a low frequency (0.5 Hz) and at a high frequency (1.5 Hz) **(A)** and the power spectral density of the respective times series and of the quiet standing task with open eyes for comparison **(B)**. Note the different scales in **B** for the voluntary sway trials (the *left Y-axis*) and for the quiet stance trial (the *right Y-axis*)

Δø was about 5°; hence, a relatively small proportion of voluntary COP shift was in the direction orthogonal to the required direction. The deviations Δø were significantly lower for the unstable conditions when compared to stable standing with open eyes in both directions ($p<0.05$); this is an expected finding since the subjects were constrained to a smaller area of support in the direction orthogonal to the voluntary sway.

Representative examples of time series of the orthogonal component of the COP shift (COP_{ORT}) are shown in Fig. 9 for the lowest frequency (0.5 Hz) and the highest frequency (1.5 Hz) of the voluntary COP shift. Panel B of Fig. 9 shows power spectral density plots for these time series and also for the COP time series observed in the same subject during quiet standing (thin, solid line in panel B). The amplitude of the peak and the area under the spectral curve for quiet standing are lower than those for the low-frequency peaks observed during voluntary COP shifts. At the low frequency of voluntary COP shift (0.5 Hz, thick, solid line), there is a peak in the COP_{ORT} spectrum close to the frequency of the movement as well as to the peak of the spectrum during quiet standing. For the high frequency voluntary COP shift (1.5 Hz, dashed line), there are two prominent peaks, one close to the frequency of the movement, and the other one at a frequency of about 0.6 Hz. Such two-peak spectra were seen in all subjects for the frequencies of voluntary COP shifts of 1 Hz, 1.25 Hz, and 1.5 Hz. At 0.5 Hz and 0.75 Hz, there was typically a single peak in the spectrum of COP_{ORT}(t) between the frequencies of 0.5 and 0.7 Hz. We would like to recall that the procedures for computing the main sway indices ($IPSD_{80}$, RMS_{80} and V_{80}) described in "Materials and methods" eliminated components of the signal at frequencies over 0.7–0.8 Hz. So, the higher frequency peaks, similar to the one illustrated in the lower panel of Fig. 9, did not affect the computed indices.

Figure 10A illustrates indices of COP_{ORT} sway, $IPSD_{80,}$ RMS_{80}, and V_{80}, for different conditions averaged across subjects (with standard error bars) normalized by values obtained in each subject during quiet stance trials in matched conditions. Values of all three indices for both directions of the sway are typically above unity with only a few exceptions. Unlike the data for sway in the direction of the voluntary COP shift (Figs. 6, 7), there were fewer significant changes in these indices computed for COP_{ORT}. In particular, three-way ANOVAs confirmed significant effects of all three factors on V_{80} ($F_{(2,14)}$=11.6, $p<0.01$; $F_{(1,7)}$=6.93, $p<0.05$; and $F_{(4,28)}$=3.67, $p<0.05$, for Condition, Direction, and Frequency, correspondingly), a significant effect of Direction on $IPSD_{80}$ ($F_{(2,14)}$=6.27,

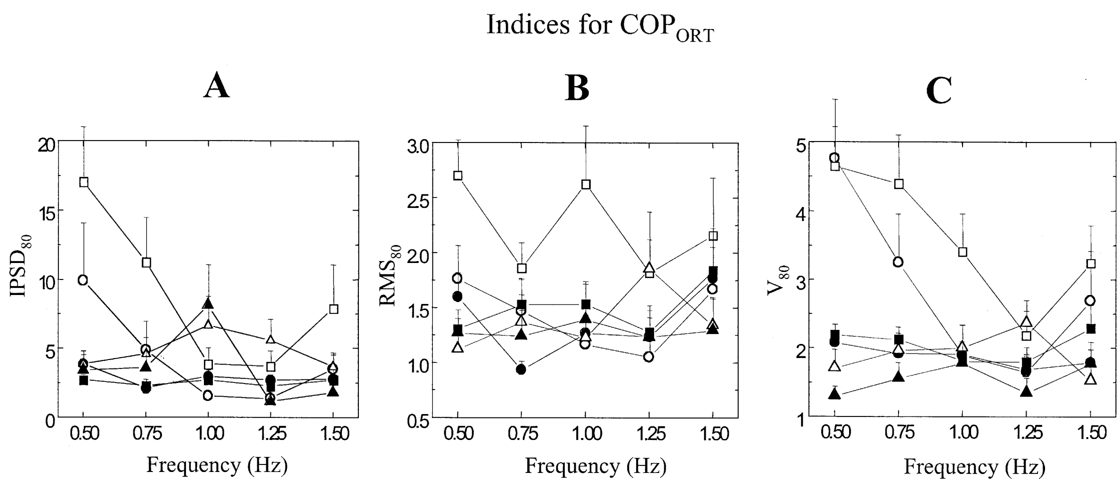

Fig. 10A–C Values of $IPSD_{80}$, RMS_{80}, V_{80} for COP(t) in the direction orthogonal to the direction of voluntary COP shift for different conditions averaged across subjects (with standard error bars) normalized by values obtained in each subject during quiet stance trials under matched conditions. **A** $IPSD_{80}$; **B** RMS_{80}; **C** V_{80}

$p<0.05$), and a significant effect of Condition on RMS_{80} ($F_{(2,14)}=4.62$, $p<0.05$). In particular, these effects reflected a tendency for V_{80} to drop at higher frequencies, a tendency for $IPSD_{80}$ and V_{80} to be higher for COP_{AP} as compared to COP_{ML}, and a tendency for RMS_{80} and V_{80} to be higher for closed eyes conditions as compared to either open eyes or unstable conditions. Significant Condition × Frequency interactions were seen for both $IPSD_{80}$ and V_{80} ($p<0.05$), reflecting a drop in both indices with an increase in the frequency of voluntary COP shift for standing in stable conditions with open or closed eyes, while such a trend was absent during standing in unstable conditions (UB).

Discussion

Our method of quantification of movement sway rests on assumptions related to two phenomena well known from the motor control literature. One is movement variability. The other is postural sway. In the next subsection, we discuss how models of motor variability can be applied to analysis of the migration of the center of pressure during its voluntary shift and how movement sway can be quantified. Further, we discuss implications of our findings for postural control during voluntary actions associated with shifts of the COP.

Variability in posture and movement

In studies of the variability of trajectories of voluntary movements, researchers frequently instruct their subjects to perform the movements “as quickly as possible” and “without corrections” (for reviews see Gottlieb et al. 1989; Newell and Corcos 1993). Such movements are sometimes addressed as “pre-planned.” Across trials, variability of the trajectories of such movements is assumed to originate, in particular, from imprecise setting of movement parameters at a control level. In a model developed by Goodman (Gutman) and his colleagues (Gutman and Gottlieb 1992; Gutman et al. 1993), two sources of motor variability are considered related to imprecise setting of two major parameters, τ and A, related to planned movement time and planned movement amplitude. Patterns of motor variability associated with changes in task parameters and in the instruction have been studied extensively (reviewed in Newell and Corcos 1993). We would like to note, however, that experimental studies and models of motor variability typically do not consider another possible source of the trajectory variability, namely spontaneous changes in the current location of the limb unrelated to its planned motion. In other words, no “sway” associated with voluntary movements is postulated.

Postural sway has been studied in tasks that require maintenance of a posture, most commonly quiet standing (Winter et al. 1998; Collins and DeLuca 1993; Zatsiorsky and Duarte 1999, 2000). There are no compelling reasons to believe, however, that sway disappears when a person performs a voluntary action associated with a shift of the COP. On the other hand, control of a voluntary shift of the COP may be expected to be associated with its own sources of variability related to imprecise setting of parameters of a planned COP shift. For the purposes of the current study, we consider the Goodman (Gutman) model of variability and assume that voluntary COP shifts are associated with selection of two parameters, T and A, directly analogous to Goodman’s τ and A. Each of the two parameters is assumed to be set with an inherent variance, Var(T) and Var(A). A straightforward modification of the Goodman model leads to the following equation for the variance of the planned COP shift related to the variances in setting T and A:

$$Var(COP(t)) = COP^2(t)\frac{Var(A)}{A^2} + t^2(dCOP(t)/dt)^2\frac{Var(T)}{T^2} \quad (1)$$

Within the current study, we have been interested in COP variability that is unrelated to variance in the selection of control parameters but reflects spontaneous COP shifts superimposed on its voluntary shift. This is what we call “movement sway.” The method described in the paper has been developed to separate the two sources of variability and assess changes in movement sway with changes in common task parameters. We have assumed that voluntary COP shifts and sway represent two independent time processes sharing the common plant. The former process has been assumed to be timed to the required motor action, while the latter has not.

The multistep data processing is described in “Materials and methods.” Here, we would only like to note that COP shifts in the orthogonal direction showed irregular patterns rather than clear cyclicity, particularly during low frequencies of voluntary COP shift (Fig. 9). The lack of a clear oscillatory pattern did not allow us to detrend these signals based on a model similar to that of Goodman. Hence, the results of analysis of COP_{ORT}(t) should be viewed as preliminary. We would like to note, however, that spectral analysis of COP_{ORT}(t) time series for voluntary COP shifts at relatively high frequencies (over 1 Hz) showed the existence of two peaks of approximately similar amplitudes, one at the frequency of the COP shift, and the other at about 0.6–0.8 Hz irrespective of the frequency of the voluntary COP shift. We view the existence of these low-frequency peaks as a strong argument in favor of the existence of movement sway.

Analysis of COP_{ORT}(t) showed no special behavior of any indices ($IPSD_{80}$, RMS_{80} and V_{80}) at low frequencies (Fig. 9). We view this observation as another supporting factor for the method of quantifying movement sway: If there were significant effects of voluntary corrections on the outcome indices, these effects could be expected to affect the computed indices mostly at low frequencies of the voluntary COP shift but not at high frequencies.

Sway and the control of postural equilibrium

We would like to consider the phenomena of postural and movement sways within a general scheme of motor control offered by the equilibrium-point (EP) hypothesis (Feldman 1986; Latash 1993; Feldman and Levin 1995). The EP hypothesis had originally been formulated for the control of a single muscle and was later expanded to control of multijoint limbs and whole-body movements (the reference frame hypothesis; Feldman and Levin 1995). According to the EP hypothesis, the CNS specifies commands that modulate spring-like properties of the muscles. Actual equilibrium configuration of the body is defined by an interaction between the centrally defined spring-like properties of the muscles and the external force field. A set of commands to postural muscles may be viewed as defining a reference body configuration.

Within this general framework, maintenance of the vertical posture by a standing subject may be associated with specification of a particular reference body configuration by the CNS. Postural sway may be viewed as a result of superposition of two processes, a migration of the reference configuration and an oscillation about the reference configuration. This interpretation is corroborated by recent studies of two components of postural sway, rambling associated with migration of an instantaneous equilibrium position (an equilibrium trajectory), and trembling interpreted as oscillations about the equilibrium trajectory (Zatsiorsky and Duarte 2000). The former component of the sway (rambling) may be either purposeful, related to exploration of the immediate environment, or a by-product of the functioning of the postural control system without a functional role.

We prefer the former interpretation since it makes the design of the system for postural control different from what could be expected from a not very well trained engineer. This interpretation fits well the hypothesis on the search function of the sway (Collins and De Luca 1993; Gatev et al. 1999; Riccio and McDonald 1998). It is also compatible with a recent suggestion that postural sway is a result of a control process of stabilizing an unstable mechanical system (Baratto et al. 2002). Indeed, if one makes a reasonable assumption that control processes are adjusted to assure exploration of the limits of postural stability, the search function hypothesis suggests what the purpose of the sway may be while the hypothesis by Baratto and colleagues suggests how the sway may come about.

Movement sway and postural sway may be viewed as results of basically similar control processes with the only difference that movement sway occurs on the background of a purposeful shift of the COP. Within the EP hypothesis, we would like to postulate two types of shifts of the reference body configuration as two independent processes whose mechanical effects are superimposed. Sway related shifts of the reference configuration may be expected to be modulated during purposeful COP shifts. Hence, further sections of the "Discussion" are based on an assumption that changes in movement sway with parameters of voluntary action, availability of visual information and conditions of postural stability reflect a purposeful adjustment of the system generating the sway.

Movement sway in the AP and ML direction

Many studies have described lower indices of postural sway in the ML direction as compared to the AP direction (Winter et al. 1998; Balasubramaniam et al. 2000; Duarte and Zatsiorsky 2000). We observed similar relations between the two sway components during quiet stance (Table 1). During voluntary COP shifts, however, indices of sway in the ML direction increased significantly more than those of sway in the AP direction. This was observed when sways in the two directions were compared across tasks, which required voluntary COP shifts both in the direction of the sway and orthogonal to the analyzed sway direction.

We would like to suggest the following tentative explanation for this finding. Large COP shifts in the AP direction are common in everyday activities such as making a step or standing up from the chair (Brenier and Do 1986; McIlroy and Maki 1993; Scholz et al. 2001). COP shifts in the ML direction occur during natural activities but they are less common and are typically of a smaller magnitude (Winter et al. 1998; Duarte and Zatsiorsky 2000). If one views sway as a search process (Collins and De Luca 1993; Gatev et al. 1999; Riccio and McDonald 1998), larger movement sway in the AP direction may be considered a consequence of a more active search in the direction the person is more likely to move, for example to make a step. However, during a voluntary COP shift, the search function of the sway may be suppressed leading to a proportionally smaller increase in the sway in the AP direction, or even to its decrease (see values under unity for open symbols in Figs. 6, 7).

Another relatively unexpected finding is a general trend for movement sway to decrease with an increase in the frequency of the voluntary COP shifts. This finding may be related to the following observation: When a person needs to make a series of steps in challenging conditions, for example to cross a stream by stepping on several stones, he or she either stands on a stone and plans the following action or tries to make a very quick sequence of steps. Very rarely, one can observe walking at a slow pace in such conditions. This choice may be based on the observed feature of sway to be the lowest during quiet stance or during fast COP shifts.

Effects of instability on movement sway

If a person stands in comfortable, secure conditions, the search function of the sway may be expected to be reduced reflected in smaller sway. If a person feels insecure in the limits of postural stability, the search for these limits may be expected to increase leading to larger sway. The more insecure the person feels, the larger the area "scanned" by the hypothesized search mechanism is.

This can explain increased postural sway observed during standing on a board with the reduced support area (cf. Mochizuki et al. 1999). In our experiments, the narrow dimension of the board was relatively wide (6 cm) such that the subject could stand without changing the sway characteristics and without danger of losing balance.

In contrast to the increased postural sway in unstable conditions (Table 1), movement sway was the smallest when the subjects performed voluntary COP shifts while standing on the unstable board. This was true for the sway components along the direction of the voluntary COP shift (i.e., along the larger dimension of the support beam) and for the sway orthogonal to this direction (i.e., along the narrow dimension of the support beam). The controller apparently has an ability to modulate the magnitude of the movement sway with the task. COP shifts while standing on a narrow board can be compared to a task of walking along a narrow plank. During performance of such a challenging task, the search function of the movement sway may be wisely suppressed leading to the observed results.

Concluding comments

The introduced method allows the quantification of spontaneous migrations of the COP that occur on the background of purposeful voluntary COP shifts. During voluntary COP shifts, the magnitude of the sway (of the order of 1 cm) is comparable to the magnitude of the COP shift (a few centimeters). As such, movement sway may be a limiting factor in some actions that require accurate COP shifts. We believe that the introduced method has a potential for applications in clinical studies of movements and other applied areas including movements of athletes.

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