

Changes in Postural Sway and Its Fractions in Conditions of Postural Instability

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We investigated changes in postural sway and its fractions associated with manipulations of the dimensions of the support area. Nine healthy adults stood as quietly as possible, with their eyes open, on a force plate as well as on 5 boards with reduced support area. The center of pressure (COP) trajectory was computed and decomposed into rambling (Rm) and trembling (Tr) trajectories. Sway components were quantified using RMS (root mean square) value, average velocity, and sway area. During standing on the force plate, the RMS was larger for the anterior-posterior (AP) sway components than for the mediolateral (ML) components. During standing on boards with reduced support area, sway increased in both directions. The increase was more pronounced when standing on boards with a smaller support area. Changes in the larger dimension of the support area also affected sway, but not as much as changes in the smaller dimension. ML instability had larger effects on indices of sway compared to AP instability. The average velocity of Rm was larger while the average velocity of Tr was smaller in the AP direction vs. the ML direction. The findings can be interpreted within the hypothesis of an active search function of postural sway. During standing on boards with reduced support area, increased sway may by itself lead to loss of balance. The findings also corroborate the hypothesis of Duarte and Zatsiorsky that Rm and Tr reveal different postural control mechanisms.

Key Words: rambling, trembling, unstable support, human

When a person is standing quietly, there are spontaneous variations in the position of the center of mass (COM) of the body commonly addressed as postural sway. There is also motion of the point of application of the vertical component of the ground reaction force (center of pressure, COP). Force plate allows for direct calculation of the COP position, while calculation of COM position during quiet stance requires application of indirect methods (reviewed by Zatsiorsky & King, 1998). In recent literature, the term “postural sway” is commonly applied to variations in the COP position, and we will use it in this context.

The origins of postural sway are generally unknown. Postural sway has been viewed as a result of a correlated random-walk process (Collins & De Luca, 1993), a result of computational noise (Kiemel, Oie, & Jeka, 2002), and/or a result of the superposition of two processes with different characteristic time constants (Zatsiorsky & Duarte, 1999). The possible importance of postural sway as a reflection of a hypothetical search process within the system of postural stabilization has been emphasized (Riccio, 1993; Riley, Wong, Mitra, & Turvey, 1997).

In earlier studies of anticipatory postural adjustments (APAs) during standing on boards with a reduced support area (Aruin, Forrest, & Latash 1998), we noticed that the participants were more likely to lose balance during standing on boards

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with a narrow support surface when its other (longer) dimension was also decreased, even when this decrease was relatively modest (e.g., 0.08 m). Note that standing on a board with a support surface 0.08 m wide and 0.5 m long did not lead to balance problems. These observations have suggested that (a) postural sway could lead to the COP migrating outside the reduced area of support, causing a loss of balance, and (b) modest changes in the relatively large dimension of the support surface could make the task of quiet standing more difficult.

Based on these pilot observations, we suggest two hypotheses: (1) Postural sway during quiet stance increases with a decrease in the effective dimensions of the support area with larger sway in more challenging conditions, and (2) Postural sway scales with the larger dimension of the support surface. Recently an increase in postural sway during standing on boards with reduced support area has been reported (Latash, Ferreira, Wiczorek, & Duarte, 2003); however, the dimensions of the support area were not manipulated in that study.

Zatsiorsky and Duarte (1999) suggested that the equilibrium is maintained with respect to a moving, rather than stationary, reference point. The developed method involves a decomposition of the sway into two processes, termed rambling (Rm) and trembling (Tr). Rm represents migration of the reference point, with respect to which the equilibrium is instantly maintained. The reference position at discrete intervals of time is estimated by recording the COP position at the instances when the horizontal ground reaction force equals zero, the so-called instant equilibrium points (IEP) (Zatsiorsky & King, 1998). The rambling trajectory is then obtained by approximating the consecutive IEP positions with cubic splines. Tr represents the COP oscillation about the Rm trajectory. Rm and Tr components may show similar behaviors, although typically Tr has smaller magnitude and somewhat higher average velocity than Rm.

If postural sway does depend on the size of the support area, a question can be asked with respect to possible changes in the Rm and Tr components of the sway: Can such a dependence be associated with differential adjustments in the two components (Rm and Tr) of the sway? Answering this question may provide further insights into the nature of the Rm and Tr sway components.

Methods

The participants were 9 healthy adults (8 M, 1 F; 32 ± 8 years old, 76 ± 10 kg weight, 1.80 ± 0.09 m height) without any physical or neurological problems. All gave informed consent according to the procedures approved by the Office for Regulatory Compliance of The Pennsylvania State University.

Apparatus

A force plate (model 4060S Bertec Inc., Worthington, OH) was used to record the three orthogonal components of the ground reaction force (Fx, Fy, and Fz) and three orthogonal moments (Mx, My, and Mz). Platform signals were conditioned and digitized at 40 Hz with a 12-bit resolution using a National Instruments board (model AT-MIO-64E-3, National Instruments Corp., Dallas, TX) and a LabView 5.1-based data acquisition software (LabView 5.1, National Instruments Corp.) installed in a Pentium 450 MHz PC computer (Gateway 2000, Inc., N. Sioux City, IA).

The participants stood on wooden boards with reduced dimensions of the support area. The size of each board was $0.5 \times 0.5 \times 0.025$ m. A small parallelepiped wooden beam was glued to the bottom of each board and oriented such that its main axes coincided with the main axes of the board. The center of the beam was always under the center of the board. Five boards were used with different sizes of the supporting beam (Figure 1). The height of each beam was 0.043 m, while the other dimensions were 0.086×0.086 m (*square*, SQ), 0.043×0.086 m (*narrow-and-short*, NS), 0.043×0.172 m (*narrow-double length*, ND), 0.043×0.500 m (*narrow-and-long*, NL), and 0.086×0.500 m (*wide-and-long*, WL). The main axes of each beam were those parallel to its sides (and also to the sides of the board). Each board was placed on the force plate such that the main axes of the supporting beam were parallel to the main axes of the force plate coordinate system; the beam was always within the force plate dimensions. We refer to the parallel direction of the smaller dimension of the supporting parallelepiped as “challenging direction” (C-Direction, Figure 1).

Procedure

The participants were instructed to stand barefoot as quietly as possible for 32 s, with their eyes

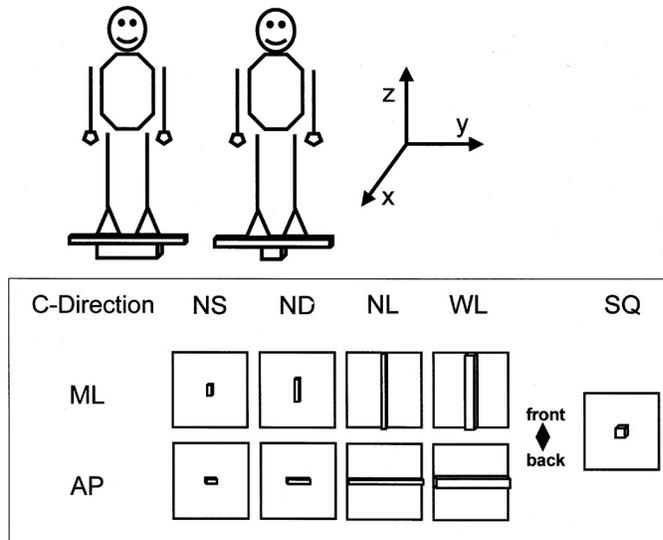


Figure 1 — Experimental setup. The top illustrates a participant standing on an unstable board, on the left under AP challenging direction, and on the right under ML challenging direction. The system of coordinates indicates the positive direction of each axis. The bottom shows the unstable boards and representation of the challenging direction (C-Direction). This bottom view shows the position and shape of different support surfaces: NS = narrow, single length support; ND = narrow, double length support; NL = narrow, long length support; WL = wide, long length support; SQ = square support. Note that both directions are equally challenging for SQ, due its support base symmetry.

open, looking straight ahead, with arms hanging loosely along the trunk and without bending the knees. They were asked to select a comfortable foot position with the feet approximately at hip width, parallel to each other. This foot position was marked on each board, and the participants were required to keep it in all trials. Each trial began after the participant had achieved equilibrium and no abrupt movement in any body part was visible.

Participants performed a total of 10 trials. These included standing on the force plate as well as standing on five different boards with reduced support area. During standing on the boards with reduced support area, the following factors were manipulated: (a) the dimensions of the effective support surface, and (b) the orientation of the narrow dimension of the support surface. The narrow dimension of the supporting surface was oriented either in a sagittal plane or in a frontal plane further addressed as AP-instability and ML-instability, respectively. The order of conditions was balanced across participants.

Before each trial, the participants were allowed to practice standing on the corresponding board. They were given up to 3 min to prepare for the trial; this practice time was enough to assure that all felt confident in their ability to stand on the board for the whole trial. In some trials the participants lost balance, i.e., the board pivoted around the edge of the support surface and hit the platform. If this happened during the first 20 s of the trial, the trial was

repeated. On average, 2 to 3 trials were repeated by each person. On the other hand, if loss of balance happened during the last 10 s of the trial, the time when the board hit the force plate was identified, and the data were analyzed over the time interval up to 2 s before the hit. On average, 1.5 such trials were accepted per person. Because the height of the supporting beam was small, there was no danger of hurting the participant while the loss of balance was obvious. In such situations the participants were instructed to try to recover vertical posture as quickly as possible. Trials associated with lost and recovered balance were analyzed separately (not presented in this paper). Fatigue was never an issue.

Data Processing

The raw data were amplified ($\times 100$) and band-pass filtered (0.06–10 Hz) using a 2nd-order, zero-lag two-way Butterworth filter. The band-pass filtering was performed to get rid of the long-range correlations in the stabilogram (Duarte & Zatsiorsky, 2000, 2001) as well as the high-frequency noise. The data collected over the first and last 2 seconds of each time series were deleted to prevent any filtering associated errors. To avoid any remaining offset on data baseline after the high-pass filtering process, each time series was demeaned prior to further analysis of each variable. The COP location during standing on the force plate was calculated using the equation: $COP_{x,y} = M_{y,x}/F_z$. During

standing on the unstable boards, the effect of shear forces on the computed COP was included taking into account the height of the unstable boards: $COP_{x,y} = (M_{y,x} - F_{x,y} * 0.068) / F_z$, where 0.068 m is the height of each board.

COP trajectory was decomposed into the Rm and Tr trajectories according to Zatsiorsky and Duarte (1999, 2000). Briefly, the method is based on the idea that when the sum of horizontal forces acting from the support surface on the body is zero, the gravity line projection and COP position coincide in the absolute system of coordinates (Zatsiorsky & King, 1998). The gravity line is a vertical line passing through the body's center of gravity. The time series of such points constitutes a sequence of instantaneous equilibrium positions. A spline interpolation of this time series has been termed Rm trajectory. Tr trajectory is obtained by subtracting the Rm trajectory from the COP trajectory. This decomposition procedure was performed separately for postural sway components in the anterior-posterior (AP) and mediolateral (ML) directions (Rm_{AP} , Tr_{AP} ; and Rm_{ML} , Tr_{ML} , correspondingly).

Figure 2 illustrates the results of such decomposition for a typical COP_{AP} time series for a participant who was standing on the force plate without instability. Note that the Rm trajectory follows closely the COP trajectory (top panel). Note also that the

typical peak-to-peak deviations of each trajectory are less than 1 cm.

All the data analyses, including COP trajectory decomposition into Rm and Tr trajectories, were performed using Matlab 5.2 and Statistica software. For each trajectory the following variables were calculated: (1) The area of excursion (E-area) was calculated using the Principal Component Analysis (Oliveira, Simpson, & Nadal, 1996) as the area of ellipses containing 83.35% of the data; (2) Root mean square (RMS); and (3) Mean velocity (V) determined by dividing the total excursion of the COP displacement by the total period of the data (28 s).

The data are presented in the text and figures as means and standard errors. Mixed-effects ANOVA was used with the following factors: *Board* (four levels: NS, ND, NL, and WL); *C-Direction* (two levels: AP and ML); *Sway-Component* (three levels: COP, Rm, and Tr); and *Sway-Direction* (two levels: AP and ML). Tukey's honestly significant difference (HSD) test was used for post hoc comparisons at $p < 0.05$. Linear regression analysis was used to test for relationships between indices of instability (support beam area, support beam perimeter, and support beam diagonal) and the RMS of the postural sway. Those indices of instability represent each *Board* x *C-Direction* condition.

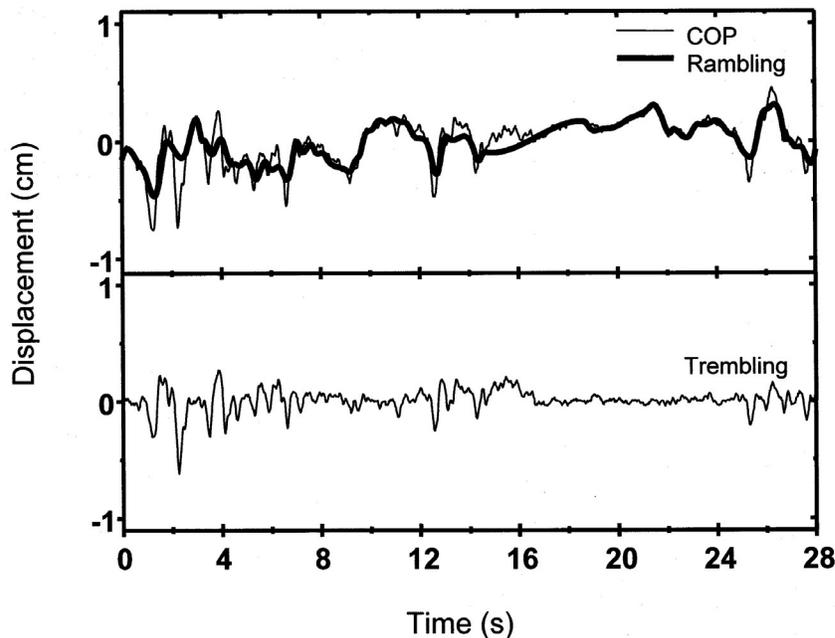


Figure 2 — Decomposition of COP into rambling (Rm) and trembling (Tr) trajectories according to Zatsiorsky and Duarte (1999). Top panel shows the COP (thin line) and Rm (bold line) trajectory. Bottom panel shows the Tr trajectory.

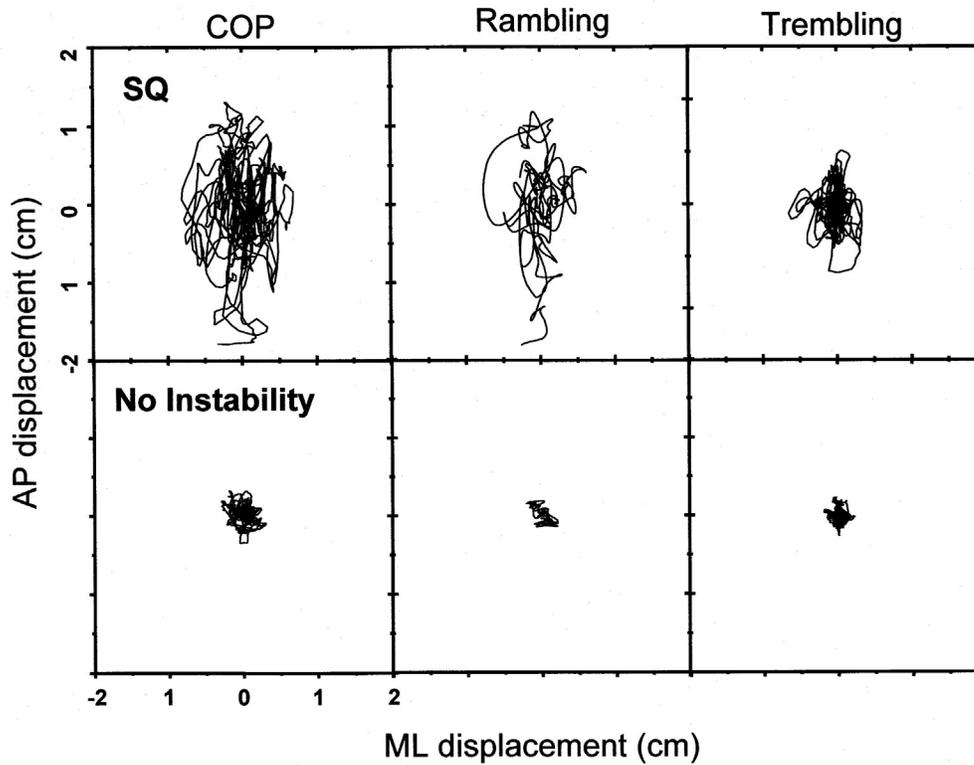


Figure 3 — The COP, rambling (Rm), and trembling (Tr) trajectories during standing on the board with the square support area (SQ, top panel) and during standing on the force plate (bottom panels). Data for a representative participant are shown. Note a substantial increase in the sway and its fractions.

Results

We start this section by showing typical characteristics of quiet standing without instability. The COP, rambling (Rm), and trembling (Tr) trajectories for a representative person standing on the force plate with his eyes open are shown in Figure 3. Averaged across participants, the magnitudes of the sway excursion areas (E-areas), mean velocity, and RMS are presented in Table 1. Characteristics of Rm and Tr components of the sway differed significantly. In particular, two-way ANOVA with factors *Sway-Direction* (two levels: AP and ML) and *Sway-Component* (three levels: COP, Rm, and Tr) showed main effects of *Sway-Direction*, $F(2, 42) = 11.3, p < 0.001$, and *Sway-Component*, $F(1, 42) = 9.4, p < 0.005$, on RMS values. Tukey’s HSD tests on RMS showed that it was the smallest for Tr, $p < 0.001$, and for the ML-direction, $p < 0.004$. For mean velocity, there was only the main effect of *Sway-Component*, $F(2, 42) = 18.5, p < 0.001$.

Table 1 Summary of Variables Related to COP, Rambling, and Trembling During Standing on Force Plate

Variable	Sway direction	RMS (cm)	Velocity (cm·s ⁻¹)	E-area (cm ²)
COP	AP	0.37 ±0.06	0.63 ±0.04	1.23 ±0.16
	ML	0.21 ±0.042	0.65 ±0.10	
Rambling	AP	0.33 ±0.07	0.19 ±0.02	0.88 ±0.19
	ML	0.20 ±0.04	0.29 ±0.03	
Trembling	AP	0.11 ±0.01	0.59 ±0.04	0.54 ±0.13
	ML	0.04 ±0.01	0.63 ±0.10	

Note: Means and standard errors of RMS, and mean velocity are presented for anterior-posterior (AP) and mediolateral (ML) sway direction. Means and standard errors of E-area are presented in the right column.

Tukey's HSD test on mean velocity showed that it was the smallest for Rm, $p < 0.001$.

The following paragraphs deal with the effects of standing on boards with reduced support area. Standing on boards with large support areas, such as WL and SQ (*wide-and-long* and *square*, see Methods) was easy for the participants. Figure 3 shows COP during standing on the SQ board. No one lost balance during any of the trials. Standing on the other three boards, NL, ND, and NS (*narrow-and-long*, *narrow-double length*, and *narrow-and-short*, Figure 1) was considerably more challenging, particularly while standing on the NS board.

Standing on a board with reduced support area was associated with substantial changes in all three sway trajectories, COP, Rm, and Tr. This happened even when the participants did not experience any apparent or self-reported problems with keeping balance. The top panel in Figure 3 illustrates typical COP, Rm, and Tr trajectories during standing on the SQ board. This was an easy task which did not lead to balance problems. Nevertheless, an increase in the excursion of the COP, Rm, and Tr trajectories is obvious as compared to those observed during standing on the force plate (bottom panels).

Tables 2 and 3 present RMS and E-area data for the two directions, AP and ML, during standing on different boards with reduced support area, averaged across participants. The data are shown for

COP, Rm, and Tr separately. Note that all boards, except the symmetrical SQ one, could be oriented to produce either AP-instability or ML-instability (see Figure 1). RMS increased during standing on boards with a smaller dimension of the support area for all three postural sway components, COP, Rm, and Tr. Three-way ANOVA with factors *Sway-Direction* (two levels: AP and ML), *Board* (four levels: NS, ND, NL, and WL), and *C-Direction* (two levels: AP and ML) showed significant main effects of *C-Direction* and *Board* on the RMS for all sway components, $F(1, 128) > 16.4$, $p < 0.001$, and a significant main effect of *Sway-Direction* on Tr, $F(1, 128) = 10.9$, $p < 0.001$. Besides, the *Sway-Direction* \times *C-Direction* significant interaction effect on RMS was only observed for Tr, $F(1, 128) = 10.9$, $p < 0.001$.

Tukey's HSD tests confirmed that RMS was always the largest during ML-instability, $p < 0.001$, for all sway components. Standing on the board with the smallest support base (NS) showed the highest RMS, while standing on the largest (WL) board was associated with the lowest RMS ($p < 0.01$ for each sway component). There was also a significant *Sway-Direction* \times *C-Direction* interaction for Tr: ML-instability led to larger RMS for the ML sway, $p < 0.001$, while during AP-instability the AP and ML sway RMS values were similar.

The observations suggest that postural sway

Table 2 Sway RMS Characteristics During Standing on Boards With Decreased Support Area

Board	COP (cm)				Rambling (cm)				Trembling (cm)			
	Mediolateral		Anterior-Post.		Mediolateral		Anterior-Post.		Mediolateral		Anterior-Post.	
	ML-inst	AP-inst										
NS	0.98 ± 0.01	1.18 ± 0.09	0.84 ± 0.02	0.83 ± 0.03	1.07 ± 0.01	0.88 ± 0.05	0.76 ± 0.03	0.71 ± 0.03	0.63 ± 0.00	0.49 ± 0.03	0.39 ± 0.02	0.35 ± 0.01
ND	0.65 ± 0.12	0.67 ± 0.17	0.61 ± 0.02	0.71 ± 0.04	0.5 ± 0.08	0.56 ± 0.14	0.45 ± 0.01	0.68 ± 0.04	0.39 ± 0.08	0.28 ± 0.07	0.35 ± 0.02	0.17 ± 0.01
NL	0.64 ± 0.08	0.92 ± 0.19	0.39 ± 0.04	0.39 ± 0.07	0.47 ± 0.04	0.72 ± 0.15	0.33 ± 0.05	0.38 ± 0.07	0.4 ± 0.07	0.42 ± 0.10	0.2 ± 0.02	0.12 ± 0.02
WL	0.55 ± 0.07	0.33 ± 0.05	0.37 ± 0.03	0.26 ± 0.03	0.51 ± 0.07	0.24 ± 0.04	0.33 ± 0.04	0.21 ± 0.03	0.15 ± 0.02	0.15 ± 0.04	0.17 ± 0.03	0.1 ± 0.02
SQ	0.46 ± 0.06		0.45 ± 0.07		0.40 ± 0.06		0.38 ± 0.06		0.18 ± 0.04		0.14 ± 0.02	

Note: Means and standard errors of RMS for COP, Rm, and Tr during standing on boards (NS, ND, NL, WL) with decreased support area for the challenging direction (ML- and AP-instability). Note that the data for the SQ board are the same for ML- and AP-instability. Data for the two directions of sway (AP and ML) are presented separately for all boards.

increases when either dimension of the support surface decreases. Apparently, however, changes in the smaller dimension of the support surface have larger effects on the sway components. We tried several functions of the two dimensions of the support surface to account for the sway changes. The best fit was obtained with a function $L_1 \cdot \log(L_2)$, where L_1 is the smaller dimension of the support area, while L_2

is the larger dimension. Linear regression analyses between RMS of the sway and its fractions and the $L_1 \cdot \log(L_2)$ function showed that changes in L_1 and L_2 accounted, on average, for 70% of the variance in RMS. These were statistically significant for 9 of the 12 relationships (3 sway indices by 2 directions of sway by 2 orientations of the board).

Table 3 Sway Area Characteristics During Standing on Boards With Decreased Support Area

Board	COP (cm ²)		Rambl. (cm ²)		Trembl. (cm ²)	
	AP-inst	ML-inst	AP-inst	ML-inst	AP-inst	ML-inst
NS	4.18 ±0.10	3.39 ±0.46	3.97 ±0.23	2.14 ±0.28	1.19 ±0.13	0.40 ±0.02
ND	1.25 ±0.18	1.72 ±0.16	1.28 ±0.26	1.19 ±0.13	0.61 ±0.08	0.23 ±0.02
NL	2.77 ±0.29	1.51 ±0.19	1.70 ±0.14	0.93 ±0.15	0.66 ±0.15	0.36 ±0.06
WL	1.28 ±0.31	1.00 ±0.20	0.58 ±0.12	0.62 ±0.16	0.43 ±0.09	0.45 ±0.10
SQ	1.75 ±0.33		0.97 ±0.19		0.48 ±0.09	

Note: Means and standard errors of the E-area for COP, Rm, and Tr trajectories during standing on boards (NS, ND, NL, WL) with decreased support area for the challenging direction (ML- and AP-instability). Note that the data for the SQ board are the same for ML- and AP-instability.

The data in Table 3 show a significant increase in the E-area for COP, Rm, and Tr with a decrease in the support area dimension. This increase was confirmed by a two-way ANOVA, *Board x C-Direction*, with significant effects of each factor, $F(1, 128) > 24, p < 0.01$. ML-instability led to larger E-area values than AP-instability for both Rm and Tr, $p < 0.01$. The largest E-area of the COP was observed during standing on the board with the smallest support area (NS-board, $p < 0.001$), as confirmed by Tukey's HSD post hoc tests.

Average velocity of the sway components (Table 4) was compared separately for the two directions of sway. Three-way *Sway-Direction x Board x C-Direction* ANOVA confirmed significant effects of *C-Direction* and *Board* on the average velocity of the COP migration, $F(1, 128) > 7.1, p < 0.01$. This analysis also showed significant effects of *Sway-Direction* on Rm and Tr, $F(1, 128) > 11.2, p < 0.001$, and significant effects of *Sway-Direction x C-Direction* interaction on Tr, $F(1, 128) = 11.3, p < 0.001$. Larger sway velocities were observed under ML-instability as confirmed by Tukey's HSD tests,

Table 4 Sway Velocity Characteristics During Standing on Boards With Decreased Support Area

Board	COP (cm·s ⁻¹)				Rambling (cm·s ⁻¹)				Trembling (cm·s ⁻¹)			
	Mediolateral		Anterior-Post.		Mediolateral		Anterior-Post.		Mediolateral		Anterior-Post.	
	ML-inst	AP-inst	ML-inst	AP-inst	ML-inst	AP-inst	ML-inst	AP-inst	ML-inst	AP-inst	ML-inst	AP-inst
NS	3.1 ±0.3	3.5 ±0.2	2.9 ±0.2	2.7 ±0.1	1.4 ±0.1	1.7 ±0.1	1.2 ±0.0	1.7 ±0.1	2.8 ±0.2	2 ±0.1	2.5 ±0.2	2.1 ±0.1
ND	3.2 ±0.7	2.7 ±0.6	3 ±0.3	2.1 ±0.2	1.2 ±0.2	1.6 ±0.4	0.8 ±0.0	1.7 ±0.2	2.9 ±0.6	2.1 ±0.5	2.9 ±0.3	1.4 ±0.1
NL	3.2 ±0.4	3.5 ±0.6	1.5 ±0.2	1.1 ±0.1	0.9 ±0.1	1.5 ±0.3	0.4 ±0.1	0.7 ±0.1	3 ±0.4	3 ±0.6	1.4 ±0.2	0.9 ±0.1
WL	1 ±0.1	1.2 ±0.2	1.1 ±0.1	0.8 ±0.1	0.3 ±0.03	0.4 ±0.02	0.3 ±0.05	0.3 ±0.04	0.9 ±0.07	1.1 ±0.2	1 ±0.11	0.7 ±0.1
SQ	1.1 ±0.1		1.2 ±0.1		0.3 ±0.04		0.5 ±0.1		1.0 ±0.1		1.0 0.05	

Note: Means and standard errors of average velocity for COP, Rm, and Tr during standing on boards (NS, ND, NL, WL) with decreased support area for the challenging direction (ML- and AP-instability). Note that the data for the SQ board are the same for the ML- and AP-instability. Data for the two directions of sway (AP and ML) are presented separately for all boards.

$p < 0.01$ (Table 4). Post hoc tests revealed that the sway components were the slowest during standing on the WL board with the largest support area, $p < 0.001$. Average velocity of Rm was larger in the AP direction than in the ML direction, $p < 0.001$, while average velocity of Tr was slower in the AP direction than the ML direction, $p < 0.001$. A significant *Sway-Direction* \times *C-Direction* interaction for Tr velocity confirmed that during ML instability, ML sway was faster than AP sway, $p < 0.001$, while during AP instability there were no differences between ML sway and AP sway.

Discussion

Let us start with addressing the two hypotheses formulated at the beginning. The first hypothesis has been that postural sway may increase when participants stand on a board with a decreased support area. Our experiments have shown that this is indeed the case (Latash et al., 2003). This effect was seen even during standing on boards with rather large support dimensions (WL and SQ). None of our participants showed visible signs of losing balance while standing on these boards despite the increase in sway. The effect was more pronounced during standing on more challenging boards. With respect to the second hypothesis, a decrease in the larger dimension of the support area led to an increase in the sway above and beyond the effects of changing the smaller dimension.

The modest 4% increase in the distance from the center of mass to the force platform was not perceived by the participants. Besides, this increase was the same across all boards with reduced support area and was unlikely to bring about the observed differences in COP migration (sway), which was computed taking into account the height of the boards. Note that typical COP excursions during standing on the platform without instability were very small, of the order of 1 cm (Figure 2). Such excursions would not have threatened balance even during standing on the most challenging boards (ND and NS), and would not even have approached the limits of the support area for WL and SQ boards. The participants could generally ignore the fact that the support area was decreased and could stand normally. This would apparently be an optimal strategy to avoid losing balance. However, they did not use this strategy. Why?

There have been several studies linking postural sway to hypothetical control processes. A classical feedback control scheme (Maurer & Peterka, 2005; Peterka, 2002) has been able to simulate sway characteristics with changing parameters of the peripheral system. An optimal control approach has been used by Kuo (1995), while a scheme combining feedback and feedforward control has been suggested by Morasso and colleagues (Baratto, Morasso, Re, & Spada, 2002; Jacono, Casadio, Morasso, & Sanguineti, 2004). A recent study has suggested that postural sway is a consequence of computational noise (Kiemel et al., 2002). However, our observations suggest that postural sway can show an increase in conditions, which allow the participants to keep their control strategy, at least at the selected level of analysis that considers shifts of the center of pressure as the major variable manipulated by the central nervous system to keep balance. As such, they are more compatible with the view that sway reflects processes at the level of planning and exploration.

As mentioned earlier, sway has been discussed as a search mechanism, testing the limits of stability for vertical posture (Ricci, 1993). If this view is accepted, changes in sway may occur due to both psychological and neuromechanical factors. When a person stands under comfortable and secure conditions, the effect of the search function of the sway can be reduced and result in a smaller sway.

If a person feels insecure in the limits of postural stability, the search for these limits may lead to larger sway. The more insecure the person feels, the larger the area “scanned” by the hypothesized search mechanism becomes. This would explain increased sway during standing on unstable boards, even when the support area was relatively large, and larger sway for boards with smaller dimensions of the support surface. This search mechanism does not seem to be constrained by anatomical factors. The anatomy of the lower limbs, in particular the ankle joint, favors larger sway in the AP direction than in the ML direction. The COP and trembling trajectories, however, showed larger sway indices during ML-instability.

A series of studies have shown a decrease in postural sway under postural threat such as during standing close to the edge of a support area elevated above the ground (Adkin, Frank, Carpenter, & Peysar 2000; Carpenter, Frank, Silcher, & Peysar,

2001). Those authors reported an increase in the apparent stiffness of the ankle joint and interpreted the findings within the inverted pendulum model of posture (Winter, Prince, Frank, Powell, & Zabjek, 1996). We would like to emphasize that in the cited experiments, the participants always knew where the edge of support was, and the height of the support area over the floor was substantial to be perceived as a threat. In contrast, in our experiments the participants did not perceive the task as a threat. They experienced loss of balance a few times over the practice trials, and knew that the worst thing that could happen was making a step. In addition, they had no visual information on the actual limits of the support area. These may be the reasons for the increased postural sway to explore the actual limits of support.

This search mechanism may result from a combination of different postural strategies, reflected in motion of the lower limbs and HAT (head, trunk, and arms). HAT movements can easily sway the body in the ML direction (Winter et al., 1996) because such movements generate asymmetrical amounts of vertical ground reaction force under the feet (Rietdyk, Patla, Winter, Ishac, & Little, 1999). As the participants lost balance in practice trials, in particular during their first experience with standing on boards with the ML-instability, they were likely to pay more attention to the difference in the vertical forces produced by the two feet leading to an increased asymmetry in these forces. However, to confirm this idea it is necessary to measure the distribution of forces under each foot.

Although effects of instability on sway characteristics were seen for all three sway trajectories (COP, Rm, and Tr), the effects were considerably larger for Rm than for Tr. This finding corroborates the original suggestion by Zatsiorsky and Duarte (1999, 2000) that Rm and Tr characterize at least partly different processes in the human body. Since Rm has been assumed to reflect migration of instantaneous equilibrium reference, this result corresponds with the earlier suggestion on the central neural causes for increased sway under instability (Latash et al., 2003).

The increase in the sway was different for the AP and ML directions. During stable standing, the sway in the ML direction was smaller than in the AP direction, while during standing on unstable boards this relationship was reversed and the sway

in the ML direction became larger. This was true for instability in both the AP and ML directions. The observations of significant *Sway-Direction* \times *C-Direction* interaction effects on RMS or velocity for Tr but not for Rm support differential effects of instability on the sway fractions.

Our regression analysis has shown that sway characteristics depend on both dimensions of the support area, although the dependence on the smaller dimension was stronger. These results support our second hypothesis, although they show that dependence of the sway on the larger dimension of the support area is weaker than on the smaller dimension. The results also provide a natural mechanism for coupling of the two orthogonal sway components since they both show dependencies on the same two characteristics of the support area. This outcome may be viewed as contradicting earlier conclusions on the lack of correlation between sway components in the AP and ML directions (Winter et al., 1996). However, that study did not analyze relationships between the AP and ML sway components in conditions of postural instability.

We conclude that in our studies the instability played a major role in the apparent coupling between the orthogonal sway components. Our findings may be viewed as compatible with conclusions by Balasubramaniam, Riley, and Turvey (2000), who argued that the orthogonal sway components and the synergies that govern their organization can be independently and flexibly assembled depending on task demands. This view has been supported in recent studies of multi-muscle synergies stabilizing COP displacements in the AP and ML directions in preparation to making a step (Wang, Zatsiorsky, & Latash, 2005). Those studies used the framework of the uncontrolled manifold hypothesis (Latash, Scholz, & Schöner, 2002; Scholz & Schöner, 1999) to quantify covaried changes in elemental variables (muscle modes, see Krishnamoorthy, Latash, Scholz, & Zatsiorsky, 2004) that stabilized COP shifts. The synergies showed different behaviors for AP and ML COP shifts.

Postural instability in our experiments may be viewed as a model of increased risk of falls. The observed substantial increase in postural sway, even when the support area was relatively large, suggests that two groups of factors may contribute to falls. One of them is objective, that is, related to the actual difficulty of a postural task, which may

be caused by such factors as small support area or low friction. The other factor is intrinsic, related in particular to the person's subjective perception of the task's difficulty. An elderly person or someone with a neurological disorder may perceive regular standing without additional support similarly to how our participants perceived standing on the unstable boards. In this case an associated increase in sway may be expected to contribute to the risk of falls. Increasing a person's confidence in the stability of postural tasks may help reduce this risk.

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