Motor Control, 2000, 4, 185-200
© 2000 Human Kinetics Publishers, Inc.

Rambling and Trembling in Quiet Standing

Vladimir M. Zatsiorsky and Marcos Duarte

The goal of this study was to explore the rambling-trembling decomposition in quiet standing. The center of pressure (COP) and the horizontal ground reaction force (F_{hor}) were registered in healthy subjects standing in an upright bipedal posture on a force platform. The COP positions at the instants when $F_{hor} = 0$ were identified (*instant equilibrium points*, IEP) for the anterior-posterior direction, then the COP time series, were partitioned into its components using 2 different techniques, *rambling-trembling decomposition* and *gravity line decomposition*. The two decomposition techniques provided very similar results. An unexpectedly large correlation between the trembling trajectory and the difference between COP and gravity line was found, $r = 0.91$ (range, $0.83 < r < 0.98$). The correlation implies that the GL moves from an IEP to the subsequent IEP along a smooth trajectory that can be predicted by the spline approximation. A substantial negative cross-correlation at a zero time lag was observed between the trembling and the F_{hor}, $-0.90 < r < -0.75$. For the rambling trajectory, the coefficients of correlation with F_{hor} were low, $-0.33 < r < -0.05$. The data support the hypothesis that during quiet standing the body sways for two reasons: the migration of the reference point (rambling) and the deviation away from that point (trembling).

Key Words: human balance, stabilogram, center of pressure, gravity line, motor control

1. Introduction

There is increasing evidence in the literature that the control system for equilibrium includes at least two subsystems, with the first one determining a reference position with respect to which the body equilibrium is maintained and the second one maintaining equilibrium about the preselected reference point. Lestienne and Gurfinkel (1988) coined these systems *conservative* and *operative*, respectively. This hypothesis has been supported by several observations. Amblard et al. (1985) reported that when stroboscopic lighting was used, two modes of visual

---

V.M. Zatsiorsky is with the Biomechanics Laboratory in the Department of Kinesiology at The Pennsylvania State University, University Park, PA 16802. M. Duarte is with the Escola de Educacao Fisica e Esporte, Universidade de Sao Paulo, Av. Mello Moraes, 65, 05508-900, Sao Paulo/SP, Brazil.

control of balance were observed that were well separated in terms of the frequency range of body sway. The first mechanism operated below 2 Hz and was strobe-resistant; the second mechanism operated above 4 Hz and was strobe-vulnerable. Postural and vestibular disturbances performed with frequencies below and above 1 Hz produce opposite effects on the reflex gain and the EMG activity of the m. soleus during standing (Fitzpatrick et al., 1992; cf. Jeka et al., 1998). This finding might suggest two different kinds of postural control acting at different time scales (Gatev et al., 1999). Other evidence comes from investigations in weightlessness (Clement et al., 1984; Lestienne & Gurfinkel, 1988).

During parabolic flights, standing body posture has been reported to change while the ability to maintain balance is retained. The authors associated the changes in body posture with the conservative control system (also called the tonic system) and the ability to retain balance with the operative (phasic) system. The conservative system was immediately affected in weightlessness, and the operative system was left almost unchanged. In another study, Gurfinkel et al. (1995) tilted slowly the supporting surface where the subjects stood at an angular velocity of 0.04°/s. During the tilting, small high-frequency oscillations of the body were superimposed on large, slow-body movements. Hence, the usual process of stabilization of the body continued, but the instant equilibrium was maintained relative to a slowly changing position rather than around a fixed set point. After application of the diffusion (random walk) analysis, Collins and De Luca (1993, 1994, 1995) discovered persistence and antipersistence in the COP diffusion rate over different time scales (approximately below and above 1 s, respectively) and explained their finding by an interaction of open- and closed-loop control mechanisms. They also suggested a model of postural control that includes two linearly superimposed random walkers. In essence, the model represents two postural control subsystems, even though the authors did not spell out this idea explicitly. Another explanation of persistence and antipersistence in the COP migration was suggested by Dijkstra (1998), who developed a feedback control model of balance. The results of his simulation confirmed the idea that balance is maintained by two feedback control systems operating at different time scales rather than by open- and closed-loop mechanisms. The two feedback systems reported by Dijkstra (1998) correspond to the operative and conservative systems described above.

To quantify the contribution of the conservative and operative systems to body sway during standing, Zatsiorsky and Duarte (1999) suggested a method of decomposing the center of pressure (COP) displacement into two components. The reference point migration was called *rambling* and the COP migration around the reference was coined *trembling*. In young healthy people, rambling amplitude was roughly three times larger than trembling amplitude, while the frequency was four times smaller. A large negative correlation at zero time lag between the horizontal force (F_{hor}) and trembling (on average $r = -0.85$) was reported. Hence, the deviation of COP from the rambling trajectory was associated with a restoring force. Correlation of F_{hor} with rambling was much smaller ($r = -0.25$). The following interpretation of the chain of events during balance maintenance was offered (the rambling-trembling hypothesis): (1) The CNS specifies an intended position of the body. The intended position is specified by a reference point on the supporting surface with respect to which body equilibrium is instantly maintained. (2) The reference point migrates and can be considered a moving attracting point. (3) The body sways because of two reasons: the migration of the reference point and the deviation away from the reference point. (4) When the deflection is not too large, the restoring force is due to the "apparent intrinsic stiffness" of the muscles.

Recently, Winter et al. (1998) and Kuczynski (1999) performed another decomposition of the stabilogram that is based on a pure biomechanical consideration, the gravity line (GL) decomposition. (The gravity line is the vertical line passing through the center of mass of the body.) In the GL decomposition, the COP migration is represented as an outcome of two processes, the GL migration and deviation of the COP from the GL trajectory, Δ_{COPGL}. Winter et al. (1998) used an optical method to determine the GL migration. They found a large negative correlation between Δ_{COPGL} and F_{hor} ($r = -0.91$) at a time lag of 4 ms and concluded that during quiet standing, the equilibrium is maintained due to restoring elastic forces.

In this study, two decompositions were performed and compared: (1) rambling-trembling decomposition and (2) GL decomposition. It was expected that a comparison of the two decompositions would allow further exploration of the operative and conservative systems of postural control and a test of the rambling-trembling hypothesis.

2. Methods

2.1 Experimental Procedure

Ten healthy adult subjects (7 males and 3 females) participated in this study. The group's age was 28 ± 5 years, the height was 179 ± 9 cm, and the mass was 78 ± 14 kg. No subjects had any known history of postural or skeletal disorder, and they provided informed consent prior to testing according to the policies established by the Office for Regulatory Compliance of The Pennsylvania State University.

The subjects were asked to stand in an upright bipedal posture on a 40–80-cm force platform (model 4080S, Bertec, Worthington, OH). During testing, the subjects stood barefoot for 30 s with their eyes open. The subjects were instructed to stand with their feet separated at a comfortable width (about shoulder width) and their arms at their sides. They were asked to maintain this position during the entire trial. Data acquisition was performed using a personal computer (model P5-100, Gateway 2000, North Sioux City, IA) with a 12 bit A/D board (model AT-MIO-64E-3, National Instruments Corporation, Dallas, TX) controlled by a special code written using LabView software (LabView 4.1, National Instruments Corporation, Dallas, TX). The signals of three force components and three moment components from the force plate were acquired with a sampling frequency of 40 Hz, the COP displacement were estimated from these data, and all the data were recorded for future processing.

2.2 Data Processing and Analysis

Before the analyses, all data were low-pass filtered with a Butterworth filter of fourth order and zero-lag phase with a cutoff frequency of 8 Hz, since most of the power of the signal is below 1 Hz (see Winter (1995) for a review). A code was written in MATLAB software (MATLAB 5.2, The MathWorks, Natick, MA) for the data processing and analysis.

Stabilogram Decomposition. Technically, both decompositions start from locating the COP positions at the instants when $F_{hor} = 0$, the instant equilibrium positions (IEP). During upright standing, when the human body is at an IEP, the COP coincides with the GL (for the proof see King & Zatsiorsky, 1997; Zatsiorsky & King, 1998; cf. Levin & Mizrahi, 1996) and with the equilibrium reference point (Zatsiorsky & Duarte, 1999).

Rambling and Trembling Decomposition. The rambling and trembling components of the COP trajectory were computed in the following way. The particular moments when F_{hor} changed its sign from positive (negative) to negative (positive) were selected and then the instants at which $F_{hor} = 0$ were estimated by local linear interpolation of the F_{hor} time-history data. The COP positions at these instants (the instant equilibrium points, IEP, or zero-force points) were determined. To obtain an estimate of the rambling trajectory, the IEP discrete positions were interpolated by cubic spline functions (de Boor, 1978). To obtain the trembling trajectory, the deviation of the COP from the rambling trajectory was determined (relative COP position). The method is described in detail elsewhere (Zatsiorsky & Duarte, 1999).

The GL and Δ_{COPGL} Decomposition. A modified version of the zero-point-to-zero-point integration method (King & Zatsiorsky, 1997; Zatsiorsky & King, 1998) was used to compute the GL trajectory. In this method, the values of the F_{hor} are divided by the body mass of the subject and then integrated twice on the intervals from one IEP point to the subsequent IEP. The method requires knowledge of the two integration constants at each IEP-to-IEP interval. The integration constants were computed as follows.

Given that at two consecutive IEP instants, $t_0|F_{hor} = 0$ and $t_f|F_{hor} = 0$, the COP positions coincide with the GL positions, the first integration constant is $x(t_0) = x_{COP}(t_0)$. The initial velocity can be determined by:

$$v(t_0) = \frac{x_{COP}(t_f) - x_{COP}(t_0) - \sum_{t_0}^{t_f} \Delta_t \sum_{t_0}^{t_f} \frac{F_x(t)}{M} \Delta_t}{(t_f - t_0)}$$

where M is the body mass. Finally, the GL trajectory is found by:

$$x(t) = x_{COP}(t_0) - v(t_0)(\mathrm{t} - \mathrm{t}_0) + \sum_{t_0}^{t_f} \Delta_t \sum_{t_0}^{t_f} \frac{F_x(t)}{M} \Delta_t$$

In addition to the GL trajectory, the deviation of the COP from the GL trajectory (COP – GL, Δ_{COPGL}) was computed.

2.3 Other Methods

Cross-Correlation Analysis. The COP, GL, Δ_{COPGL}, rambling, and trembling trajectory data were cross-correlated with the $F_{hor}(t)$, where $F_{hor}(t)$ is a time series of the horizontal force. The cross correlation was estimated using a maximal time lag of 1 s.

Fourier Frequency Analysis. The Power Spectral Density (PSD) of the signals was estimated using Welch's averaged periodogram method (MATLAB Signal Processing Toolbox, The MathWorks, 1996) with a resolution of 0.039 Hz.

Phase Portrait Analysis. This method involves plotting a signal versus its first time derivative and has been used for stabilographic analysis before (Riley et al., 1995).

Routine Statistical Methods. These were employed to analyze the experimental data. Because of the non-Gaussian distribution of the correlation coefficient variable, we present the group data as the median values and the total range. With the exception of the force-field analysis explained later in the text, only the data for the anterior-posterior direction are analyzed in this paper.

3. Results

3.1 Correlation Analysis

The results of the cross-correlation analysis were very close to the previously reported values that were obtained on another group of subjects (Zatsiorsky & Duarte, 1999). In particular, the maximal values of the coefficients of correlation with the F_{ap} were always negative and observed at zero time lag. The correlation matrix computed at zero time lag is presented in Table 1. Two groups of correlation coefficients attract attention, correlations between (a) parameters of the two COP decompositions and (b) characteristics of the COP displacement and the horizontal force.

A large correlation between the trembling trajectory and the difference Δ_{COPGL} was found, $r = 0.91$ (range, 0.83 ↔ 0.98). The similarity means that over the IEP-to-IEP intervals, the curves obtained as a piecewise spline approximation

Table 1 Correlation Matrix: Median (First Row) and Minimum and Maximum Values (Second Row)

Variable	F_{hor}	COP	Rambling	Trembling	GL	Δ_{COPGL}
F_{hor}	1	–0.35*** –0.53↔–0.13	–0.19 –0.33↔–0.05	–0.87*** –0.90↔–0.75	–0.22* –0.35↔–0.05	–0.92*** –0.94↔–0.89
COP		1	0.98*** 0.97↔0.99	0.30** 0.04↔0.55	0.99*** 0.96↔0.99	0.31** 0.11↔0.53
Rambling			1	0.13 –0.12↔0.35	0.99*** 0.98↔0.99	0.18 0.01↔0.33
Trembling				1	0.17 –0.07↔0.38	0.91*** 0.83↔0.98
GL					1	0.17 –0.02↔0.35
Δ_{COPGL}						1

$*p < .05$; $**p < .01$; $***p < .001$.

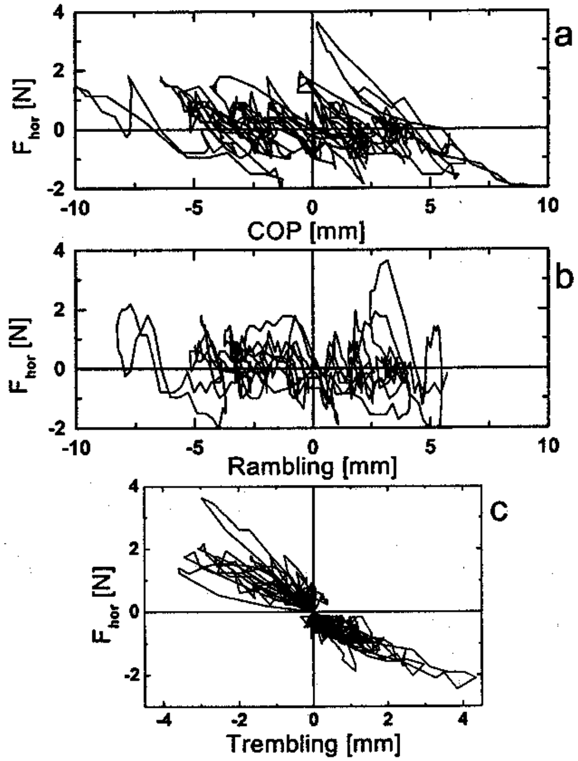

Figure 1 — A representative example of the relationship between the parameters (COP, rambling, and trembling) and the horizontal ground reaction force, F_{hor}. For the COP position, the anterior direction is to the right; for F_{hor} the anterior direction is up (subject BF). (a) COP versus F_{hor} ($r = -0.49$). The COP positions along the $F_{hor} = 0$ line represent the IEP migration. Note the inclined COP–F_{hor} loops over short-range intervals of time. An inclined loop signifies a negative correlation over short-range intervals of time. The positive ($F_{hor} > 0$) and negative ($F_{hor} < 0$) loops are approximately equally inclined and scattered along the COP position axis. It seems that neither the sign of the loop nor the loop inclination depends on their location. (b) Rambling versus F_{hor} ($r = -0.24$). The short-range correlation disappeared; the loops are oriented vertically. It appears that displacement of the rambling trajectory is not related to changes in F_{hor}. (c) Trembling versus F_{hor} ($r = -0.89$). A large negative correlation was observed. Note the "butterfly" appearance of the curves. The coefficient of regression was $s_{RMA} = -1.33$ mm/N.

of the IEP trajectory (rambling) were very close to the curves computed as a second integral of the horizontal force (GL trajectory). Also, very high coefficients of correlation between the COP, rambling, and GL trajectories were observed ($r > 0.97$). Because all three trajectories intercept at the IEP, this correlation was expected and is trivial.

A large negative cross-correlation between the F_{hor} and trembling at zero time lag was obtained, $-0.75 > r > -0.90$. The deviation of the COP from the rambling trajectory gave rise to the force directed opposite to the deviation. Hence, the force was analogous to a restoring force. For the difference Δ_{COPGL}, the coefficients of correlation with F_{hor} were similar to those observed for trembling, $-0.89 > r > -0.94$. The data for the difference Δ_{COPGL} are in good agreement with the coefficient reported by Winter et al. (1998), $r = -0.91$. Note that different methods were used in these two studies to estimate the GL trajectory.

For the rambling trajectory, the coefficients of correlation with F_{hor} were low, $-0.03 > r > -0.33$. The coefficients of correlation of the GL trajectory with F_{hor} were also low, $-0.05 > r > -0.35$.

A more detailed analysis of the scattergrams revealed that the correlation of COP with F_{hor} was chiefly observed during the short-range intervals of time (Figure 1a). Note the inclined COP-F_{hor} loops in Figure 1a. With the exception of the extreme positions of COP, F_{hor} did not depend on the COP location with respect to the external system of coordinates. Large displacements of COP were not accompanied by a rise in F_{hor}. However, a rise in F_{hor} was observed when COP displaced slightly at any current COP location. When F_{hor} values were compared with the rambling trajectory, the same loops were oriented vertically, and the correlation almost disappeared (Figure 1b). The plots of the trembling trajectory versus F_{hor} exhibited a large negative correlation (Figure 1c). As it was expected, each loop started at the origin of the system of coordinates.

The amplitude and frequency characteristics are presented in Table 2 and Figure 2. In comparison with rambling, trembling is a low-amplitude, high-frequency process. The frequency of trembling is much larger than the rambling frequency. Note the evident similarity between the frequency characteristics of trembling and Δ_{COPGL}.

4. Discussion

4.1 Similarity Between the Trembling and Δ_{COPGL}

The correlation between the trembling trajectory and the difference Δ_{COPGL} was unexpectedly strong; the group median is $r = 0.91$. Hence, the rambling and GL trajectories were close to each other during the inter-IEP intervals.

Table 2 Amplitude and Frequency Characteristics (Average for the Group ± *SD*)

Characteristics	F_{hor}	COP	Rambling	Trembling	GL	Δ_{COPGL}
St. deviation (n or mm)	0.60 ± 0.16	4.62 ± 1.00	4.42 ± 1.05	0.80 ± 0.21	4.40 ± 1.04	0.73 ± 0.19
Mean frequency (Hz)	1.35 ± 0.14	0.33 ± 0.06	0.22 ± 0.04	0.91 ± 0.18	0.22 ± 0.03	1.02 ± 0.09
Median frequency (Hz)	1.00 ± 0.14	0.25 ± 0.04	0.21 ± 0.03	0.74 ± 0.18	0.21 ± 0.03	0.85 ± 0.09
Peak frequency (Hz)	0.66 ± 0.26	0.17 ± 0.02	0.16 ± 0.01	0.57 ± 0.19	0.16 ± 0.01	0.66 ± 0.21

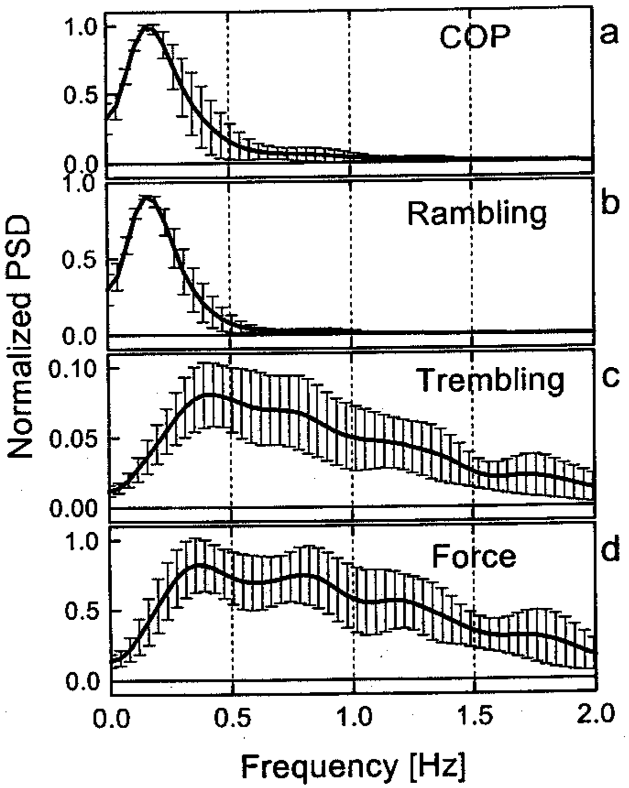

Figure 2 — Power spectral density (PSD) of the COP, rambling, trembling, and F_{hor} ($n = 10$, a-p direction). For each subject, the PSD data (in mm²/Hz) were normalized with respect to the individual peak values of PSD, then the normalized data were averaged for the group. For comparison, the rambling and trembling PSD were normalized again by the mean peak of the COP PSD. The vertical lines are ±1 *SD*. The PSD of trembling and F_{hor} look similar. The contribution of trembling to the COP PSD is less than 10%.

To estimate the trajectory of the reference point (i.e., the point with respect to which the equilibrium is instantaneously maintained), we approximated the discrete IEP trajectory by cubic splines. When using cubic splines, each segment between the data points is connected by a third order polynomial, and the slope of each cubic polynomial is matched at the data points. To estimate the GL trajectory, we integrated twice the horizontal acceleration of the center of mass (F_{hor} divided by the body mass) on the interval from one IEP to the subsequent IEP.

The observed similarity between trembling and the difference Δ_{COPGL} means that GL moves from an IEP to the subsequent IEP along the trajectory that was predicted by the cubic spline approximation. Because the only distinguishable quality of splines is their smoothness, an analogy can be established between the GL migration during upright standing and body limb movements. It has been reported that human arm movement is coordinated in such a way as to produce the smoothest possible movement of the hand (Flash & Hogan, 1985). However, in the arm movement studies, the smoothness was characterized by jerk, the third time derivative of displacement and, hence, the parameterization was done with respect to time. In this study, the smoothness of the GL migration in the IEP-to-IEP intervals refers only to the movement geometry, the trajectory of GL. It seems that during the IEP-to-IEP intervals, the GL moves along a smooth trajectory predicted by the spline approximation. It is quite possible that the smoothness of the GL trajectory is determined by pure mechanical reasons, in particular by the inertia of the body.

In general, the two decompositions yielded very similar results.

4.2 On the Rambling-Trembling Hypothesis

In the literature, two renditions of balance maintenance in upright posture are most accepted. According to the first point of view, the upright posture can be compared to (and modeled as) an inverted or compound pendulum oscillating around a fixed reference point (Hayashi et al., 1977; Karlsson & Winter, 1995b; Lanshammar, 1997; Winter et al., 1998). An opposing idea is that the postural control system allows a certain amount of sloppiness in balance control; in particular, the system allows the COP to drift for some time and/or displacement before feedback mechanisms are activated (Collins & De Luca, 1993, 1994, 1995), see also (Newell et al., 1997; Riley et al., 1997).

The rambling-trembling hypothesis combines the two theories. According to this hypothesis, body sway during upright standing arises from both the deviation from the reference position (trembling, pendular-like movement) and the reference point migration (rambling). Movement along the rambling trajectory does not induce substantial restoring forces, but the deviation from the rambling trajectory does. The following evidence seems to support this interpretation:

1. The large short-range correlation with the restoring force and a low value of correlation over the long-range intervals of time (Figures 1a and 1c). The F_{hor} directed opposite to the deflection always accompanies the deflection of the COP from the rambling trajectory.
2. The independence of the short-range correlation from the COP position on the force platform (Figure 1a).
3. The lack (or a low value) of correlation between the displacement along the rambling trajectory and the F_{hor}. Motion along the rambling trajectory is not associated with a substantial rise of the restoring force (Figure 1b).

Some additional considerations, such as the phase portraits of the signals and the postural force fields, also support the hypothesis.

Phase Portraits. The position-velocity loops for the COP and rambling do not have a single pole: the loops migrate along the position axis (Figure 3). The phase portrait of trembling resembles a limit cycle attractor that corresponds to the steady fluctuation of the process around a certain position.

Postural Force Fields. In mathematics, a vector field is defined as a function that assigns a vector to each point in some region in the plane or space. To

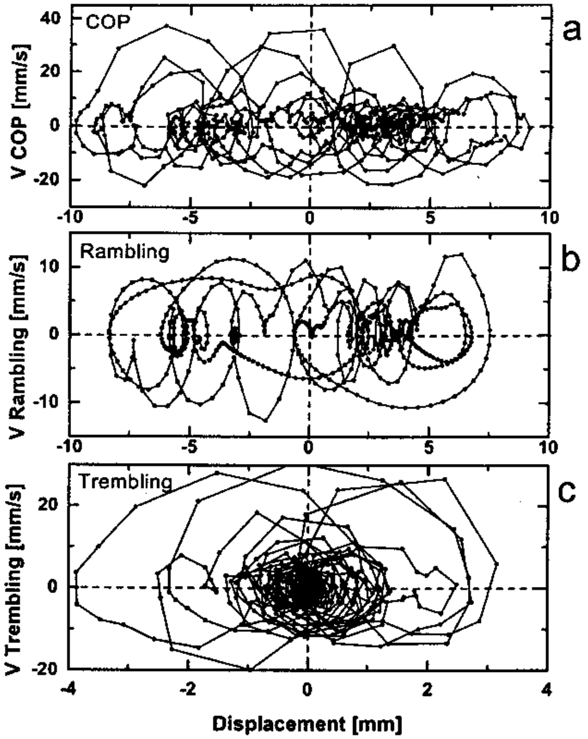

Figure 3 — Phase portraits of the COP, rambling and trembling. A representative example (Subject BF, a-p direction). Note the different scales in the graphs. While the amplitude of rambling is larger than the amplitude of trembling, the velocity of trembling is roughly twice that of rambling. It seems that the COP amplitude is determined mainly by the amplitude of rambling, but the COP velocity is influenced chiefly by the trembling velocity.

study postural force fields during standing, we plotted the force vectors along with the COP trajectory in the horizontal plane (Figure 4). The arrows depicting the force vectors are drawn with the tails at the COP trajectory.

The vectors that originated at different parts of the COP trajectory converged at dissimilar poles (compare the parts of the curve marked with numbers 1 and 2). Hence over long-range intervals of time, the restoring forces do not form a constant vector field converging to a single pole. However, the forces registered during short-range intervals of time seem to converge to one pole (parts of the curve marked 1 and 2). This suggests that at each instant of time the restoring forces form a vector field. However, the vector field is not constant but migrates. These findings do not support the explanations of balance maintenance as a pendular-like movement about a fixed equilibrium position or the opposing idea that the body drifts freely over some time without corrections. If the body were oscillating around a fixed center, the following would happen: (a) the IEP would not move and, thus, the rambling trajectory would be a straight line; (b) the restoring forces would highly correlate with the deviation from the center (i.e., with the COP); in reality, this correlation is much lower than the correlation with trembling; (c) the phase portraits of the COP migration (position-velocity plots) would be circular trajectories around the center; and (d) a converging vector force field would be found. None of these was observed.

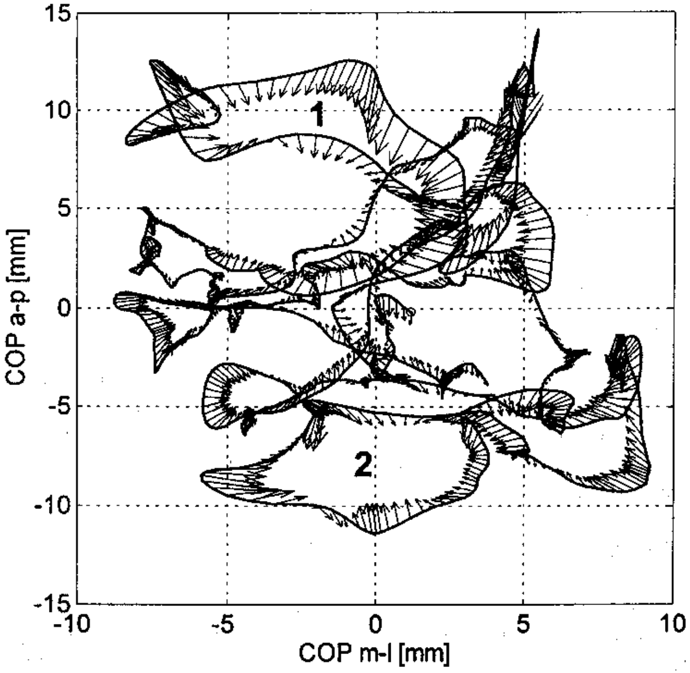

Figure 4 — Postural force field: 2-D representation of the COP trajectory with the F_{hor} vectors. Note that (a) over short-range intervals of time, consecutive force vectors converge to (approximately) one pole, and over long-range intervals of time they converge to different poles, and (b) the force vectors are directed at an angle to the preceding COP force-to-force displacement. Oftentimes, the displacement-force angles are almost to the right angles (subject KD).

If the COP were allowed to drift freely over some time without corrections, the high negative correlation over short-range intervals between the F_{hor} and trembling would not be observed. Rather, a large negative correlation between the F_{hor} and rambling would be expected.

The concept of the migrating reference point with respect to which balance is maintained is similar in spirit to the concept of the virtual trajectory (Bizzi et al., 1984; Hogan, 1984; Katayama & Kawato, 1993) developed in the framework of the equilibrium-point hypothesis (Feldman & Levin, 1995; Latash, 1993) to explain arm movement. However, the rambling trajectory does not specify a unique joint configuration. The same location of the set point for equilibrium may correspond to different body postures.

The reason for the perpetual set-point migration (rambling) is unknown at this time. The rambling trajectory can be due to "noise" in the central nervous system and muscles that carries little useful information (Fitzpatrick et al., 1992; Ishida & Imai, 1980; see also De Luca, 1997; Turvey & Carello, 1996). Or, it can be the result of a certain searching process performed to update sensory information instrumental to standing balance (Riccio, 1993).

Also, the high correlation between trembling and F_{hor} may be interpreted differently. Trembling is a high-frequency oscillation around the rambling trajectory. It is not clear whether the correlation with F_{hor} is high because the oscillation is *fast* or because the oscillation takes place *around the rambling trajectory*. Since trembling is a high-frequency process, the body's acceleration and consequently the horizontal force induced by trembling is much larger than the force induced by rambling (cf. Gurfinkel, 1973). As a result, the coefficients of correlation between F_{hor} and trembling are much larger than the coefficients of correlation between F_{hor} and rambling. Another topic of contention is the origin of the restoring forces in standing.

4.3 Restoring Forces in Quiet Standing

The following explanation of stable equilibrium is commonly accepted in the literature: When a body deflects from an equilibrium position, restoring forces drive the body back to equilibrium. In a semi-symbolic way, this can be written as: When X deviates from Y, restoring force Z is acting. The problem that we are going to discuss is: What are X, Y, and Z in quiet standing? In other words, deviation of what from what induces restoring forces?

In this study, F_{hor} behaved as a restoring force: The coefficients of correlation at zero time lag between the horizontal force, on the one hand, and the COP, trembling, and Δ_{COPGL}, on the other, were always negative. The behavior of F_{hor} resembled elastic forces that are (a) directed opposite to the deflection, (b) proportional to the magnitude of the deflection, and (c) acting without time delay. The maximal values of the coefficients were always observed at zero time lag (Winter et al., 1998, reported for the F_{hor}-Δ_{COPGL} correlation, a lag of 4 ms). These data seem to support the idea that small deviations from an equilibrium position during quiet standing are counterbalanced by "apparent muscle stiffness" (Grillner, 1972; Gurfinkel et al., 1974; Winter et al., 1998). However, to prove the elastic nature of F_{hor}, the force should be compared with the body (X) deflection from an equilibrium position Y.

We started this study with the assumption that X is the gravity line and Y is the instant equilibrium reference (i.e., the rambling trajectory). An idea that stabilization of the GL is a basic posture control mechanism has been addressed in the literature (Horstmann & Dietz, 1990). However, in this study we were not able to confirm experimentally that the deviation of the GL from the rambling trajectory is associated in quiet standing with the rise of a restoring force. (We were not able to reject this hypothesis either.) The correlation between the difference GL – rambling and the F_{hor} was on average only –0.34 (n = 10). Hence, we were not able to prove that the rise of the horizontal force was associated with deviation of the GL from the rambling trajectory.

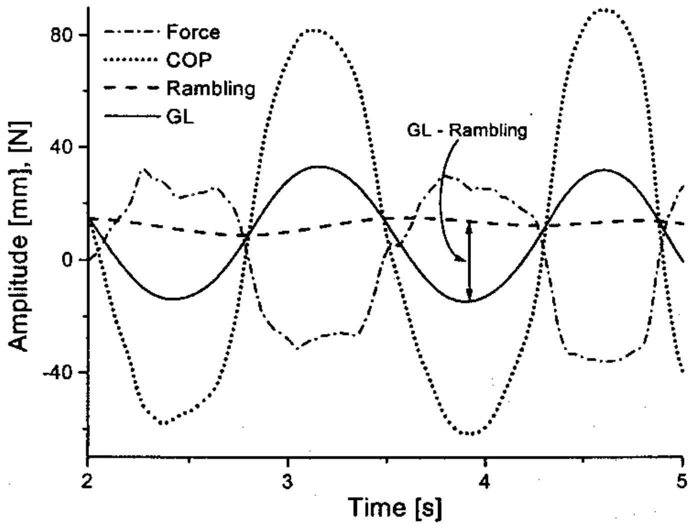

Figure 5 — Experimental parameters during the ankle sway for subject FD.

We offer two hypothetical explanations for this finding. The first explanation is that during quiet standing, the rambling trajectory and the GL trajectory were so close to each other that the employed methods were not sensitive enough to discern the difference. To explore this rationale further we asked a subject to perform intentional body sway either at the ankle joints ("ankle sway") or at the hip joints ("hip sway"). The correlation between the difference GL – rambling and F_{hor} increased to –0.97 during the ankle sway and to –0.89 during the hip sway. Hence, the deviation of the gravity line from the rambling trajectory gave rise to the restoring force. However, during the ankle sway the F_{hor} was highly correlated ($r > -0.95$) with the GL-rambling difference; and also with the COP, GL, trembling, and the COP-GL difference. (The correlation with the rambling was around zero.) During the ankle sway the body oscillated as a single inverted pendulum with large amplitude around a slightly moving reference (rambling trajectory), and all the parameters that characterize the deviation from the reference were highly correlated (multicollinear; see Figure 5). During the hip sway, however, the multicollinearity was absent; the correlation with F_{hor} was for the COP, $r = -0.69$; for rambling, $r = -0.07$; for trembling, $r = -0.80$; for GL, $r = -0.39$; and for Δ_{COPGL}, $r = -0.68$. Although the high negative correlation observed between the deviation of the GL from the rambling trajectory and F_{hor} seems to support the rambling-trembling hypothesis, it cannot be considered a final proof of it because of the difference in the tasks. During intentional body sway, the deviation of the GL from the rambling trajectory as well as the restoring forces were preprogrammed; however, during quiet standing, according to the hypothesis, this deviation is a signal that triggers the restoring force.

The second explanation is that the CNS does not use the GL displacement as an immediate source of information and relies on other signals (e.g., the COP position, joint configuration). After all, the CNS has no means to calculate such an abstract parameter as a GL location. At least two candidates can replace the GL in the control of upright posture. The first is the stretching of the ankle joint muscles that induces restoring forces of an elastic nature. The mechanical response is instantaneous, in contrast to built-in time delay that occurs with feedback response (Grillner, 1972; Gurfinkel et al., 1974; Winter et al., 1998). Theoretically, the displacement of GL may not correspond to ankle joint movement due to the motion of other joints (e.g., the hip joint; Kuo et al., 1998). However, according to experimental evidence, the anterior posterior motion of COP during quiet standing is in phase with the angular motion at the ankle joints (Gatev et al., 1999). Hence, this mechanism is feasible. The second explanation is that regulation of bipedal stance depends mainly on load receptors (Dietz et al., 1992). In this scenario, the COP location and velocity, rather than the GL location, serves as a main source of information. Gatev et al. (1999) recently found that in quiet standing anterior posterior motion of the GL lags behind the EMG activity of the m. lateral gastrocnemius in intervals ranging from 260 to 350 ms. They suggested that this precursory muscle activity is due to some feedforward control. The possibility of feedforward control mechanisms of balance maintenance cannot be excluded, especially for the rambling (cf. Fitzpatrick et al., 1996). However, for the trembling it does not look probable.

If the COP location is an X variable in the previously described scheme, there are two candidates for the Y variable: a fixed center or a moving reference. The assumption about the fixed center was not confirmed in this study (see the preceding discussion). The assumption about the moving reference leads to the rambling-trembling hypothesis. The large negative correlation between trembling and F_{hor} seems to support the idea that X is a relative deviation of the COP from the rambling trajectory Y. The problem, however, is that this correlation can be induced largely by pure mechanical factors. Changes in the ankle joint moment are directly manifested as COP displacements and indirectly as changes in the horizontal force (via acceleration of the center of mass due to the ankle joint moment). For the mechanical analysis, see King and Zatsiorsky (1997) and Zatsiorsky and King (1998). Hence, the question of what exactly induces the restoring force during quiet standing remains unanswered.

References

Amblard, B., Crémieux, J., Marchand, A.R., & Carblanc, A. (1985). Lateral orientation and stabilization of human stance: static versus dynamic visual cues. *Experimental Brain Research*, **61**, 21-37.

Bizzi, E., Accornero, N., Chapple, W., & Hogan, N. (1984). Posture control and trajectory formation during arm movement. *Journal of Neuroscience*, **4**, 2738-2744.

Clement, G., Gurfinkel, V.S., Lestienne, F., Lipschits, M.I. & Popov, K.B. (1984). Adaptation of postural control to weightlessness. *Experimental Brain Research*, **57**, 61-72.

Collins, J.J., & De Luca, C. J. (1994). Random walking during quiet standing. *Physical Review Letters*, **73**, 764-767.

Collins, J.J., & De Luca, C.J. (1993). Open-loop and closed-loop control of posture: A random walk analysis of center-of-pressure trajectories. *Experimental Brain Research*, **95**, 308-318.

Collins, J.J., & De Luca, C.J. (1995). The effects of visual input on open-loop and closed-loop control mechanisms. *Experimental Brain Research*, **103**, 151-163.

de Boor, C. (1978). *A practical guide to splines*. New York: Springer-Verlag.

De Luca, C.J. (1997). The use of surface electromyography in biomechanics. *Journal of Applied Biomechanics*, **13**, 135-163.

Dietz, V. (1992). Human neuronal control of automatic functional movements: Interaction between central programs and afferent input. *Physiological Reviews*, **72**, 33-69.

Dijkstra, T.M.H. (1998). Dynamics of frame of reference captures the two scaling regimes of human postural control. *Abstracts of the Society of Neuroscience*, 28th Annual Meeting (pp. 1768).

Feldman, A.G., & Levin, M.F. (1995). Positional frames of reference in motor control: Their origin and use. *Behavioral & Brain Sciences*, **18**, 723-806.

Fitzpatrick, R.C., Gorman, R.B., Burke, D., & Gandevia S.C. (1992). Postural proprioceptive reflexes in standing human subjects: bandwidth of response and transmission characteristics. *Journal of Physiology*, **458**, 69-83.

Fitzpatrick, R.C., Burke, D., & Gandevia, S.C. (1996). Loop gain of reflexes controlling human standing measured with the use of postural and vestibular disturbances. *Journal of Neurophysiology*, **76**, 3994-4008.

Flash, T., & Hogan, N. (1985). The coordination of arm movements: An experimentally confirmed model. *Journal of Neuroscience*, **5**, 1688-1703.

Gatev, P., Thomas, S., Kepple, T., & Hallett, M. (1999). Forward ankle strategy of balance during quiet standing in adults. *Journal of Physiology*, **514**, 915-928.

Grillner, S. (1972). The role of muscle stiffness in meeting the changing postural and locomotor requirements for force development by the ankle extensors. *Acta Physiologica Scandinavica*, **86**, 92-108.

Gurfinkel, E.V. (1973). Physical foundations of stabilography. *Agressologie*, **14C**, 9-14.

Gurfinkel, V.S., Lipshits, M.I., & Popov, K.E. (1974). Is the stretch reflex the main mechanism in the system of regulation of the vertical posture of man? *Biophysics*, **19**, 761-766.

Gurfinkel, V.S., Ivanenko, Yu.P., Levik, YU.S., & Babakova, I.A. (1995). Kinesthetic reference for human orthograde posture. *Neuroscience*, **68**, 229-243.

Hogan, N. (1984). An organizing principle for a class of voluntary movements. *Journal of Neuroscience*, **4**, 2745-2754.

Horstmann, G.A., & Dietz, V. (1990). A basic posture control mechanism: The stabilization of the centre of gravity. *Electroencephalography and Clinical Neurophysiology*, **76**, 165-176.

Ishida, A., & Imai, S. (1980). Responses of the posture-control system to pseudorandom acceleration disturbances. *Medical and Biological Engineering and Computing*, **18**, 433-438.

Jeka, J., Oie, K., Schöner, G., Dijkstra, T., & Henson, E. (1998). Position and velocity coupling of postural sway to somatosensory drive. *Journal of Physiology*, **79**, 1661-1674.

Katayama, M., & Kawato, M. (1993). Virtual trajectory and stiffness ellipse during multijoint arm movement predicted by neural inverse models. *Biological Cybernetics*, **69**, 353-362.

King, D.L., & Zatsiorsky, V.M. (1997). Extracting gravity line displacement from stabilographic recordings. *Gait and Posture*, **6**, 27-38.

Kuczynsky, M. (1999). The second order autoregressive model in the evaluation of postural stability. *Gait and Posture*, **9**, 50-56.

Kuo, A.D., Speers, R.A., Peterka, R.J., & Horak, F.B. (1998). Effect of altered sensory conditions on multivariate descriptors of human postural sway. *Experimental Brain Research*, **122**, 185-195.

Latash, M.L. (1993). *Control of human movement.* Champaign, IL: Human Kinetics.

Lestienne, F.G., & Gurfinkel, V.S. (1988). Posture as on organizational structure based on a dual process: A formal basis to interpret changes of posture in weightlessness. In O. Pompeiano & J.H.J. Allum (Eds.), *Progress in brain research* (**76**, pp. 307-313). Amsterdam: Elsevier Science.

Levin, O., & Mizrahi, J. (1996). An iterative procedure for estimation of center of pressure from bilateral reactive force measurements in standing sway. *Gait and Posture*, **4**, 89-99.

The MathWorks. (1996). *Signal processing toolbox user's guide.* Natick, MA: Author.

Newell, K.M., Slobounov, S.M., Slobounova, E.S., & Molenaar, P.C.M. (1997). Stochastic processes in postural center-of-pressure profiles. *Experimental Brain Research*, **113**, 158-164.

Riccio, G.E. (1993). Information in movement variability about the qualitative dynamics of posture and orientation. In K. Newell and D. Corcos (Eds.), *Variability and motor control* (pp. 317-358). Champaign, IL: Human Kinetics.

Riley, M.A., Mitra, S., Stoffregen, T.A., & Turvey, M.T. (1997). Influences of body lean and vision on unperturbed postural sway. *Motor Control*, **1**, 229-246.

Riley, P.O., Benda, B.J., Gill-Body, K.M., & Krebs, D.E. (1995). Phase plane analysis of stability in quiet standing. *Journal of Rehabilitation Research Development*, **32**, 227-235.

Turvey, M.T., & Carello, C. (1996). Dynamics of Bernstein's levels of synergies. In M.L. Latash and M.T. Turvey (Eds.), *Dexterity and its development* (pp. 339-376). Mahwah, NJ: Lawrence Erlbaum.

Winter, D.A. (1990). *Biomechanics and motor control of human movement.* New York: J. Wiley.

Winter, D.A. (1995). *A.B.C. (anatomy, biomechanics and control) of balance during standing and walking.* Waterloo: Waterloo Biomechanics.

Winter, D.A., Patla, A.E., Prince, F., Ishac, M., & Gielo-Perczak, F. (1998). Stiffness control of balance in quiet standing. *Journal of Neurophysiology*, **80**, 1211-1221.

Zatsiorsky, V.M., & King, D.L. (1998). An algorithm for determining gravity line location from posturographic recordings. *Journal of Biomechanics*, **31**, 161-164.

Zatsiorsky, V.M., & Duarte, M. (1999). Instant equilibrium point and its migration in standing tasks: Rambling and trembling components of the stabilogram. *Motor Control*, **3**, 28-38.

Acknowledgments

The authors thank Dr. M. Latash, K. Deutsch, and M. Duffey for their valuable comments. M. Duarte is thankful to Fundacao de Amparo a Pesquisa do Estado de Sao Paulo (FAPESP/Brasil) for his scholarship.

Manuscript submitted: February 15, 1999
Accepted for publication: June 15, 1999