Published in final edited form as:

J Mot Behav. 2008 May ; 40(3): 179–185. doi:10.3200/JMBR.40.3.179-185.

Is Voluntary Control of Natural Postural Sway Possible?

Alessander Danna-Dos-Santos, Adriana Menezes Degani, Vladimir M. Zatsiorsky, and Mark L. Latash

Department of Kinesiology, The Pennsylvania State University, University Park

Abstract

The authors explored whether standing human participants could voluntarily decrease the amplitude of their natural postural sway when presented with explicit visual feedback and a target. Participants ($N = 9$) stood quietly, without any feedback and with feedback on the center of pressure coordinate or the head orientation. They were unable to decrease sway amplitude when presented with visual feedback and a target. Decreasing target size led to contrasting effects on the 2 fractions of sway: rambling and trembling. The smaller target was associated with a decrease in rambling and an increase in trembling. Those observations suggest that sway represents a superposition of at least 2 independent processes. They also suggest that providing visual feedback on a variable tied to body sway may not be an effective way to decrease postural sway in young healthy people.

Keywords

posture; rambling; reference configuration hypothesis; sway; trembling

When a person stands quietly, the center of mass of the body and the point of application of the ground reaction force (center of pressure; COP) show a natural migration referred to as *postural sway*. In an influential model of quiet standing, researchers have used a single-axis (ankle joint) inverted-pendulum approximation and have considered control of vertical posture to be based on modulation of the apparent stiffness of the ankle joint (Winter, Patla, Rietdyk, & Ishac, 2001). That model has been criticized (Baratto, Morasso, Re, & Spada, 2002; Loram & Lakie, 2002), and, more recently, some researchers have argued for the inadequacy of the single-axis inverted-pendulum model (Hsu, Scholz, Schöner, Jeka, & Kiemel, 2007).

One of the postulates of the inverted-pendulum with a spring model is that the model considers possible changes in spring stiffness but not in another parameter, namely, the resting angle of the spring (Winter, Patla, Prince, Ishac, & Gielo-Perczak, 1998; Winter et al., 2001). Zatsiorsky and Duarte (1999, 2000) formulated an alternative view on the basis of the decomposition of COP trajectories into two components, one termed *rambling* (RM) and the other termed *trembling* (TR). The alternative view is compatible with the equilibrium-point hypothesis of motor control (Feldman, 1986; Feldman & Levin, 1995) and considers standing to be a superposition of two processes: migration of the resting position (i.e., RM) and motion about that migrating resting position (i.e., TR; Zatsiorsky & Duarte, 1999, 2000). Investigators have assumed that (a) RM reflects supraspinal processes that define an instantaneous point about which the body is stabilized and (b) TR reflects the action of spinal reflexes and the mechanical properties of the muscles and joints.

Only a few investigators have reported differences in the behavior of RM and TR trajectories. In particular, Mochizuki, Duarte, Amadio, Zatsiorsky, and Latash (2006) showed different changes in characteristics of RM and TR with changes in effective support area and suggested that RM could reflect a search strategy (see also Bottaro, Casadio, Morasso, & Sanguineti, 2005; Riccio, 1993; Riley, Wong, Mitra, & Turvey, 1997).

In this study, we asked the following question: Can humans voluntarily decrease the natural body sway magnitude? More specifically we asked the following: Can a person stand with smaller COP migration (in comparison with natural quiet stance) if he or she is given feedback on COP or another related variable and an explicit target, small or large? We modified explicit accuracy constraints on sway by using visual feedback on two mechanical variables. One of the variables was the current location of the COP, which researchers commonly use to estimate sway quantitatively. The other was projection of a laser beam mounted on the cap that the participant wore, which may be viewed as a more intuitive target, although the projection reflected both body sway and head motion. We hypothesized that participants would respond to more demanding targets by decreasing RM trajectory (which is purportedly under supraspinal control), whereas they may maintain or even increase the TR trajectory because of changes in the contraction of muscles acting at the major leg joints and modulation of spinal reflex gains. We expected that participants would use head motion to stabilize the laser beam projection and, as a result, would demonstrate smaller effects of accuracy constraints on the RM trajectory.

Method

Participants

Nine people (4 men and 5 women; age = 27.8 ± 3.1 years [$M \pm SD$], weight = 72.5 ± 17.1 kg, and height = 171 ± 5.9 cm) participated in the study. All participants were healthy and had no known neurological or muscular disorder. Participants gave informed consent on the basis of procedures approved by the Office for Research Protection of The Pennsylvania State University.

Apparatus

We used a force platform (AMTI, Watertown, MA; Model OR-6) to record the moments of force around the frontal and sagittal axes (M_y and M_x , respectively). We also recorded the vertical (F_z) and horizontal components of the ground reaction force (F_x and F_y). The signals from the force platform were sampled at 200 Hz with a 12-bit resolution. We used a personal computer (Gateway, 450 MHz) to control the experiment and to collect the data with the customized LabVIEW-based software (National Instruments, Austin, TX; LabVIEW-5).

In some series, the participant wore a customized cap with a lightweight laser pointer attached to the cap's brim at its midline. The laser pointer was aligned horizontally so that its beam projected on the wall 3.1 m away from the participant (see Figure 1).

Procedures

We began the experiment with one control trial, which we used for normalization of target sizes in further series. This trial also provided reference data for quiet standing when no feedback was provided; we will refer to that phase as the *pretest*. During the control trial, we instructed participants to stand quietly for 60 s, with their feet parallel and 15 cm apart, while they looked at a fixed reference point attached to the center of a monitor screen that was positioned at eye level 0.8 m away from participants. The participants' arms hung loosely along the body sides. The laser pointer was turned on, but no feedback was available to participants because the monitor blocked their view of the beam's projection on the wall (see Figure 1).

An experimenter observed the motion of the pointer's projection on the wall and measured its maximum displacement in the upward-downward direction. We used that value to set the target size in further trials. We computed COP displacement in both anteroposterior (AP) and mediolateral (ML) directions over the control trial and used those values to set the target size in further trials in which we provided COP feedback to participants. We computed the COP signal as

$$\text{COP}_{\text{AP}} = \left[-M_y + (F_x \times h) \right] / F_z, \quad (1)$$

$$\text{COP}_{\text{ML}} = \left[M_x + (F_y \times h) \right] / F_z, \quad (2)$$

where h is the distance between the force plate sensors and its surface top ($h = 36$ mm). We based target size in further trials on a reference size that we defined as the maximum displacement of COP (AP or ML) or laser projection (up-down or ML) during the control trial.

During the main part of the experiment, we instructed participants to stand on the force plate for 60 s in the same posture in which they stood during the control trial. The foot position was marked on the top of the platform and was reproduced across all trials. We provided participants with one of the two sources of visual feedback in each trial. Participants could see either (a) the COP migration in both ML and AP directions (the AP coordinate was shown as the up-down trace displacement) displayed on the screen 0.8 m in front of their eyes with a gain of two (the COP condition; see Figure 1A) or (b) the projection of the laser pointer on the wall (the head condition; see Figure 1B). In experiments with the laser pointer, participants could see the projection of the laser beam on the wall and a circular target. We instructed them to keep the feedback signal—either the COP signal or the laser beam projection—inside the boundaries of the explicit target. We used two target sizes with diameters corresponding to 150% (easy target) and 25% (difficult target) of the aforementioned reference size. We used the larger target to explore possible effects of the presence of any target, even an apparently nonconstraining one, on COP migration. Our choice of the 25% target size was a compromise between the ability of participants to accomplish the task and its relative difficulty. In the pilot series with only a few participants, we obtained qualitatively similar results for the 50% target size. Note that because we modified target size in percent to the values observed during natural sway in both cases, its angular size was independent of the distance to the monitor (or wall). There were a total of five conditions: no feedback, COP feedback (easy and difficult targets), and head feedback (easy and difficult targets). To explore effects of different types of feedback, we used a relatively artificial task that is directly linked to postural sway (COP feedback) and a relatively more natural task (head feedback) in which the feedback was likely affected by both sway and motion of joints along the body vertical axis.

We gave a 5-min familiarization period to each of the participants before data collection. During the familiarization period, participants stood while we provided continuous visual feedback on COP location or the pointer projection. They then performed three trials for each condition. The order of feedback conditions was balanced across participants. We provided a rest period of 30 s between trials; during the rest period we allowed participants to sit but not to change their foot position on the force plate. One more control trial without feedback, identical to the first control trial, was performed at the end of the session (posttest). The average duration of the experiment was 30 min, and none of the participants complained of fatigue or discomfort.

Data Processing

We processed all signals offline by using LabVIEW-5 and MATLAB Version 6.5 (The MathWorks, Natick, MA) software packages. Signals from the force plate were filtered with a 20-Hz low-pass, second-order, zero-lag Butterworth filter. We computed COP coordinates

in the AP and ML directions (COP_{AP} and COP_{ML} , respectively) by using the aforementioned Equations 1 and 2. Once we calculated COP_{AP} and COP_{ML} , we deleted the first and last 10 s of each time series. We band-pass filtered (0.04–10.00 Hz) the remaining 40 s of the data by using a second-order, zero-lag Butterworth filter. We used band-pass filtering to remove possible long-range correlations in the COP time series and high-frequency noise (Duarte & Zatsiorsky, 2001). Each time series was also demeaned and decomposed into RM and TR trajectories according to Zatsiorsky and Duarte (1999,2000). We performed the decomposition for the AP and ML directions separately. An example of a decomposition of the COP_{AP} signal obtained during the control trial is shown in Figure 2A (solid black line). The decomposition first identified instant equilibrium points (IEPs) as the COP (COP_{AP} in Figure 2) positions at instances when the horizontal force was zero. The extrapolation of the individual IEPs formed the RM trajectory (see Figure 2A, gray line), whereas the difference between COP and RM trajectories was the TR trajectory (see Figure 2B).

We used the area of an ellipse (E-area) containing 85.3% of each trajectory (COP, RM, and TR) that combined its AP and ML components to describe the sway-associated time series.

Statistics

We used standard methods of descriptive statistics and parametric statistical methods (SPSS-15). We analyzed COP trajectory characteristics separately for the RM and TR fractions. We performed all analyses of variance (ANOVAs) as mixed designs, and we kept the significance level at $p = .05$. We used the factors (a) control (pretest, posttest) and (b) component (COP, RM, and TR) to test possible differences between pretest and posttest in the E-area values and (c) feedback-source (COP and head), (d) target-size (easy and difficult), and (e) component (RM and TR) on the E-area indices to study effects of the feedback on different fractions of the sway. We checked the data for normality before applying parametric methods.

Results

E-Areas of COP, RM, and TR Trajectories

There were no differences between the control pretests and posttests for the E-area indices that we computed for all three sway trajectories. A two-way ANOVA with factors control (pretest and posttest) and component (COP, RM, and TR) showed no significant effect of control on E-area and no significant interaction, $p > .1$, and therefore confirmed that finding. Hence, in further analyses we used indices averaged across the two control trials. There was a significant effect of component, $F(2, 48) = 22.31$, $p < .001$, which reflected inequalities: $E\text{-area}(COP) > E\text{-area}(RM) > E\text{-area}(TR)$, as confirmed by Tukey's pair-wise contrasts, $p < .05$.

When presented with any visual target, even an easy target that we did not expect to constrain sway, some participants showed an increase in postural sway. This effect is illustrated in Figure 3 for a representative participant. Notice that, once we provided feedback, COP trajectory area increased (cf. Figures 3A-C).

E-area indices for COP, averaged across participants, are shown in Figure 4A. Notice a slight increase in the E-area when a visual target was presented. The increase was somewhat higher for easy target conditions. However, because of across-participants variability, the effect did not reach significance according to the paired t tests. Under feedback on the COP coordinate, the effect approached significance, $p = .1$. The graphs in Figure 4 suggest that participants struggled with the difficult (small) target condition. Their struggle is obvious from the fact that the target was set at 25% of maximum COP excursion in the control trial, and the E-area of the COP migration did not decrease. Instead, it showed a tendency to increase in comparison

with that in the control trial. Indeed, participants spent, on average, 58.4% of the trial time outside the target area when presented with the difficult target.

The other two panels of Figure 4 display averaged across-participants E-area indices for the two components of sway, RM and TR. Presentation of a target led to more pronounced changes in RM and TR E-area indices (see Figures 4B and 4C) than in the COP E-area index. The two fractions of the sway showed contrasting effects of feedback. In particular, there was a decrease in RM E-area for smaller targets, whereas we found an opposite effect for TR E-area (solid arrows). When the source of feedback changed from the COP to the laser beam projection, RM E-area increased, whereas TR E-area decreased (dashed arrows).

We confirmed those findings with a three-way ANOVA with factors feedback source (COP and head), target size (large and small), and component (RM and TR). The ANOVA revealed significant interactions between feedback source and component, $F(1, 64) = 6.6, p < .05$, and between target size and component, $F(1, 64) = 3.98, p < .05$. The ANOVA also showed a significant effect of component, $F(1, 64) = 3.98, p < .05$, confirming the larger E-area for RM than for TR, but no significant effects of feedback source, $F(1, 64) = 0.10, p > .5$, and target size, $F(1, 64) = 0.11, p > .5$.

Discussion

Our main question—Can a person stand with smaller COP migration (in comparison with that of natural quiet stance) if he or she is given feedback on COP or another related variable and an explicit target, small or large?—received a negative answer in the experiments. The sway area showed a counterintuitive and seemingly counterproductive tendency to increase, but the effect varied across participants and did not reach significance. Significant effects of feedback were seen in the two sway fractions, RM and TR, and those effects did follow the predictions we outlined in the introductory comments.

In comparison with presentation of the large (easy) target, presentation of the small (difficult) target, regardless of whether we provided it by using the COP signal or the laser beam projection from the head, led to a decrease in RM. That finding fits the prediction based on an idea that RM reflects supraspinal neural processes and thus is under volitional control. It also fits the general framework of the equilibrium-point hypothesis and its generalization to whole-body actions in the form of the reference configuration hypothesis (Feldman, Goussev, Sangole, & Levin, 2007; Feldman & Levin, 1995). Note, however, that in comparison with the control condition (quiet standing with-out any explicit feedback on sway), RM tended to increase when the easy target was presented. That observation is similar to the reported increase in sway when accuracy constraints are implicit, that is, when participants stand on a surface with a decreased support area (Latash, Ferreira, Wiczorek, & Duarte, 2003; Mochizuki et al., 2006). Researchers have interpreted that observation as a reflection of individuals' search for borders of postural stability in challenging conditions. In our experiment, however, borders of stability were unchanged.

We offer the following interpretation of the present results. COP can shift for two reasons. First, there is a neural process leading to spontaneous changes in the body reference configuration (RM), which may be related to scanning the limits of postural stability (cf. Riley et al., 1997). During natural, quiet standing, the amplitude of the RM sway component is close to a minimum for a given individual. Second, there are processes associated with purposeful changes in the reference body configuration: for example, when postural stability is endangered, when an explicit target is presented, or during natural actions such as stepping (Crenna & Frigo, 1991). Our attempts to help participants to decrease postural sway with visual

feedback failed, suggesting that the sway was originally at its minimum. As a result, we observed a tendency for RM to increase.

We observed a counterintuitive increase in RM when we provided feedback on head orientation rather than the COP coordinate. That result, however, fits well the idea of multieffector synergies that stabilize performance variables (reviewed in Latash, Scholz, & Schöner, 2007). Covaried changes in the whole-body orientation (affected by COP shifts) and head motion could stabilize the laser beam projection. Hence, larger variations in each of the two signals could be expected, compatible with the accuracy constraints.

Effects on the other sway component, TR, were opposite those on RM. We interpreted that result as a reflection of mechanical factors and segmental reflex effects associated with an increase in muscle activation levels (necessitated by the increase in RM). In particular, we would expect an increase in the apparent stiffness of major postural joints to lead to a decrease in the sway component that reflects those factors (cf. Winter et al., 2001) and to affect TR without affecting RM.

In sum, the results of our experiment have shown that participants did not decrease their COP displacement under the two studied feedback conditions. The limited number of conditions does not allow us to reach a firmer conclusion, but the results suggest that providing visual feedback on COP migration or on another variable tied to body sway may not be an effective way to decrease postural sway in young healthy persons. The contrasting effects on RM and TR support the idea that sway represents superposition of two processes that may reflect changes in the body reference configuration and changes in the properties of the mechanical and neural structures implementing the supraspinal control signals.

ACKNOWLEDGMENT

National Institutes of Health grants NS-035032 and NS-050880 in part supported this study. Alessander Danna-Dos-Santos is grateful to Coordenação de aperfeiçoamento de Pessoal de Nível Superior (CAPES), Brazilian Federal Government, for supporting his doctoral studies at The Pennsylvania State University.

Biographical Notes

Alessander Danna-Dos-Santos is a doctoral degree student in the Motor Control Laboratory at The Pennsylvania State University. His research interests include the neurophysiological basis of human postural control.

Adriana Menezes Degani is a research assistant in the Motor Control Laboratory at The Pennsylvania State University. Her research interests include the neuophysiological basis of human posture control.

Vladimir M. Zatsiorsky is professor of kinesiology at The Pennsylvania State University. The courses he teaches include advanced biomechanics of human motion. In his research, he focuses on the biomechanical basis of motor control, with an emphasis on the biomechanics of hand and posture.

Mark L. Latash is a professor of kinesiology at The Pennsylvania State University. The courses he teaches include the neurophysiological basis of movement and movement disorders. His research is focused on the control and coordination of multielement systems participating in the production of voluntary movements.

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FIGURE 1.

Schematic representation of the experimental setup used during a control trial. The same setup was used during actual trials; however, only one of the two sources of feedback was given at a time, either (A) center of pressure position or (B) head orientation. Different target sizes used during actual trials are not represented in the figure.

FIGURE 2.

An example of decomposition of a 40-s anteroposterior (COP_{AP}) signal into (A) rambling (RM) and (B) trembling (TR) trajectories.

FIGURE 3.

Center of pressure (COP), rambling (RM), and trembling (TR) trajectories in the anteroposterior (AP) and mediolateral (ML) directions from a representative participant. The first column (**A**, **D**, and **G**) shows the trajectories when no sway-related feedback was provided. The second (**B**, **E**, and **H**) and third (**C**, **F**, and **I**) columns show the three trajectories with feedback on COP migration in the presence of an easy and a difficult target, respectively.

FIGURE 4.

Averages across participants and standard error of (A) ellipse (E-) area of center of pressure (COP) and (B and C) its rambling (RM) E-area and trembling (TR) E-area components during no-feedback, force plate feedback (COP), and head position (Head) feedback conditions. Solid arrows show the interaction between target sizes (easy and difficult) and the RM and TR components. Dotted arrows show the interaction among the sources of feedback (force plate and head) and the RM and TR components.