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RESEARCH ARTICLE

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Effects of body lean and visual information on the equilibrium maintenance during stance

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Abstract Maintenance of equilibrium was tested in conditions when humans assume different leaning postures during upright standing. Subjects (n=11) stood in 13 different body postures specified by visual center of pressure (COP) targets within their base of support (BOS). Different types of visual information were tested: continuous presentation of visual target, no vision after target presentation, and with simultaneous visual feedback of the COP. The following variables were used to describe the equilibrium maintenance: the mean of the COP position, the area of the ellipse covering the COP sway, and the resultant median frequency of the power spectral density of the COP displacement. The variability of the COP displacement, quantified by the COP area variable, increased when subjects occupied leaning postures, irrespective of the kind of visual information provided. This variability also increased when vision was removed in relation to when vision was present. Without vision, drifts in the COP data were observed which were larger for COP targets farther away from the neutral position. When COP feedback was given in addition to the visual target, the postural control system did not control stance better than in the condition with only visual information. These results indicate that the visual information is used by the postural control system at both short and long time scales.

Keywords Posture · Standing · Balance · Stabilogram · Center of pressure · Human movement

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Introduction

Since humans adopted a bipedal upright stance, they have been challenged to maintain an unstable equilibrium of the body with a high location of the body center of gravity (COG) over a small base of support (BOS; Borelli 1680/1989). To regulate the COG position during standing, the most widely accepted theory is that the postural control system uses the variable center of pressure (COP)[1] to control the COG, since no specific receptors exist in the human body to detect the COG (Morasso and Schieppati 1999). During quiet standing, we normally adopt an upright posture close to the vertical alignment. Yet, under certain circumstances, for example when a perturbation is expected, a number of studies have reported that subjects intentionally lean, i.e., such that the projection of the COG moves closer to the borders of the BOS (Keshner et al. 1987; Horak et al. 1989a; Maki and Ostrovsky 1993). Leaning while standing can also be a requirement for completing a task such as leaning forward to catch a ball or standing on an inclined surface. Few studies have investigated the performance of the postural control system when regulating a steady equilibrium around different mean locations of the COG projection on the BOS, i.e., different leaning positions (Blaszczyk et al. 1993; Horak and Moore 1993; Schieppati et al. 1994; Sinha and Maki 1996; Riley et al. 1997). Besides, those studies did not perform a detailed mapping of the equilibrium around different lean body positions on the BOS plane. Such description can be useful to evaluate the

[1] The COP is the point of application of the resultant of vertical forces acting on the surface of support and therefore represents the collective outcome of the activity of the postural control system and the force of gravity. It can be recorded using a force plate and has become the most frequently investigated parameter in studies on postural balance. The COP position is different from the COG position as the latter indicates the global position of the body, while the COP includes dynamic components due to the body's acceleration. However, at sway frequencies below 0.1 Hz, the COP and the projection on the horizontal plane of the COG, called the gravity line (GL), are almost identical (Gurfinkel 1973; Winter 1995)

performance of the postural control system to control the equilibrium in dangerous situations where people can fall. Locations close to the borders of the BOS, i.e., close to the limits of stability, correspond to the region of transition from an ankle or hip strategy to a stepping strategy, where one can no longer maintain the equilibrium without moving the foot (Horak et al. 1989b). The degree of instability in maintaining equilibrium close to such locations can be an important factor for the postural control system to decide on a stepping strategy even if a leaning posture is mechanically possible. In this sense, an evaluation of how equilibrium is maintained in leaning positions may be relevant to understand the transitions between postural strategies. Lestienne and Gurfinkel (1988) have suggested that different systems of postural control are used to regulate balance. First, a reference position for equilibrium is specified by a conservative system. Second, the equilibrium about the preselected reference position is maintained by an operative system. Some experiments have shown that these two systems can be manipulated separately and act at different time scales (Clement et al. 1984; Lestienne and Gurfinkel 1988; Gurfinkel et al. 1995). Duarte and Zatsiorsky (1999) have applied this hypothesis of two postural control systems to interpret characteristics of the COP time series during natural standing, where people can freely move to adopt different body postures. They conclude that the reference position set by the conservative system could vary during natural standing. In light of this hypothesis, the present experiment aims to investigate the performance of the operative system when different reference positions (the imposed leaning positions) are set by the conservative system. For the maintenance of equilibrium in any unstable condition, the postural control system must use information from at least one of the following sources: the visual, vestibular, and somatosensory systems. It has been reported that the dependence on visual information on the control of balance is greater when standing in a leaning position than in a normal or neutral position (Blaszczyk et al. 1993; Schieppati et al. 1994; Riley et al. 1997). Another source of visual information, the visual feedback of the subject's equilibrium, commonly given by the COP position, has generally been successful for the training of balance, but only one study has investigated the role of the COP feedback during quiet standing in different leaning positions (Hirvonen et al. 1997). However, the experimental protocol of that study only allowed the evaluation of the postural control in the COP-feedback condition and the only dependent measure was the limits of stability. The study of the maintenance of equilibrium in different leaning positions under different conditions of visual information may help to better understand the role of visual information during control of equilibrium. In summary, the objective of the present paper was to study the maintenance of equilibrium in humans in conditions with different leaning postures and with different visual information during standing. The different leaning postures were specified as visual targets in the subject's base of support.

Methods

Sample

Eleven adults (eight men and three women) volunteered for this study. The subjects' mean age was 29±4 years, their mean height was 1.73±0.13 m, and their mean mass was 78±12 kg. All participants were healthy adults, with no prior physical or mental illnesses, and they had normal or corrected-to-normal vision. The local ethics committee, the Office of Regulatory Compliance of The Pennsylvania State University, approved this work.

Task

The main task was to stand on a 40×90 cm^2 force platform (model 4090S; Bertec, Worthington, Ohio, USA) and to maintain the COP in one of the 13 different target positions located within the subject's BOS. Software written in Labview (Labview 5.1; National Instruments, Dallas, Texas, USA) calculated the anterior-posterior (a-p) and medial-lateral (m-l) coordinates of the COP and displayed them as visual feedback in false real-time on the computer screen. The data were sampled at 50 Hz and the acquisition was performed by a standard PC with a 12-bit A/D card (model AT-MIO-64E-3; National Instruments, Dallas, Texas, USA) controlled by the same software written in Labview.

In each trial, one of the 13 targets and the instantaneous time-varying COP position of the subject were displayed on a computer monitor located in front of the subject. The subject was asked to stand in a comfortable position with the feet approximately one shoulder-width apart (the angle between the orientation of the subjects' feet and the a-p direction ranged from 5 to 10°). First, the neutral COP position of the subject was determined as the mean COP position during quiet stance in a 40-s-long trial with eyes open and no COP feedback given. In a second trial preceding the main experiment, the subject was asked to explore their BOS in order to determine their limits of stability (LOS). The determination of the LOS was performed in the following way: While the COP position was displayed on the monitor, the subject was instructed to slowly displace the COP position in all directions as far as possible, keeping both feet completely on the ground. There was no time limit and subjects generally took 1–2 min to complete the task. The 13 COP locations were specified as fractional distances between the LOS and the neutral COP position and are exemplified in Fig. 2a: 0% (the neutral or normal position), 40% and 80% of the distance between the neutral position and the forward (backward) LOS in the anterior (posterior) direction; 40% and 80% of half the distance between the left LOS and the right LOS to the right and to the left in relation to the neutral position; and four positions in the main diagonals: 40% to right and to forward, 40% to left and to forward, 40% to left and to backward, 40% to right and to backward. Figure 2b–d shows an example of the BOS, the LOS, the positions of the 13 different targets, the achieved mean positions, and the ellipses where 85.35% of the COP oscillation lie inside during the trial.

There were three conditions of visual information for each of the 13 targets: (a) with eyes open, termed vision condition; (b) with eyes closed, termed no-vision condition; and (c) with eyes open and the visual feedback of the COP, termed COP-feedback condition. In total, there were 39 trials that were randomized within each block. Between trials, the subjects were allowed to rest, walk or sit, as they preferred, and fatigue was never an issue. Their feet position on the force plate was marked with a pen. If the subjects moved between trials, they were asked to return to the same position. Before the beginning of the main experiment, each subject stood on the force platform with their eyes open and with the visual COP feedback present. According to the displayed target's location on the computer screen, the subject should lean their body in order to move the COP position toward the target. The subjects were instructed to move the COP position to the target location and subsequently keep the COP at the target for the remainder of the trial. When the subject signaled that they were on the target, the

COP feedback was either removed or maintained, or the subject was asked to close their eyes according to the condition for that trial and the data collection started (it took approx. 10 s for a subject to get the COP into a target; longer for the most extreme targets). In the condition with eyes open and no feedback, the subjects were instructed to look at the stationary target on the screen. During the trial, the COP feedback gain (the ratio between the COP displacement in the screen and the actual COP displacement on the force plate) was set to 2, after Krizková et al. (1993), who reported that the gain, which results in the optimal subject's performance, is between 2 and 4.

Data analysis

The first 5 s of the 40-s time series were considered as an adaptation period and were discarded for the data analysis after the filtering processes. The COP data were low-pass filtered at 10 Hz with a fourth-order and zero-lag Butterworth filter, since most of the power of the signal was below 2 Hz (see Winter 1995 for a review). The major part of the time series for the vision and no-vision conditions showed long-period trends or drifts reflecting that the subjects tended to move toward the neutral position when the target was far from this position. This trend constituted a nonstationarity in the data and had to be removed in order to perform standard statistical and spectral analyses (Bendat and Piersol 1986; Duarte and Zatsiorsky 2000). To this end, we used a high-pass Butterworth filter of 4th order and zero lag, with a cutoff frequency twice the frequency of the longest complete period in the time series (T=40 s, F=0.05 Hz). Before the high-pass filtering, the means of the time series were calculated and added back to the time series after the filtering process in order to keep information about the mean locations of the trials. The foot contours on the force plate surface were digitized using a sonic digitizing system with proprietary software (model SAC GP-12XL 3D; Stratford, Conn., USA). The BOS and its area were estimated from the digitized data by calculating the convex area delimiting the data. A similar procedure was used to estimate the LOS and its area from the COP data. The data were analyzed in both space-time and frequency domain. The following variables were computed: mean COP position, area of an ellipse covering the COP sway (COP area), and the median frequency of the power spectral density of the COP displacement (F_{med}). The area was estimated by fitting an ellipse to the COP data (a-p versus m-l) by means of the principal component analysis method. In such a method, the two main axes of the ellipse are found from the eigenvalues of the covariance matrix between the COP data. By construction, 85.35% of the data were inside the ellipse. A code in Matlab language to calculate such an ellipse is given in the Appendix. The median frequency was calculated by the Welch periodogram method with a resolution of 0.039 Hz. The resultant frequency was calculated as the weighted mean of the a-p and m-l components, with the weights given by the respective power of the signals. All analyses were performed using the Matlab 5.3 software (Mathworks, Natick, Mass., USA).

The mean results for the COP area and F_{med} variables for the 13 COP targets and for each of the three visual conditions were fitted by quadratic surfaces of the type $z=ax^2+bx+dy^2+ey+c$, where x and y indicate the a-p and m-l directions; a, b, c, d, and e are empirical constants; and z is the value of the variables, using the least-squares method. The results were also analyzed separately for the targets in the two orthogonal directions and these data were fitted by a quadratic function using a least-squares method. To simplify the analysis, 5 of the 13 COP targets were chosen as representative of the task and were used to test the effect of visual information on the area of the ellipse and median frequency of the COP displacement: the neutral and the four extreme targets (far forward, far backward, far left, and far right). A 5×3 ANOVA was performed with a P-level set to 0.05. Post hoc Tukey tests were used to determine the intralevel difference with a P-level of 0.05. Only the significant interactions among different visual information conditions will be reported.

Results

All subjects were able to successfully complete all trials. The mean and standard deviation values of some parameters of the BOS and LOS for the 11 subjects are described next and represented in Fig. 1. The area of the BOS is 829±103 cm^2 and the area circumscribed by the LOS is 372±76 cm^2 (45.1±7.1% of the BOS). These areas are significantly correlated across subjects (r=0.59, P<0.05). The mean area of the COP displacement during quiet standing in the neutral position with eyes open is 0.29±0.17 cm^2, as shown in Table 1, representing 0.035±0.002% of the area of the BOS. There is no significant correlation between the area of the COP displacement and either the BOS area or the area circumscribed by the LOS, for any target and any condition.

Figure 2 shows a representative example of the BOS, the LOS, the mean positions of the 13 trials, and the ellipses which covered 85.35% of the COP displacement for each of the three conditions. Two features deserve attention in Fig. 2: first, the ellipses in the no-vision condition are bigger than the respective ellipses in the vision and COP-feedback conditions; second, there is a mismatch between the specified target position and the achieved mean position for the targets in the vision and no-vision conditions. For all subjects, we observed slow drifts in the raw COP time series of the trials far from the neutral position in the vision and no-vision conditions, as exemplified in Fig. 3a. For the farthest-forward target in the a-p direction, the difference between the specified target and the achieved mean position by the subjects normalized by the position of the target (relative deviation) was about 6% in the vision condition, 13% in the no-vision condition, and 1% in the COP-feedback condition. A nonparametric Mann-Whitney test revealed that the differences between these relative deviations of the mean

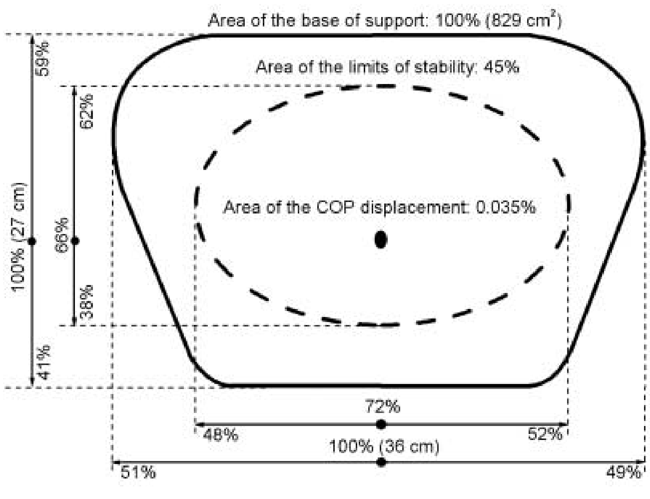


Fig. 1 The mean base of support (*continuous line*), the ellipse representing the mean explored limits of stability (*dashed line*), and the ellipse covering the center of pressure (*COP*) displacement during quiet standing with eyes open. (n=11)

Table 1 Means and standard deviations of the area and of the resultant median frequency of the center of pressure (COP) displacement for the COP targets. See Fig. 2a for all target positions, for the three conditions of visual information: with vision (*V*); with no vision (*NV*); and with COP feedback (*F*). Significant interactions between different visual information are reported. A 5×3 ANOVA and Tukey post hoc tests were used

Target	COP area (cm^2)		COP median frequency (Hz)	
	Significance	Mean±SD	Significance	Mean±SD
Neutral (3)	V, NV**; NV, F**	V=0.29±0.17 NV=0.57±0.43 F=0.32±0.20	NV, F*	V=0.48±0.13 NV=0.42±0.12 F=0.57±0.14
Far forward (1)	V, NV**; NV, F*	V=0.64±0.45 NV=2.03±1.75 F=0.92±0.58	NV, F*	V=0.53±0.17 NV=0.47±0.11 F=0.62±0.12
Far backward (5)	V, NV**; NV, F**	V=0.54±0.39 NV=1.75±1.29 F=0.55±0.20	NV, F*	V=0.56±0.18 NV=0.49±0.10 F=0.63±0.13
Far left (6)	V, NV*	V=0.49±0.26 NV=1.30±1.26 F=0.63±0.36	V, NV**; V, F*; NV, F***	V=0.58±0.12 NV=0.43±0.07 F=0.71±0.12
Far right (9)	V, NV**; NV, F**	V=0.54±0.36 NV=1.38±1.07 F=0.60±0.30	V, F*; NV, F***	V=0.57±0.18 NV=0.46±0.10 F=0.71±0.10

Significance levels:*P<0.05; **P<0.01; ***P<0.001

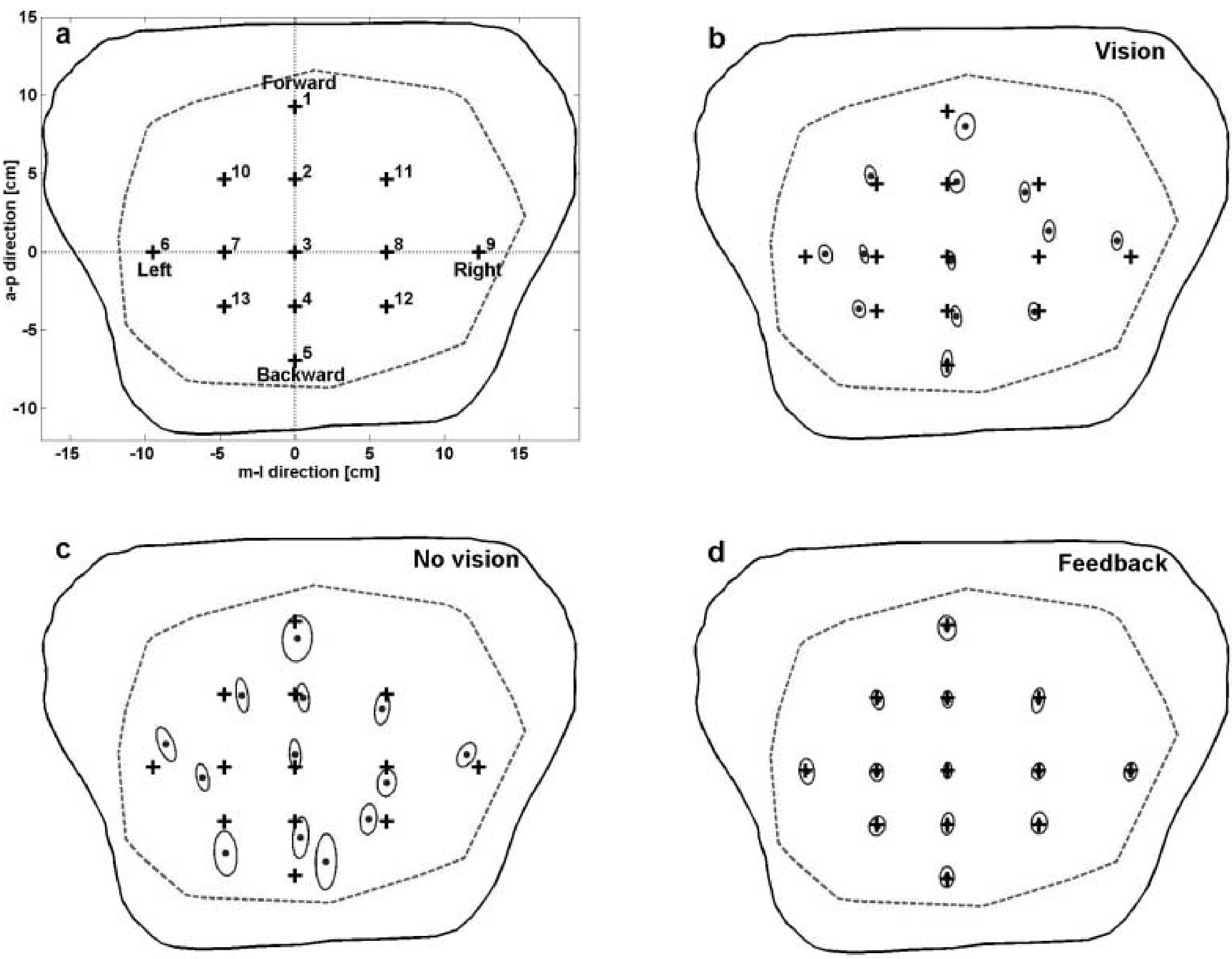


Fig. 2 **a** Example of the 13 target positions (*numbered plus markers*), borders of the base of support (*continuous line*) and the limits of stability (*dashed line*). **b–d** Example of the 13 target positions, achieved mean positions (*dot markers*), and the ellipses representing the COP displacement area for each of the three conditions: vision (**b**), no vision (**c**), and with the COP feedback (**d**)

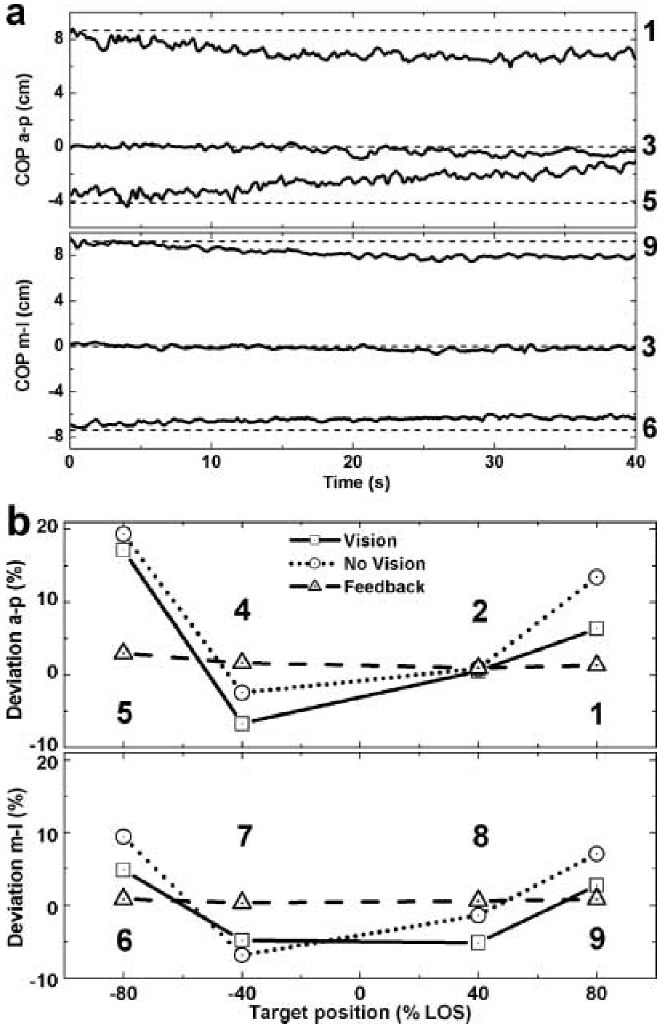


Fig. 3 **a** Example of raw time series of the COP displacement for the no-vision condition in the a-p direction (*upper panel*) and m-l direction (*lower panel*), showing low trends for three targets in each direction (shown as *dashed lines* and identified by the *numbers on the right*). **b** Mean deviation of the trials calculated as the difference between the target position and the mean achieved position for that trial divided by the target position (the targets are identified by the *numbers*). (n=11). The positions of all targets are shown in Fig. 2a

COP position were statistically significant (P<0.05). For the farthest-backward target in the a-p direction, the relative deviations were greater in all conditions than the farthest-forward target but they were not statistically different from each other. For the m-l direction, the relative deviations were about half of those for the a-p direction in all conditions. Statistically significant differences were found for the comparisons between the no-vision and COP-feedback conditions for the extreme-right and the extreme-left targets. The results for the relative deviations of the mean COP position are shown in Fig. 3b.

The values of the COP displacement areas for the 13 COP targets mapped in the a-p versus m-l plane were successfully fitted by quadratic surfaces in the three different conditions of visual information (Fig. 4, upper panel). In the left lower panel of Fig. 4, results are shown separately for the five targets in the m-l direction (the targets numbered 6, 7, 3, 8, and 9 in Fig. 2a); the right lower panel shows similar results for the targets in the a-p direction (the targets numbered 1, 2, 3, 4, and 5 in Fig. 2a). It can be seen in Fig. 4 that the COP area values are greater when the targets are far from the neutral position and that the values for all targets in the no-vision condition are greater than in the other conditions. Also, the higher concavity of the quadratic fit in the no-vision condition indicates a stronger dependence upon the distance to the neutral position.

Figure 5 is organized similarly to Fig. 4. It shows the resultant median frequency of the power spectral density of the COP displacement. Again, the median frequency values are higher when the targets are farther away from the neutral position, with the exception of one value in the nonvision condition in the m-l direction. An inverse order of the quadratic surfaces compared with Fig. 4 is observed. The no-vision condition presents the lowest values, followed by the vision condition, and then the COP-feedback condition with the highest values. The fitted quadratic functions for the median frequency do not show high concavities as for the COP displacement area, indicating a weaker dependence on the distance to the neutral position.

Table 1 shows the mean values of the variables area and COP median frequency for 5 of the 13 COP targets, termed neutral (target 3), far forward (1), far backward (5), far left (6), and far right (9) for the three conditions of visual information and the significant interactions among these conditions.

Discussion

The goal of this work is to describe the maintenance of the postural equilibrium in humans when assuming different leaning positions. Different visual information was provided to specify the target location of the COP away from the neutral position. The specification of the COP targets in the BOS by the COP feedback allowed a more accurate and reliable mapping of the equilibrium maintenance than if one had used the instructions such as ‘lean well forward’ or ‘to lean forward or backward as far as possible,’ as employed in other studies (Blaszczyk et al. 1993; Schieppati et al. 1994; Riley et al. 1997). The subjects (n=11) stood in 13 different body postures shown by COP targets in the subject’s BOS as shown in Fig. 2. Three variables were chosen to describe the equilibrium in the space-time and frequency domains: mean, area (COP area), and the resultant median frequency (F_{med}) of the COP displacement. These results are shown in Figs. 3, 4, and 5, respectively. The mean values and interactions of the variables COP area and F_{med} are summarized in Table 1 for 5 of the 13 targets.

During normal quiet standing, the area covered by the COP displacement was about 0.03% of the BOS, which was close to 1,000 cm^2. This huge difference evidences that humans appear to choose an equilibrium state with

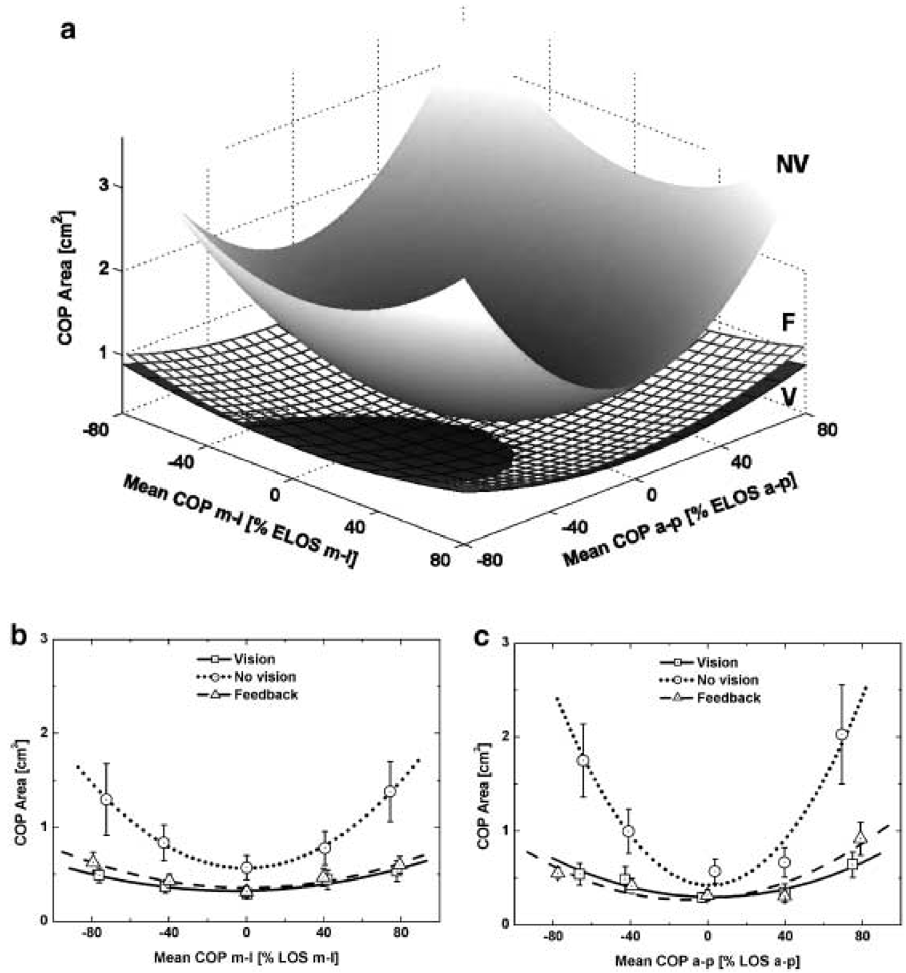


Fig. 4a–c Quadratic surfaces fitting the mean area of the COP displacement (*COP area*) for the 13 COP targets in relation to the limits of stability (*LOS*, *ELOS*) in each direction (**a**), mean and standard error of the mean values and the respective fitted quadratic functions for the five targets in the m-l direction (**b**) and in the a-p direction (**c**) for the three conditions of visual information (*V* with vision, *NV* no vision, *F* with COP feedback). Anterior (*a-p direction*) and rightward displacements (*m-l direction*) were assigned positive values, while posterior and leftward displacements were assigned negative values. (n=11)

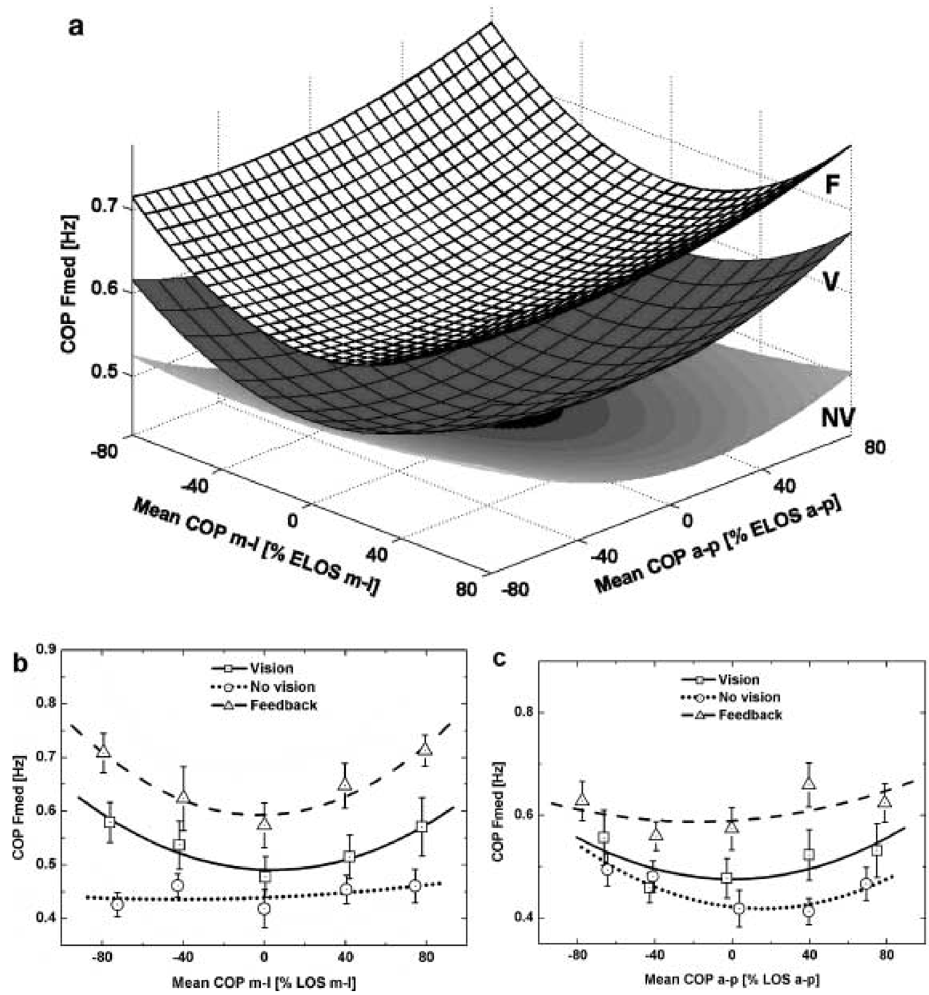
small amplitude oscillations, which offers certain advantages. First, when keeping the body with small amplitude oscillations close to the vertical alignment, less muscle activity is necessary, which therefore requires less energy; second, keeping the gravity line far from the boundaries is safer and the recovery from perturbations is more successful; third, in a state with smaller oscillations it is easier to stabilize the head.

The observed slow drifts in the raw COP time series for the trials far from the neutral position in the vision and no-vision conditions indicated that the subjects tended to slowly move back toward the neutral position. This shift can be interpreted as an attractor, which acted more strongly in the no-vision condition than in the other two conditions with visual feedback, as showed in Fig. 3. These results provide evidence for a dependency on vision to maintain the target position. The values of the variables area and median frequency were successfully fitted by quadratic surface functions in the a-p versus m-l plane (Figs. 4, 5). For the COP area variable, the quadratic surface presents minima close to the neutral position and similar values in the vision and the COP-feedback conditions, with a higher concavity for the no-vision condition. It is important to notice that a direct comparison of the quantitative values of the present study with other experiments reported in the literature is not entirely valid, because there are differences in the signal acquisition and processing. For instance, in the present study, all the data were bandpass-filtered at 0.05–10 Hz; this process affected both area and frequency measurements by removing the trends and high-frequency noise in the signal. Also, there are many different ways to calculate the area of the COP displacement.

Area of the COP displacement

The results indicate that the COP spatial variability, measured by the area of the stabilogram, increased with the increase in body leaning in all directions and for all three visual information conditions. Similar results for the vision and no-vision conditions have been reported by Blaszczyk and coauthors (1993), for both a-p and m-l directions separately (they did not study diagonal directions), Schieppati and coauthors (1994), and Riley and coauthors (1997), who studied only the a-p direction. Many factors can account for the increase in the body sway in a leaning posture. First, it could be related to the variability of the joint moments necessary to maintain this posture. For example, considering a simple inverted

Fig. 5a–c Quadratic surfaces fitting the mean resultant median frequency of the COP displacement (*COP Fmed*) for the 13 COP targets in relation to the limits of stability (*LOS*, *ELOS*) in each direction (**a**), mean and standard error of the mean values and the respective fitted quadratic functions for the five targets in the m-l direction (**b**) and in the a-p direction (**c**) for the three conditions of visual information (*V* with vision, *NV* no vision, *F* with COP feedback). Anterior (*a-p direction*) and rightward displacements (*m-l direction*) were assigned positive values, while posterior and leftward displacements were assigned negative values. (n=11)



pendulum model for the body in a static configuration, the moment at the ankle joint necessary to support the body in the most extreme forward position in the a-p direction is approximately 50% higher than in the neutral position (Sinha and Maki 1996); for the other leaning positions, higher moments are also necessary. But for higher activations levels, muscles present higher variability in the force output (Joyce and Rack 1974), which would generate more instability in the posture control. Second, the fact that humans are more used and adapted to the erect posture may also account for the increasing fluctuations in the leaned postures. Perhaps if subjects practiced this posture the fluctuations could decrease. Finally, another reason for increased fluctuations would be that in the leaning positions the pressure distribution on the sole of the feet is very asymmetrical, concentrated on the anterior (or posterior) part of the sole of the foot (or on only one foot during the lateral leaning). This can affect the use of this information by the postural control system. Kavounoudias and collaborators (1998) have suggested that the tactile information from different parts of the foot soles is used as a 'dynamometric map' by the postural control system to control balance. The change of the pressure distribution by leaning would modify this map, diminishing the usefulness of this information.

The increase in the COP spatial variability, as measured by the area of the COP displacement, with the body leaning was markedly higher for the no-vision condition, in agreement with the results for the a-p direction of Schieppati and collaborators (1994). The hypothesis of the increase in the variability of the joint moments cannot account for the COP spatial variability increase in the eyes-closed condition, since the moments are similar under the same body leaning. As stated earlier, probably the proprioceptive information from the mechanoreceptors of the sole of the feet would be diminished during leaning, and the postural control system would have to rely more on visual and vestibular information to control balance in a leaning position, and solely on the vestibular information in the no-vision condition. Indeed, it has been shown that the vestibular system plays an important role in perceiving body orientation (Gurfinkel et al. 1995; Teasdale et al. 1999; Bourdin et al. 2001).

For the neutral or normal body position, the reported values for the area of the COP displacement, 0.29±0.17 cm^2 (eyes open) and 0.57±0.43 cm^2 (eyes closed), are in the range of the values reported by Oliveira and collaborators (1996), who used the same procedure to calculate the area: 0.47±0.28 cm^2 (eyes open) and 0.46±0.26 cm^2 (eyes closed). But in the present study, the area of sway in the neutral position in the closed-eyes condition was approximately twice as big as in the open-eyes condition. The effect of vision on the maintenance of equilibrium during standing is somewhat controversial in the literature. While some authors report that when subjects close their eyes while standing under normal conditions, the body sway increases (Edwards 1946; Perrin et al. 1997; Paulus et al. 1984; Day et al. 1993; Kuo et al. 1998), other studies observe only little or no effect of vision on postural sway (Crémieux and Mesure 1994; Collins and De Luca 1995; Gatev et al. 1999). The different effects of vision on postural stability may be explained by the redundancy of the sensory systems, such that subjects use a compensatory strategy reweighing the available sources of information (Gatev et al. 1999). In addition, there are also large, intersubject differences in how the different sensory systems are utilized.

The area of the ellipse calculated here using principal component analysis contains only 85.35% of the data and naturally it will give a lower value than calculating the area by multiplying the ranges in the a-p and m-l direction, for example (but this last method is less robust). In addition, the high-pass filtering used for detrending the data has a great effect on diminishing the area values. The COP area computed by the same method but with no detrending gives the following values for the neutral position: 0.79±0.36 cm^2 (eyes open) and 1.22±0.99 cm^2 (eyes closed). Compared with the values reported earlier, these values are more than twice as high.

Frequency of the COP displacement

The variable median frequency shows an inverse behavior to the variable area. The no-vision condition presents the lowest frequencies, followed by higher values in the vision condition, and even higher values for the COP-feedback condition. Although the subjects appear to have used the COP feedback information (as reflected by the higher frequency values), this information was not effective in decreasing the COP spatial variability, measured by the area of the COP displacement, when compared with the condition with vision only. In the neutral position, the median frequency values for the vision and no-vision conditions of the present study, 0.48±0.13 Hz and 0.42±0.12 Hz, respectively (the data were bandpass-filtered at 0.05–10 Hz), are below the values of about 0.8 Hz found by McClenaghan, Williams, and collaborators (McClenaghan et al. 1996; Williams et al. 1997), who did not employ a low-pass filter, but well above the value of 0.12 Hz reported by Winter (1995), who low-pass filtered the data at 6 Hz. These different results can be in part explained by the different signal processing in the reported studies. The high COP frequency values in the leaning positions for all conditions may be due to the higher instability in those positions, as discussed earlier, as well as to the subsequent greater necessity of postural corrections to maintain a leaning position.

The COP feedback was not effective in decreasing the COP spatial variability when compared with the vision condition for all body leanings. In a study of the effect of the COP feedback in a neutral position, Krizková and collaborators (1993) reported a decrease in the COP variability in both a-p and m-l directions with the COP feedback condition in relation to the condition with vision only. They showed that the contribution of the feedback of the COP position to the decrease in the COP variability was in low frequencies, up to 0.05 Hz. Such low frequencies were related to the trends observed in our data and were eliminated with the high-pass filtering. Across all visual information conditions, it seems that visual information is being used at a relatively large time scale (low frequencies), and increasing the frequency and strength of the visual information by giving the COP feedback does not improve the performance of the postural control system. Most probably, the postural control system is already tuned to the best frequency of the visual stimulus for a given task. Numerous reports have shown that the visual sensory system uses information on a relatively low-frequency scale, on the order of tenths of hertz (Lestienne et al. 1977; Diener et al. 1982; Fukuoka et al. 1999). Even though the median frequency variable did not show any significant difference between the open- and closed-eyes conditions, our results on the area variable show that the COP displacement increases when vision is removed, even after detrending the COP data, i.e., removing the low-frequency components of the data. This evidences that the visual information also plays a role on a relatively high frequency scale.

A reference position and the control of equilibrium during standing

Lestienne and Gurfinkel (1988) have suggested that different systems of postural control are used to regulate balance. First, a reference position for equilibrium is specified by a conservative system. Second, the equilibrium about the preselected reference position is maintained by an operative system. As described earlier, to properly analyze the COP time series, the data in the present study were detrended by high-pass filtering the data with a cut-off frequency of 0.05 Hz. In practical terms, this filtering eliminated all long fluctuations with periods of many seconds, which can be associated with the movement of the reference position (Gurfinkel et al. 1995; Duarte and Zatsiorsky 1999). The analysis of the detrended COP data evaluated the performance of the operative postural control system, while the analysis of the mean positions and drifts of the COP displacement evaluated the performance of the conservative system. The slow drifts observed during the maintenance of balance in leaning positions reveal a certain incapacity of the conservative system to specify reference positions far from the neutral position in the present experimental protocol. The greater drifts and relative deviations observed in the no-vision condition evidence a dependence of the conservative system on the visual information. The performance of the operative system was related to the specified reference positions: closer to the borders of the BOS, the balance maintenance was worse. The higher COP fluctuations, measured by the COP area variable, of the detrended COP data in the no-vision condition suggest that the operative system is also dependent of the visual information.

In summary, we observed a deterioration of the equilibrium when the quiet standing task was performed in leaning positions under all conditions of visual information. This variability also increased when vision was removed in relation to when vision was present. When, in addition to the visual information of target location, feedback about the COP was given, the postural control system was unable to use such information to improve control of the stance over the situation with vision only. Also, when vision was removed, we observed drifts in the COP data, which were larger for COP targets far from the neutral position. These results indicate that the visual information is used by the postural control system at both short and long time scales.

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Appendix

This Matlab code calculates an ellipse to fit the a-p and m-l COP data by means of the principal component analysis method:

```
V=cov(ml,ap); % covariance matrix between
the a-p and m-l COP data
[vec,val]=eig(V); % eigenvectors and eigenvalues
of the covariance matrix
axes=1.96*sqrt(svd(val)); % axes lengths (major axis first)
angles=atan2(vec(2,:),vec(1,:)); % respective angles
area=pi*prod(axes); % area of the ellipse
% ellipse data:
t=linspace(0,2*pi);
ellipse=vec*1.96*sqrt(val)*[cos(t); sin(t)]+repmat([mean(ml);
mean(ap)],1,100);
```

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