Postural sway during standing is accompanied by multidirectional acceleration of body center of mass in humans

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Key words: human; standing posture; ground reaction force; center of mass; acceleration

Abstract

The body sway during human standing was studied by analyzing the variation of center of body mass (CoM) acceleration and center of foot pressure (CoP) displacement. Six postures were defined as a function of body lean (forward lean, neutral or backward lean) and body height (upright or bent). Each posture was examined in vision and no-vision conditions. The CoM acceleration and CoP displacement were computed from ground reaction force signals. In all postures, body sway was accompanied by multidirectional variation of CoM acceleration involving vertical direction. The variation of both CoM acceleration and CoP displacement in the bent postures were greater compared to erect postures. In both erect and bent postures, the CoM acceleration and CoP displacement varied more when the body leaned forward or backward, compared to the neutral standing. This contrast was manifested by the removal of vision. As the body lean changed from backward to forward in the sagittal plane of the subject on the left side, the major principal component axis of covariance ellipse for CoM acceleration rotated in a clockwise direction relative to the vertical. These results indicate that instability in maintaining standing posture is characterized by the multidirectional changes of body acceleration in three-dimensional space, of which the pattern of variation changes as a function of body lean and body height.

1. Introduction

Human standing posture is characterized by spontaneous sway of the body, such that the vertical projection of the body center of mass (CoM) on the base of support does not coincide with position of center of pressure (CoP) most of the time. In order to stabilize the body during standing, therefore, the postural control system uses the variable CoP to generate restoring force accelerating the CoM toward the intended equilibrium position. Many studies have used an inverted pendulum model to account for the dynamics behind their empirical findings about control of upright standing postures (e.g., Winter et al., 2001; Masani et al., 2003; Morasso & Shieppati, 1999; Fitzpatrick et al., 1996). The sagittal plane model, for example, assumes that the whole body above the ankle joint consists of a single rigid body, and sways around the ankle joint. These assumptions simplify the dynamics of the multi-segmented human body into a planar situation; i.e., the ankle joint torque is linearly transformed into changes of CoP position, and the resulting restoring force to accelerate the body CoM is generated in proportion to the difference between body CoM and CoP position on the base of support (Masani et al., 2003; Morasso & Shieppati, 1999; Winter et al., 1998)

On the other hand, recent studies have suggested that the maintenance of body equilibrium during standing involves coordinating multiple joint motions even in natural upright standing. Besides the ankle joint as the main actuator in the postural control system, hip and knee joints as well as their interactions with the ankle joints play crucial roles in the dynamic regulation of upright standing postures (Aramaki et al., 2001; Day et al., 1993; Gatev et al., 1999). Motion analyses performed in the different body segment have shown that momentary balancing adjustments of many body parts occur in three dimensions (3D) (Kejonen, 2002). In light of these findings, the instability of human standing postures may be characterized as the changes of position of individual body segments of the whole body in 3D space, and hence the effective stabilization of a whole body is achieved by the precise position control of the body CoM based on the interjoint coordination.

In the present study, the body CoM acceleration, CoP displacement and their mutual interaction during standing were examined in different body postures. It will be shown that according to the changes of body postures, these variables present systematic changes in magnitude and direction of variation. The results suggest that postural control is a multidirectional and thus complex motor task than has been described in a rigid one-link model.

2. Methods

2.1. Tasks

Experiments were performed on five healthy male subjects. All subjects gave informed consent, which was approved by the ethical committee of Kinjo Gakuin University.

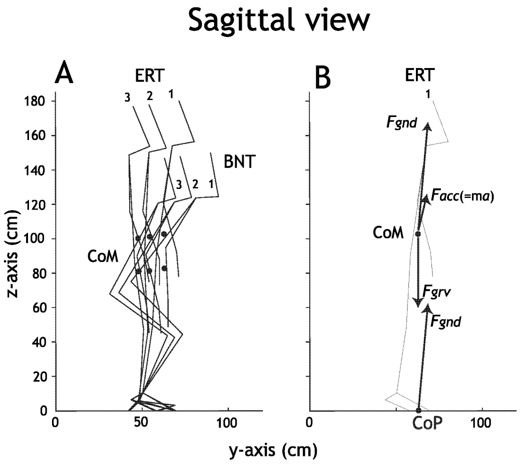

Figure 1

A: Schematic illustration of body postures examined. Six different postures were defined as the function of body heights (ERT and BNT) and body leans [1(LF), 2 (LN) and 3 (LB)]. B: Three force vectors used in the present study. Note that stick picture for ELT_LF in panel A is used. F_{gnd}, F_{grv} and F_{acc} designate the vector that represents the instantaneous ground reaction force, gravitational force and inertial force acting on the body CoM, respectively. F_{acc} is the resultant or sum of F_{gnd} and F_{grv} (see text).

As shown in Fig. 1A, six different standing body postures were examined. In all postures, the subjects stood on the center of the force platform with feet 10 cm apart at the heel position and 15 cm apart at the toe position. The subjects hung their hands naturally at their sides and focused on a fixed target located at eye height 2m away. Body postures were defined by the combination of one of two body heights, i.e., erect (upright) (ERT) or bent (BNT) condition, and one of three different body leans as below. The BNT posture was defined by lowering the horizontal eye level 30∼35 cm relative to target in ERT posture, such that both hip and knee joint are flexed nearly 90 degrees relative to full extension. Once one of the body height conditions was achieved with either of ERT or BNT postures, the subject was asked to take one of the following three leaned body postures: remain standing with neutral position (LN), lean forward (LF) or lean backward (LB) while maintaining the eye level of the LN condition. For the LF and LB conditions, the subject body weight was placed on the toes or heels, such that heels or toes were off the ground by 2〜3 cm in the LF and LB condition, respectively. These six different postures were examined under eyes open (EO) and eyes closed (EC) condition. The twelve different tasks were randomized between subjects. For each task the subjects stood for one minute with inter-trial rests of 5 minutes.

2.2. Apparatus and measured variables

A force plate (Takei Sci. Instru., TKK123A, Japan) was used to measure the time series of three orthogonal components of ground reaction force $\boldsymbol{F_{gnd}}$ (F_x, F_y, F_z), where subscripts x, y and z are the medio-lateral, anterio-posterior and vertical direction, respectively. F_z was derived from the sum of signals (F_{z1}, F_{z2}, F_{z3}, F_{z4}) recorded from each of four transducers located at the corners of the force plate. Transducer signals were carefully zero-balanced on a trial basis, and sampled at a frequency of 100Hz. For off-line analyses, the force signals were low-pass filtered at 10Hz with second-order and zero lag Butterworth filter.

The time series of acceleration of the body CoM were computed from the record of ground reaction force (Fig. 1B). In contact with a stable surface like the ground, the external force acting on the body is equal to the inertial force of acceleration ($\boldsymbol{F_{acc}}$) of the body CoM

$$\boldsymbol{F_{grv}} + \boldsymbol{F_{gnd}} = \boldsymbol{F_{acc}}$$

where the left side represents the sum of external forces due to gravity ($\boldsymbol{F_{grv}}$) and ground reaction force ($\boldsymbol{F_{gnd}}$). This form designates that using known variables of $\boldsymbol{F_{gnd}}$ and subject's body mass, we can derive $\boldsymbol{a}$ (a_x, a_y, a_z), the acceleration vector of the body CoM. The same acceleration vector was measured in a rigid concrete block (65kg), which weight was comparable to the mean of the five subject's body weight, to estimate the net measurements noise in the force platform.

The position of the point of application of $\boldsymbol{F_{gnd}}$ in two dimensions on the force plate, which is referred to as the center of foot pressure vector, $\boldsymbol{P}$ (x_p, y_p), was calculated by the standard formulation using $F_{z1\text{-}z4}$ signals (Winter, 1990). The time series of CoP displacement showing long-period drifts moving around the mean positions was detrended by zero lag second-order Butterworth high-pass filter at 0.15Hz.

A digital video camera (Victor GR-DV2000) placed 3 m apart away from the mid-sagittal plane of the subject on the left side was used to check the standing body configurations. This information was also used to estimate the mean location of the body CoM and joint angles. To this end, a stick diagram of the body was created by digitizing the spatial positions of all body segments (Fig. 1). The segmental center of mass locations and masses were determined from anthropometric tables (Winter, 1990). Further analyses about CoM or joint kinematics were not carried out due to the limited resolution of the video system.

2.3. Data analysis

Off-line analyses were carried out by computing the covariance among time series of data sets for three orthogonal components of the CoM acceleration vector $\boldsymbol{a}$, and for two orthogonal components of the CoP displacement vector $\boldsymbol{p}$ (see Fig. 2) Quantitative and qualitative descriptions of covariance are obtained by computing the eigenvalues and eigenvectors of the covariance matrix of a set of variables. The eigenvalues describe the squared lengths of the principal component (PC) axes, while the eigenvectors describe their orientation. For visualization, both measures were used to create a covariance spheroid or an ellipse in 3D or 2D space, respectively.

The first analysis was to quantify the respective variation of the CoM acceleration in 3D space and CoP displacement in 2D (horizontal) space. In both cases, the axis length corresponding to a 95% confidence level ($1\text{-}\sigma$) was used to quantify the volume of the covariance spheroid for the CoM acceleration and area of covariance ellipse for the CoP displacement (see Duarte & Zatsiorsky, 2002). To enable comparison of these two measures across the tasks and subjects, the set of original values for each measure over the tasks of a single subject were transformed to z-scores. This normalization has the effect of eliminating differences between the mean and standard deviations of original data set across subjects. Second, eigenvectors of major PC axis of the CoM spheroid were evaluated in order to specify the contribution of each of the three orthogonal components in creating this axis. This method was also used in the

CoM acceleration ellipse in the sagittal (y-z) plane. The linear relationship among the three orthogonal components of the CoM acceleration vector was quantified by correlation coefficient values. Finally, to assess the linear relationship between CoM acceleration and CoP displacement, the correlation coefficients of paired variables taken from one of three components for the CoM acceleration vector and from one of two components of the CoP displacement vector were compared in different tasks.

The task dependent changes of parameters of the covariance spheroid or ellipse were tested by a three-way repeated measures ANOVA, where body lean (LF, LN and LB) was a primary factor, and the body bend (ERT and BNT) and vision (EO and EC) were secondary factors. Where significant interactions ($P<0.05$) that involved the primary factor were present, the simple main effects of secondary factors within each level of the primary factors were compared.

3. Results

3.1. Size of variation

A typical illustration of a covariance spheroid of CoM acceleration vector ***a*** and the corresponding CoP displacement vector ***p*** are shown in Fig. 2A and 2B, respectively. The body configuration for this task is ERT, LF posture with EC

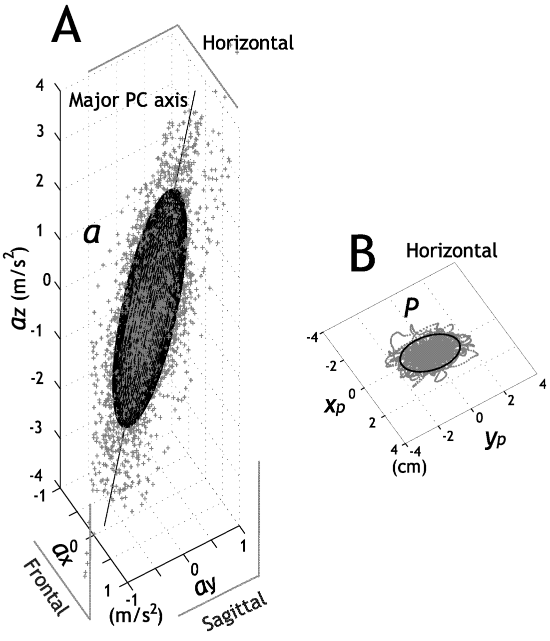

Figure 2

Typical illustration of covariance spheroid of CoM acceleration (A) and corresponding ellipse of CoP displacement (B) in the tasks of ERT_LF posture with EC condition. In panel A, the covariance spheroid of CoM acceleration in 3D space is depicted by meshed surface with 1-σ contour of covariance, and superimposed on the scattered plots for raw data. The center of the spheroid defines the level of gravitational acceleration ($9.807\mathrm{m/s^2}$) in the vertical direction and zero acceleration in the horizontal direction. The straight line penetrating the spheroid is a major PC axis. In panel B, the lower illustration is the ellipse for the CoP excursion with the same 1-σ contour of covariance, which is superimposed on the original scattered plots in the horizontal (x-y) plane.

condition (hereafter, task combination is referred to as ERT_LF_EC). The center of the spheroid defines the body weight level in the vertical direction and zero acceleration (or inertial force) in the horizontal direction. It is noticed that the variation of CoM acceleration vector is multidirectional with respect to the origin (zero acceleration), and a covariance spheroid ***a*** is anisotropic and its major PC axis inclines from the vertical (e.g., in the anterior direction for this task).

The spheroid volume of CoM acceleration varied task dependently. For example, the volume of the spheroid in Fig. 2A was $1.48(\mathrm{m/s^2})^3$. For this subject, the value was the second maximal for all tasks, but roughly compatible to maximal of $1.87(\mathrm{m/s^2})^3$ in the BNT_LF_EC conditions. The minimal value of $0.02(\mathrm{m/s^2})^3$ was obtained in the ERT_LN_EO condition. Fig. 3A shows the normalized spheroid volume for all subjects and tasks taken together. In each combination of body heights (ERT; BNT) and visions (EO; EC), the volume of the spheroid changed in a v-shaped manner as a function of body lean, i.e., the variation in the LN postures are always smaller than that in the LF and LB postures. ANOVA test revealed that the main effects of all three factors (i.e., body lean, body height and vision) were significant ($p<0.05$), while 2-way interaction was seen in the body lean and vision ($p<0.05$). This arose because in both ERT and BNT postures, the differences in spheroid volume of the LF vs. LN, and LB vs. LN were markedly increased in the EC condition ($p<0.001$).

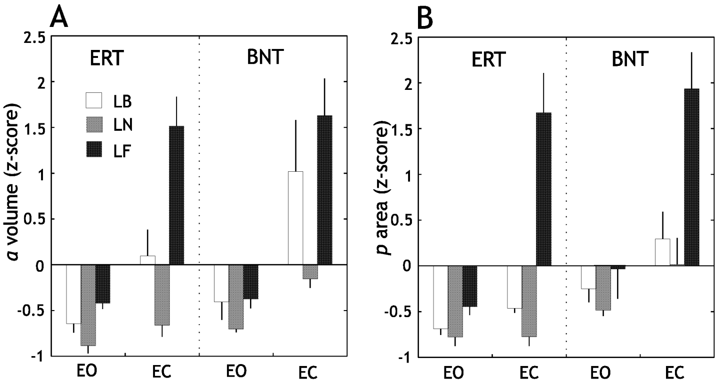

Figure 3

Quantitative comparison between CoM acceleration and CoP displacement. A: normalized spheroid volume for CoM acceleration at different tasks (i.e., body height, ERT/BNT; body lean, LF/LN/LB; vision, EO/EC). B: normalized ellipse area for CoM acceleration at different tasks. In both measures, the set of original values for each measure over the tasks of a single subject were transformed to z-scores and averaged.

The ellipse area of CoP displacement also varied task dependently. For example, the area of the ellipse in Fig. 2B was 5.24cm^2 for this task (ERT_LF_EC). This value was the maximal across the tasks, but nearly compatible to the second maximum of 4.40cm^2 in the BNT_LF_EC conditions. The minimal value of 0.36cm^2 was obtained in the ERT_LN_EO condition. As shown in Fig. 3B, the size of the normalized CoP ellipse area averaged for all subjects varied in a v-shaped manner as a function of body lean, i.e., the variation was small in the LN posture, but large in the LF and LB conditions. The main effects of all three factors (body lean, vision and body height) were significant ($p<0.05$), while 2-way interaction was seen between body lean and eye condition, because the difference of variation of the ellipse area among the three body lean conditions was increased more when vision was removed ($p<0.001$, for LF vs. LN, LF vs. LB and LN vs. LB).

In addition, it is notable that global trend of task-dependent variations of spheroid volume of CoM acceleration in Fig 3A was compatible with that of ellipse area of CoP displacement in Fig. 3B. The correlation coefficient paired between normalized volume of CoM in Fig. 3A and area of CoP excursion in Fig. 3B was 0.932 ($p<0.001$, $n=12$). This suggests that the variation of the CoM acceleration is modulated in association with that of the CoP displacement, or vice versa.

3.2. Covariance of CoM acceleration vector

In most tasks, the CoM spheroid is anisotropic, showing greatest variation along the major PC axis. As shown in Fig. 2A, for example, the CoM spheroid in this task leans in the anterior direction. Eigenvector components of the major PC axis were 0.979, 0.203 and 0.000 for a_z, a_y and a_x components, respectively. We repeated this analysis for all tasks performed by all subjects, and absolute values of three components were compared. As a result, eigenvector components of the major PC axis were averaged 0.974±0.006 (mean±SE), 0.197±0.046 and 0.044±0.026 for a_z, a_y and a_x components, respectively. This means that the major PC axis exists near z-axis in the sagittal (y-z) plane, whilst the contribution of a_x in creating the major PC axis is very limited. Also, the covariance ellipse of CoM acceleration in the sagittal plane changed the orientation as a function of body lean as described below, whilst the same systematic changes of ellipse orientation was not seen in the frontal (x-z) plane as well as horizontal (x-y) plane. This might be attributable that all of the body lean conditions examined in this study were defined in the sagittal (y-z) plane.

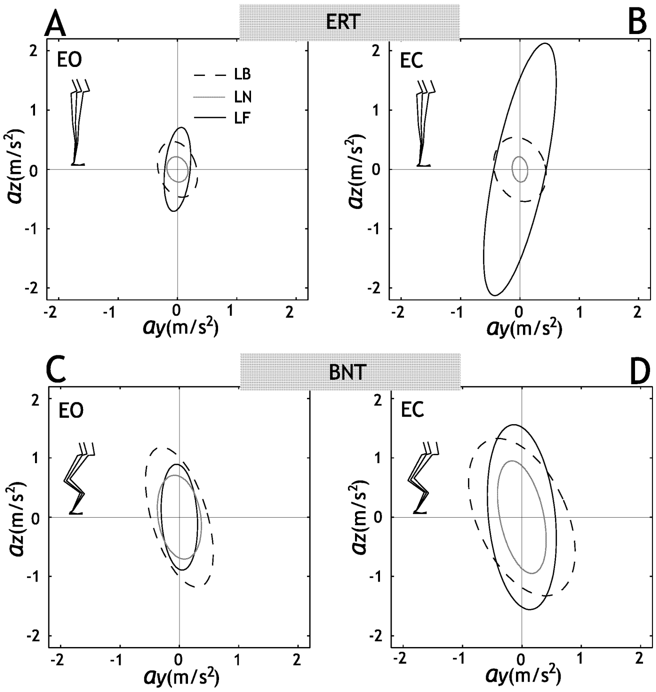

Figure 4

Typical illustration of covariance ellipse for the CoM acceleration in the sagittal (y-z) plane. Twelve different tasks obtained from a single subject were shown in four panels. The ellipses in panels A and B represents 1-σ contour of covariance in EO and EC condition, respectively, in the ERT condition. Similarly, panels C and D represent the same contour of covariance in EO and EC condition, respectively, in the BNT condition. In each panel, three ellipses were depicted for the three body lean conditions (LB, LN and LF).

Fig. 4 illustrates a typical example of CoM acceleration ellipses obtained for twelve different tasks. During ERT_LB postures (panels A and B), the CoM ellipse oriented -17.40 and -20.72 degrees from the vertical in EO (panel A) and EC conditions (panel B), respectively. In the LF conditions, however, forward orientation of CoM ellipse can be seen in both EO (panel A) and EC conditions (panel B) (i.e., 5.74 and 11.73 degrees from the vertical for EO and EC, respectively). Thus, the ellipse shows clockwise rotation as the body lean was changed from backward to forward. The same clockwise rotation of an ellipse was seen in BNT postures (panels C and D). The ellipse oriented -16.76 and -24.01 degrees in the BNT_LB postures with EO and EC conditions, respectively, while in BNT_LF postures they were -3.44 and -5.68 degrees for EO and EC conditions, respectively.

Quantitative measures of covariance between a_y and a_z are given by correlation coefficients. Fig. 5A shows the averaged values across five subjects. In the ERT conditions, negative correlation coefficients for the LB posture were averaged -0.226±0.045 and -0.208±0.050 for EO and EC conditions, respectively. In LN postures, negative correlations were -0.089±0.047 and -0.060±0.055 for EO and EC conditions, respectively. In contrast, correlation coefficients for the LF posture were both positive and averaged 0.403±0.078 and 0.431±0.087 for EO and EC condition, respectively. Thus, in the ERT postures the change of correlation coefficients from negative to positive with the direction of body leans mirrors the clockwise rotation of the ellipse in Fig. 4. Although the same clockwise rotation of acceleration ellipses can be seen in the BNT postures, the correlation coefficients values were different among the same body lean conditions in the ERT posture. In the BNT_LB postures, the magnitude of negative correlation coefficient values of -0.327±0.087 and -0.379±0.051 for EO and EC positions, respectively, were greater than compared to the same body lean condition in ERT postures. In the BNT_LF condition, correlation coefficients of -0.001±0.075 and 0.013±0.117 for EO and EC positions, respectively, were smaller in magnitude compared to the same body lean condition in ERT postures. ANOVA tests for the differences of correlation coefficients revealed that two main effects of body height and body lean were significant ($p<0.01$) without significant interaction ($p>0.05$), whilst vision was not significant ($p>0.05$). This means that both body lean and body height independently affect the correlation of a_y and a_z components, while under the same body configurations, little effect of vision on the their correlation was seen in the comparison of EO and EC condition.

3.3 Covariance between CoM acceleration and CoP displacement

Covariance analysis in the sagittal plane was extended to the relationships between CoM acceleration and CoP displacement. As shown in Fig. 5B, in all tasks a negative correlation was found in the relationship between a_y and y_p, and averaged −0.525±0.068 (mean±SE) across all tasks of all subjects. In the ERT_LN condition, the same measures were averaged −0.213±0.027 and −0.352±0.065 for EO and EC conditions, which were first and second minimal among all tasks, respectively. In both body height and body lean conditions, the correlation coefficient values changed task-dependently, showing greater negative correlation coefficient in LF and LB conditions compared to that in LN conditions, regardless of vision. The main effects of body lean and vision were significant ($p<0.05$) without significant interaction ($p>0.05$), while the main effect of body height was not significant ($p>0.05$). Multiple comparisons showed significant differences for LF vs. LN and LB vs. LN ($p<0.05$ for both), but not for LF vs. LB ($p>0.05$).

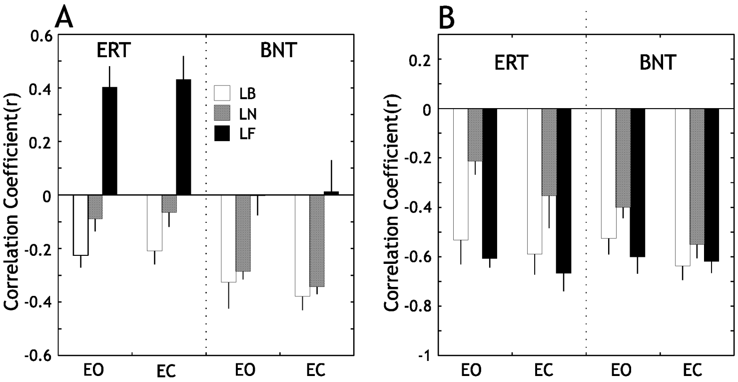

Figure 5

A: Comparison of correlation coefficients of CoM acceleration in the anterior-posterior direction (a_y) and vertical direction (a_z) among twelve different tasks. B: Correlation coefficient of CoM acceleration and CoP displacement in the sagittal plane (i.e., a_y and y_p for CoM acceleration and CoP displacement, respectively).

The similar negative correlation was also found in the relationship between a_x and x_p, and averaged -0.798 ± 0.015 (mean±SE) across twelve tasks of all subjects (data not shown). This negative value was greater than the same average (-0.525) between a_y and y_p described above. By contrast, the absolute value of correlation coefficients between a_x and a_z was averaged 0.034 (±0.014). This value was very small, nearly one sevenths of the corresponding value between a_y and a_z (i.e., 0.231 ± 0.078). This implies that the a_x modulation that was negatively correlated with x_p, is independent of the CoM acceleration in the vertical direction (a_z). Thus, the minor contribution of a_x component in adjusting the spatial orientation of the CoM acceleration spheroid (e.g., see Fig. 2A), can be confirmed.

4. Discussion

4.1. Magnitude of body sway in altered body configurations

The spatial characteristics of body sway during the human standing at different body postures were studied by the pattern of variation of CoM acceleration and corresponding CoP displacement. It was found that in all tasks examined in the present study, the CoM acceleration accompanying body sway was multidirectional and its preferential axis and magnitude of variation were modulated as a function of body lean or body height. The body CoM acceleration in the vertical direction has been rarely commented upon in previous studies, which advocated the analogy between the dynamics of human upright standing and a single inverted pendulum.

The comparison of musculo-skeletal biomechanics during ERT and BNT postures deserves consideration first. The bent body increases reaction moments acting on the hip and knee joints and the effective vertical spring stiffness of the legs is decreased relative to ERT posture (McMahon, 1984). In the BNT posture, therefore, an elevation of joint stiffness would be needed to support the same body. The muscle stiffness is increased with muscle activation level (Cannon & Zahalak, 1982), and higher activation levels would accompany higher variability in force output (Joyce & Rack, 1974). This may lead to greater variability of CoM acceleration as well as CoP displacement in the BNT posture relative to ERT posture. The same reasoning holds for greater CoM acceleration in the ERT_LF condition, where the line of gravity is far from the ankle joint relative to that expected in ELT_LN or ELT_LB conditions. This increases the ankle joint moment necessary to support the body (Sinha & Maki, 1996), and leads to greater variation in the ankle torque output and enhancement of the variability of the CoM acceleration.

As for the body lean condition, the size of the CoP ellipse in the LN position was small compared to other two conditions of LF and LB postures, in agreement with previous reports (Duarte & Zatsiorsky, 2002; Schieppati et al., 1994; Riley et al., 1997) (Fig. 3B). The same holds true for the size of the CoM spheroid shown in Fig. 3A. Altering the body lean affects the available base of support and changes the relationship of the body CoM relative to the limits of stability of the feet, which would generate more instability. In neuronal control perspective, the proprioceptive information from mechanoreceptors on the soles of the feet would be diminished or changed during body learnings (Kavounoudias et al., 1998). Therefore, the postural control system would have to rely more on visual and vestibular information to control balance in leaned body positions, and solely on the vestibular information in the no-vision condition. As shown in Fig. 3, however, the effect of vision on the magnitude of postural sway became manifest when the body leaned forward (LF) or backward (LB) (see also Duarte & Zatsiorsky, 2002; Schieppati et al., 1994; Riley et al., 1997)(Fig. 3B). This suggests a limited ability of compensatory strategies when the vision is removed in altered body orientations.

4.2. Implications of multidirectional control of body sway

The inverted pendulum model assumes that change of the CoM acceleration in the vertical direction is negligible and so the system takes an inertial force of acceleration in the horizontal direction only (Winter et al., 2001; Morasso & Shieppati, 1999). However, recent empirical studies have shown that during natural upright standing, the body does not behave as a completely rigid pendulum (Aramaki et al., 2001; Day et al., 1993; Gatev et al., 1999; Rogers et al., 2001). Gatev et al. (1999) have revealed, for example, that anterior-posterior sway of the trunk and knee are cross-correlated, and the knee joint rotates with comparable degrees to those observed in the hip and ankle joint (0.5 degrees by our estimation). Motion analysis also revealed that the balancing adjustments of many body segments occur in the vertical as well as the horizontal direction (Kejonen, 2002). Based on the mathematical optimization model of human standing, Kuo and Zajac (1993) demonstrated that when the knee joint is constrained to be straight, the CoM acceleration that leg muscles can induce during upright posture is severely limited vertically but not horizontally. As a related matter, without a specific instruction to fix the knee in a fully extended position, subjects tend to keep the knee in a slightly flexed position for balancing upright (Woollacott & Shumway-Cook, 1990). Based on these empirical and theoretical observations, the variation for momentary distribution of many body segments arising due to multijoint action would be compounded and lead to vertical acceleration of the body CoM. The multidirectional acceleration of the body CoM, which was manifested in altered body configurations, might be a necessary element of control of standing body postures.

According to the inverted pendulum model (e.g., Morasso & Shieppati, 1999; Winter et al., 1998), CoP oscillates around the CoM to give a moment defined as the cross-product of CoM-CoP error and gravitational force. This moment would contribute to accelerate the CoM in the horizontal plane. We speculate that under the gravitational field, such a pendular-like balancing strategy underlies the control of standing posture even though the vertical motion of the body is involved concomitantly in this sway. In our data, the similarity in the task-dependent size modulation for the variation of CoM acceleration and CoP displacement (Fig. 3A and 3B) suggest a close interaction between these two measures. Also, the presence of the preferential axis of CoM acceleration suggests that the response for a set of vertical and horizontal acceleration is coupled in phase on many parts of time series. Therefore, the postural control system might organize a set of horizontal and vertical responses in association with the horizontal positioning of the CoP position with respect to the CoM position on the base of support. The resulting CoP-CoM error in 2D space could be transformed into the control response inducing a multidirectional response of acceleration of the body CoM in 3D space.

The covariance ellipse of CoM acceleration was anisotropic and changes in orientation depended on the body configurations. Although it is very difficult to offer a hypothetical account of how and why the ellipse changed its direction and size depending on the body postures, an evaluation of how equilibrium is maintained in various body postures may be relevant to understand how the transition from one posture to another is regulated or prevented (Horak & Moore, 1993; Perry et al., 2001; Bortolami et al., 2003). In other words, the degree of variation and its orientation of the CoM acceleration in maintaining equilibrium at different body configurations might be an important factor for the postural control system to choose the preferential direction of movement as well as the maintenance of corresponding posture (see Duarte & Zatsiorsky, 2002). Near the vertical in the sagittal plane, for example, the covariance CoM ellipse in ERT postures orients backward and forward from vertical in the LB and LF postures, respectively (Fig. 4). If the generation of the inertial force of acceleration is facilitated along the major axis of CoM ellipse, the forward and backward orientation of the ellipse might be suitable for the forward and backward motion of the whole body, keeping body height under the gravitational field.

Another important aspect of ellipse orientation may be related to the reduction of degree of freedom problem. The presence of the preferential axis of CoM acceleration may suggest that some sort of dynamics constraint (or coordinative structure) underlies the organization of multijoint dynamics. In this point, the preservation of orientation of major axis of CoM ellipses in both vision and no-vision conditions may reflect the system's utilization of a common interjoint coordination for the maintenance of posture in both conditions.

In the present study, the correlation coefficients between horizontal CoM accleration and CoP displacement in the normal upright standing were averaged －0.213 and －0.352 for the EO and EC condition, respectively, in the anterioposteriordirection. In contrast, when a CoP displacement was measured with respect to the position of vertical projection of the CoM (CoP-CoM error), larger negative correlation coefficients over −0.90 were reported (Winter et al., 1998; Zatsiorsky & Duarte, 2000). The CoP excursion generally involves slow drifts. Since this slow component moves in-phase with the CoM excursion on the base of support without inducing substantial restoring forces in the postural control system (Zatsiorsky & Duarte, 2000), we intended to reject them from analysis by filtering. However, the low-cut level for the detrending processing seems to be imperfect in selectively diminishing slow drift components. The relatively low level correlation coefficients in the present study may be ascribed to the lack of measure for the CoP-CoM error that should to be related to restoring force (or CoM acceleration).

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