Backward and forward leaning postures modelled by an fBm framework

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Abstract

Body leaning effects on postural control have been assessed by recording the centre of pressure (CP) displacements in healthy subjects under three experimental conditions (REF, BWD and FWD corresponding to upright, backward leaning and forward leaning of the body, respectively). The CP displacements were used to compute the motions of the vertical projections of the centre of gravity (CGv) and those of the difference CP − CGv. A frequential analysis shows that the main effect takes place on CP − CGv motions, suggesting increased muscular activity in these leaning postures. In addition, changes also occur on CGv motions, especially in the antero-posterior (AP) direction. Modelling these motions as fractional Brownian motion (fBm) indicates that leaning the body induces, in the AP direction, a shift in the time interval \( t \) at which the corrective process takes over the initial one operating in open-loop. In FWD and BWD conditions, the \( t \) is diminished whilst the mean distance covered at this \( t \) is increased for both CGv and CP − CGv motions. Moreover, more determinism in the overall upright stance control is observed in the corrective (closed-loop) process involving CGv motions. These facts emphasize the inability for the CP displacements to express properly the overall body sway in upright stance control. © 2001 Elsevier Science Ireland Ltd and the Japan Neuroscience Society. All rights reserved.

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1. Introduction

Because of the physical properties of the body, the only way to secure an upright position is to exert a precise control of the centre of gravity (CG) in order to keep its vertical projection (CGv) within the base of support, i.e. the surface delimited by the outer borders of the feet. One may note that these two motions, according to Winter (1995), correspond to the centre of mass and the relative centre of gravity, respectively. To this end, muscular contractions, mainly involving the plantar flexor muscles, allow the body to exert reaction forces against the support which is the only way of controlling the centre of gravity motions when standing still is required. One classical way of characterising these force fluctuations is to compute a resultant trajectory, that of the centre of pressure (CP), whose successive positions express the displacements of the point of application of the resultant reactive force. Some investigations, conducted by Okada and Fujiwara (1983, 1984), have specified the natural positioning to be about 40–50% of the foot length. These studies have also demonstrated that muscular activity increases rapidly as CGv moves away from this reference. It is likely that these increases in the forward direction are due to the augmented force moments occurring at the ankle joint level whereas extreme backward leaning presents the particularity of calling into play antagonistic muscles (tibialis anterior), usually inactive in upright stance control.

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As demonstrated by various investigations which have studied the relationship between CP and CG (Brenière et al., 1987; Winter et al., 1996; Caron et al., 2000) an increased amount of CP displacement, the controlling variable, does not necessarily induce a similar trend for CG motions, the controlled variable. Moreover, a constancy in the average amplitudes for these CG horizontal motions does not necessarily induce a constancy in the control mechanisms set by the CNS. In parallel, there has also been growing evidence that the frequency distribution of the difference in the horizontal plane between CP and CG (CP − CGv) could advantageously express the resultant joint stiffness (Winter et al., 1998; Caron et al., 2000) and, thus, can be directly affected by the body leaning. Interestingly, a mathematical relationship has been assessed in order to compute the CGv motions from the CP displacements in instantaneous upright stance (Caron et al., 1997).

A simple and useful way to understand how each of these variables is controlled for the purpose of equilibrium is through recourse to mathematical concepts such as fractional Brownian motion (fBm). With this framework, some insight can be gained into the nature and the temporal organisation of the control mechanisms called into play. In a pioneering study, Collins and De Luca (1993) demonstrated that two control mechanisms, a short-term (persistent) and a long-term (anti-persistent) one, act together in a successive manner to control body sway motions, these two mechanisms being interpreted as open- and closed-loop control, respectively. Applied to elementary motions such as CGv and CP − CGv (Rougier and Caron, 2000), this method has demonstrated that the CP − CGv is the only motion to be controlled during the shortest time intervals Δt until the CGv motions, in turn, take over during the longest Δt. In addition, when one motion is controlled, the other behaves stochastically. This feature has also been found in several investigations involving loss of vision (Rougier and Farenc, 2000) or visual feedback effects (Rougier, 2001).

The aim of this study is to investigate the control organisation set by the CNS in order to secure an instantaneous upright stance in backward and forward leaning positions. To be more precise, these extreme leanings, as previously mentioned, are expected either to incite further increased recruitment of motor units in the triceps surae or to call into play muscles whose primary function does not consist in developing sustained isometric contractions. Lastly, investigating the postural mechanisms aimed at controlling body inclinations is clearly justified since a shift of the CP along the antero-posterior direction can be observed as a direct result of various causes such as repetition of the task (Tarantola et al., 1997) or strenuous exercise (Nardone et al., 1998).

2. Methods

The methodology has been detailed previously in recent articles (Rougier and Caron, 2000; Rougier and Farenc, 2000). Only the main points will thus be discussed here.

2.1. Experimental procedure

Eighteen healthy adults (nine males and nine females) volunteered for this investigation. Their ages ranged from 20 to 47 years (body weight 67.2 ± 8.7 kg; height 173.5 ± 8.1 cm; mean ± standard deviation). The subjects stood barefoot on a triangular force platform (Equi+, model PF01) in a natural position (feet abducted at 30°, heels separated by 3 cm) and were asked to sway as little as possible with their arms at their sides. The signals issued from the load cells, on which the steel plate lay, were amplified and converted from analogue to digital form before being recorded on a personal computer. No smoothing or filtering algorithms were applied to the recorded data. The CP trajectory was then processed, as seen above, in different ways. ML and AP characterise, in the co-ordinates system, medio-lateral and antero-posterior directions, respectively. Three experimental conditions were successively and randomly performed in closed eyes condition: a normal stance condition (REF) where subjects were instructed to remain still and upright, a forward leaning (FWD) and a backward leaning (BWD) condition where subjects were asked, by pivoting around the ankle joint, to incline their body as far as possible and to hold these postures. Each experimental condition included five trials of 64 s with a 64 Hz sample frequency. Rest periods of a similar duration and of about 10 min were allowed between each trial and each condition, respectively, and automatically managed by the recording program.

2.2. CGv and CP − CGv motions’ calculation

As stated in Section 1, CGv and CP − CGv motions were determined from the CP trajectories computed from the force platform. Interestingly, a relationship between the amplitude ratio of the vertical projection of the centre of gravity (CGv) and CP motions (CGv/CP) and sway frequencies allows to determine, through a simple method, the CGv and consequently CP − CGv motions. Body sways being particularly reduced, standing still can therefore theoretically be modelled as an inverse pendulum where CGv and CP behave as periodic functions in phase with each other. The method, initially proposed by Brenière (1996) and then extended to instantaneous stance by Caron et al. (1997), is given by the following formula:
CGv/CP = Ω^2/(Ω^2 + ω^2)

where $\Omega = 2\pi f$ is the pulsation (rad s$^{-1}$) and $\Omega_0 = [mgh/(I_G + mh^2)]^{1/2}$ (Hz), termed natural body frequency, is a biomechanical constant relative to the anthropometry of the subject (m, g, h, $I_G$: mass of the subject, gravity acceleration, distance from CG to the ground, and moment of body inertia around the ML or AP axis with respect to the CG). Depending on the direction, two distinct relationships were used to characterise the subjects’ anthropometry since the moments of inertia are different. According to Ledebt and Brerière (1994), these moments of inertia are given by the following relationships:

$I_{GML} = 0.0572mH_s^2$ and $I_{GAP} = 0.0533mH_s^2$

where $H_s$ represents the height of the subjects.

From this CGv/CP relation, it is relevant therefore to consider that CP oscillations operating over too high frequencies would not infer appreciable CG movements. The principle of this model is that the body constitutes a low-pass filter, which would explain the loss in amplitude observed between CP and CGv as the sway frequency increases. In fact, as shown by Fig. 1, the CGv calculation consists in multiplying the data, transformed in the frequential domain through a Fast Fourier Transform (FFT), by the above-mentioned filter and recovering to the time domain by processing an inverse FFT.

2.3. Signal processing

Three approaches were adopted to study the CGv and CP−CGv elementary motions: (1) a traditional method including variances of positions along each direction; (2) a frequential method based on RMS and Median Frequency (MF) parameters aimed at characterising the mean spectral decompositions of the sway motions on specific bandwidths (0−0.5 Hz for CGv and 0−3 Hz for CP−CGv); and (3) a mathematical model termed fractional Brownian motion (fBm) by Mandelbrot and Van Ness (1968). Interestingly, the frequential parameters are irrespective of the characteristics of the recording (duration, sample frequency). Complementarily, fBm modelling provides a quantitative measurement of wiggle in a trajectory. Through this feature, the non-integer dimension of a trajectory can be characterised. For instance, in the present case, a trajectory expressed as a function of time can be quantified by a dimension ranging between 0 and 1 since the trajectory fills more space than a simple point but less than a line. In turn, $H$ can be deduced from the relation

$\langle \Delta x^2 \rangle = \Delta t^{2H}$

where $\langle \Delta x^2 \rangle$, in mm$^2$, is the mean square distance covered by a given point and $\Delta t$, in s, represents the increasing time intervals. Note that the squared distances are only used to prevent a null mean displacement. Graphically, $H$, the Hurst exponent, corresponds to the half-slope of a variogram, i.e. the relation, de-

![Figure 1](image-url)

Fig. 1. The centre of pressure trajectories can be depicted as a function of time along each ML and AP direction (upper part, left side) or combined in order to be displayed over the plane of support (upper part, right side). In order to obtain, for instance along the AP direction, the centre of gravity vertical projection, and consequently the difference CP−CGv, a mathematical low-pass filter expressing an amplitude ratio between CGv and CP as a function of the movement frequency, is used. With this aim in mind, the CP displacements are processed through a Fast Fourier Transform (FFT) in order to obtain the amplitude distribution as a function of the frequency. Once this CP spectrum is obtained, a multiplication with the aforementioned filter will give the CGv spectrum and a subtraction will give the CP−CGv spectral power distribution. By this stage, through an inverse FFT (iFFT), it is possible to return to the temporal domain and obtain CGv, and consequently CP−CGv, time series. A last step consists in modelling these elementary motions as fBm processes. To this end, variograms, which consist of displaying the mean square displacements as a function of increasing time intervals $\Delta t$ through a bi-logarithmic plotting, are established. Transition points $\Delta t$ are obtained through CP variograms whereas parameters characterising the successive slopes (scaling exponents) and spatial co-ordinates of the transition points are extracted from CGv and CP−CGv variograms (from Rougier and Farenc, 2000).
picted bi-logarithmically, between \(<\Delta x^2>\) and increasing \(\Delta t\). Knowledge of the \(H\) value is also important since the relative contribution of stochastic (randomly controlled) and deterministic trends in the overall control process can be assessed. A median value of 0.5 for \(H\) indicates a lack of correlation between past and future increments and suggests that a pure stochastic (or random-walk) process operates. On the other hand, i.e. if \(H\) differs from 0.5, positive (0.5 < \(H\)) or negative (\(H < 0.5\)) correlations can be inferred indicating that persistent and anti-persistent processes, respectively, operate. Persistent and anti-persistent scaling regimes indicate the greater probability for a material point to continue along or to turn back from a given direction, respectively. An increased contribution of deterministic processes is revealed by scaling regimes \(H\) moving away from the 0.5 median value. On the other hand, the closer the regimes are to 0.5, the lesser the determinism and the greater the stochastic activity.

When modelling a trajectory as fBm, the first step in the data analysis consists in calculating for each subject and condition the averaged variograms, grouping all trials, for each direction. As is classically seen in bipedal instantaneous stance, two successive portions are also distinguishable in both ML and AP directions for \(CG_v\) and \(CP - CG_v\) motions, indicating that a somewhat deterministic (persistent or anti-persistent) scaling regime precedes or succeeds a completely stochastic one. As expected, since the shift between successive mechanisms appears identical for all \(CP\), \(CG_v\) and \(CP - CG_v\) motions (Fig. 2), the method retained initially solely for \(CP\) trajectories was kept (Rougier, 1999). Its principle lies on a comparison between experimental and average stochastic variograms. For \(CP\) motions, the complete stochastic process is characterised in a bi-logarithmic scaling by a one-slope straight line (in such a case \(H\) is thus equal to 0.5). The maximal distance between an experimental variogram and the ‘stochastic’ straight line is thought to correspond to the \(\Delta t\) co-ordinate of the transition point. However, it should be pointed out that the stochastic behaviour, taken as a reference, is itself modified by the low- or high-pass filter used for the computation of \(CG_v\) and \(CP - CG_v\) motions. As seen in the upper part of Fig. 2, the filter effect leads in fact to curvilinear functions moving progressively away from or closer to the one-slope mentioned above. Scaling regimes relative to ‘average stochastic variograms’ over the same \(\Delta t\) must therefore be taken as a reference in such a way that

\[
H_{\text{cal}} = (H_{\text{exp}} - H_{\text{sto}}) + 0.5
\]

where \(H_{\text{cal}}\), \(H_{\text{exp}}\) and \(H_{\text{sto}}\) represent the calculated, experimental and stochastic scaling regimes, respectively. For this purpose, the temporal order of the increments constituting the \(CP\) trajectories was randomly shuffled in order to destroy any temporal correlation (Theiler et al., 1992). As suggested by Scheinkman and LeBaron (1989), the increments were then recombined to generate stochastic trajectories that were processed in order to determine \(CG_v\) and \(CP - CG_v\) motions, as for any other \(CP\) trajectory. Finally, these stochastic motions were used to compute the ‘average stochastic variograms’ mentioned above. Thus, for each of the two motions investigated and each ML and AP component, two scaling exponents (indexed as short and long latencies: \(H_a\) and \(H_b\)) as well as the co-ordinates of the transition point were extracted. Finally, since the slopes of the variograms do not seem to vary significantly over \(\Delta t\) of 10 s, this limit was adopted to compute the various aforementioned parameters.

To evaluate the body leaning effects on the whole set of parameters, the results, issued from REF, BWD and FWD conditions, were processed through a one-
way ANOVA. Simple effects were then treated through a non-parametric statistical analysis, the Wilcoxon T-test, the first level of significance being set at $P < 0.05$.

3. Results

3.1. Traditional parameters

As expected, the mean position of the CG, (which by definition is similar to that of the CP) in the AP direction presents a huge statistical effect, as revealed by the ANOVA ($F(2,51) = 209.9; p < 0.001$). Expressed as a percentage of the feet length, BWD, REF and FWD induce in the AP direction $23.21 \pm 3.09$, $35.92 \pm 4.59$, $59.06 \pm 6.72$, respectively. On the other hand, it is relevant to mention that modifying the body lean does not affect the mean position in the perpendicular ML direction.

As indicated by the histograms of Fig. 3, leaning forward or backward induces larger variances for CP–CG motions measured in both directions (ML: $F(2,51) = 7.02, p < 0.01$; AP: $F(2,51) = 8.76, p < 0.001$). Conversely, the CG motions seem to be less affected by body leaning since no statistical effect has been found. In all cases, when the ANOVA demonstrates statistical results, as for CP–CG motions, the simple effects consist in an enhancement of the parameters in both BWD and FWD conditions when compared to REF.

3.2. Frequential parameters

The average frequential spectra of Fig. 4 show a slight increase in the amplitudes of CP–CG motions for both ML and AP directions when leaning forward and a more significant one when leaning backward. As shown by the histograms of Fig. 3, this feature is confirmed by the ANOVA since larger variations are noticed for the RMS in the AP direction ($F(2,51) = 11.44; p < 0.001$) when compared to the ML one ($F(2,51) = 6.77; p < 0.01$). Since this effect on spectra involves the complete bandwidth (Fig. 4), no statistical effects are therefore observed for the MF.

Concerning the CG motions, some slight differences are noticed in the $0.05–0.4$ Hz bandwidth in the ML direction. On the other hand, larger amplitudes are observed when leaning either backward or forward in the same bandwidth whilst a decrease characterises the lowermost frequencies. Consequently, as seen through the histograms of Fig. 3, an effect appears for the RMS in the ML direction ($F(2,51) = 3.48; P < 0.05$) and for the MF in the AP one ($F(2,51) = 6.98; P < 0.01$).

The simple effects indicate that the CP–CG rates are always smaller in the REF condition, when compared to either BWD or FWD ones. In parallel, the main effect on CG, motions consists in reduced MF in the REF condition.

![Fig. 3. Histograms showing group means and standard deviations for traditional and frequential parameters. The significant effects assessed by the ANOVA are presented above the histograms whilst those relative to the simple effects are displayed below (the one between BWD and REF in the left side, the one between FWD and REF in the right side) (**: $P < 0.001$; ***: $P < 0.01$; *: $P < 0.05$).](image)
3.3. fBm modelling

Variograms depicted in Fig. 5 reveal the lack of global effect of body leaning for CP – CGv motions. A slight increase in the slopes of the initial line portions ($H_0$) is worth mentioning for the ML direction for BWD versus REF (Fig. 6). On the other hand, variograms computed from CGv motions display some changes for $H_{ij}$ according to the condition, especially in the AP direction (Figs. 5 and 6). These visual impressions are confirmed by the ANOVA since a statistical effect is only observed for the AP direction ($F(2,51) = 12.26; p < .001$), as shown by the histograms of Fig. 6.

Leaning the body forward or backward induces, in addition, some effects on the spatio-temporal coordinates of the transition points, i.e. the point corresponding to the onset of the corrective mechanisms operating over the longest $\Delta t$ (Fig. 6). Precisely, BWD and FWD conditions induce earlier temporal coordinates ($F(2,51) = 5.43; p < 0.01$) in the AP direction. This $\Delta t$ diminution is accompanied by a concomitant decrease of $\langle \Delta x^2 \rangle$ for both CP – CGv ($F(2,51) = 7.9; p < 0.001$) and CGv motions ($F(2,51) = 5.88; p < 0.01$) in the ML direction whereas this feature is observed only in the AP direction for CP – CGv motions ($F(2,51) = 8.89; p < 0.001$). All these effects can be observed via the histograms of Fig. 6.

4. Discussion

Traditional parameters used to quantify the sway territory covered by elementary motions (CP – CGv and CGv) obtained from the decomposition of the CP appear to be affected differentially. Results indeed demonstrate that leaning the body outward from the usual positioning induces an increase in both ML and AP variances for CP – CGv motions. On the other hand, only tendencies to increase or slightly decrease are observed for CGv motions. In the light of the
4.1. Leaning effects on CP – CG, motions

In the light of these CP – CG, amplitudes, which can be seen as an expression of the initial horizontal acceleration communicated to the CG (Brenière et al., 1987; Winter et al., 1998), these results would therefore suggest a concomitant increase of the level of muscular activity as long as the body is maintained in a leaning position. Naturally, this increased muscular activity would mainly be explained by the greater momentum of gravity exerted at the ankle level for the FWD condition. On the other hand, this momentum, according to Okada and Fujiwara (1984) appears particularly reduced when a backward leaning posture is solicited. It thus seems foreseeable that a co-contraction mechanism, involving both plantar flexors and extensors, would be at the origin of this phenomenon in the BWD.

Fig. 5. Relative variograms for each direction (ML and AP) characterising the whole sample population (mean in continuous lines ± S.D. in thinnest dashed lines) for CP – CG, and CG, motions for the three experimental conditions. As in the lower part of Fig. 2, these relative variograms express the distances (in arbitrary units), as a function of increasing Δt, between experimental mean variograms and the average stochastic variograms. Note the differences in the slopes of the line portions characterising these CG, motions for the longest Δt, especially in the AP direction.
Fig. 6. Histograms showing group means and standard deviations for parameters issued from the fBm modelling: spatio-temporal co-ordinates of the transition point \((\Delta x, \Delta t)\) on the upper part and scaling exponents \(H_{sl}\) and \(H_{ll}\) on the lower part. As in Fig. 3, statistical results are expressed above and below the histograms (**: \(P < 0.001\); ***: \(P < 0.01\); *: \(P < 0.05\)). Note the significant effects in \(H_{ll}\) for CPv motions assessed by the ANOVA in the AP direction.

4.2. Leaning effects on CGv motions

Overall, our results demonstrate various effects on CGv motions, depending on the direction. In particular, increases observed in the ML direction suggest that the musculature involved in stance control for these BWD and FWD leaning postures (abductor–adductor muscles of the hip according to Winter et al., 1996) is impaired. In fact, it appears that the body behaves in these inclined positions as a tilted rigid inverted pendu-
lum for which the only degree of freedom consists in oscillating around the points of insertion of the stabilising muscles. On the other hand, a lack of effect on CGv motions for BWD and FWD conditions in the AP direction is noticed and is initially highlighted by frequent spatial parameters. The increase of the median frequency (MF), observed in the AP direction, signifies that a diminution of the period needed for the CGv to return to a similar position, occurs. On the other hand, the decrease in RMS values in the ML direction is likely to be more closely related to spatial parameters. Following this train of thought, fBm modelling, once again, is able to provide additional insight. As indicated by the present results, the augmented spatial coordinates of the transition points observed in the ML direction for extreme leaning postures serve mainly to explain the increased RMS noticed for CGv motions. On the other hand, the MF decrease in the AP direction would therefore be mainly due to more controlled CGv motions, especially those aimed at making the CG return more directly to its initial position. This particularity, by inferring a larger contribution of deterministic processes in these corrective mechanisms, would once more highlight the priority nature of this CG control.

These larger distances covered before a corrective mechanism begins to operate could also be explained by the impairment in perception caused by the leaning posture. This would explain why normal subjects to whom cooling of the soles is applied (Asai et al., 1994) or elderly patients and those suffering from Parkinson’s disease (Schieppati et al., 1994) have great difficulty in performing this particular task. Consequently, as proposed by the latter study, this impairment in forward leaning would naturally affect, in turn, the gait initiation process.

Finally, addressing more determinism in the corrective control of the CG can be perceived as a consequence of the larger amount of sway in general and in particular as an effect of the increase in the mean squared distances \( \langle \Delta x^2 \rangle \) covered before correction began to take place. Although several studies using the same model can be seen to confirm this hypothesis, it is worth noting that others demonstrate the opposite. For instance, Rougier and Farenc (2000), have shown that blind individuals, in comparison to normal sighted people required to close their eyes, demonstrate both smaller \( \langle \Delta x^2 \rangle \) and more deterministic scaling regimes \( H_q \) for the CGv motions, emphasising the independent relationship between these two parameters.

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