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RESEARCH ARTICLE

How a plantar pressure-based, tongue-placed tactile biofeedback modifies postural control mechanisms during quiet standing

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Abstract The purpose of the present study was to determine the effects of a plantar pressure-based, tongue-placed tactile biofeedback on postural control mechanisms during quiet standing. To this aim, 16 young healthy adults were asked to stand as immobile as possible with their eyes closed in two conditions of No-biofeedback and Biofeedback. Centre of foot pressure (CoP) displacements, recorded using a force platform, were used to compute the horizontal displacements of the vertical projection of the centre of gravity (CoG_v) and those of the difference between the CoP and the vertical projection of the CoG (CoP-CoG_v). Analysis of the CoP-CoG_v displacements showed larger root mean square (RMS) and mean power frequencies (MPF) in the Biofeedback than in the No-biofeedback condition. Stabilogram-diffusion analysis further showed a concomitant increased spatial and reduced temporal transition point co-ordinates at which the corrective processes were initiated and an increased persistent behaviour of the CoP-CoG_v displacements over the short-term region. Analysis of the CoG_v displacements showed decreased RMS and increased MPF in the Biofeedback relative to the No-biofeedback condition. Stabilogram-diffusion analysis further indicated that these effects mainly stem from reduced spatio-temporal transition point co-ordinates at which the corrective process involving CoG_v displacements is initiated and an increased anti-persistent behaviour of the CoG_v displacements over the long-term region. Altogether, the present findings suggest that the main way the plantar pressure-based, tongue-placed tactile biofeedback improves postural control during quiet standing is via both a reduction of the correction thresholds and an increased efficiency of the corrective mechanism involving the CoG_v displacements.

Keywords Balance · Biofeedback · Tongue Display Unit · Plantar pressure · Centre of foot pressure · Centre of gravity · Stabilogram-diffusion analysis

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Introduction

Maintaining an upright stance represents a complex task, which is achieved by integrating sensory information from the visual, vestibular and somatosensory systems. When one of these sensory inputs becomes unavailable and/or inaccurate and/or unreliable, postural control generally is degraded. One way to solve this problem is to supplement and/or substitute limited/altered/missing sensory information by providing additional sensory information to the central nervous system via an alternative sensory modality.

Along these lines, an original biofeedback system, whose underlying principle consists in supplying the user with supplementary sensory information related to foot sole pressure distribution through a tongue-placed tactile output device, was recently developed with the aim of improving balance. In recent studies, the effectiveness of this system in decreasing centre of foot pressure (CoP) displacements during upright quiet standing has been established, suggesting that an artificial tongue-placed tactile biofeedback could be efficiently integrated with other sensory cues by the postural control system (Vuillerme et al. 2006a, 2007). At this point, however, no information was provided regarding how the central nervous system (CNS) used this biofeedback information for

controlling posture, or, in other words, how this plantar pressure-based, tongue-placed tactile biofeedback modified the control mechanisms involved in postural control during quiet standing. The present experiment was thus designed to address this issue.

To achieve this goal, a method of analysis consisting of the dissociation of CoP trajectories into two elementary components, (1) the horizontal displacement of the vertical projection the centre of gravity (CoG_v) and (2) those of the difference between the CoP and the vertical projection of the CoG (CoP-CoG_v) (e.g. Rougier and Caron 2000) was first used. During bipedal quiet standing, indeed, the CoP assumes two distinct tasks: it counteracts the centre of gravity (CoG) in its falling motion and makes it remain in a particular zone within the base of support (Winter et al. 1996; Rougier and Caron 2000). In other words, the CoP displacements are aimed at facilitating the displacements of the CoG to return to a position more compatible with equilibrium, in the first case, and reducing the displacements of the CoG as much as possible, in the second case (Winter et al. 1996; Rougier and Caron 2000). Interestingly, CoG_v and CoP-CoG_v are recognised to present specific attributes in postural control. The former, representing the whole body motions, can be considered sometimes as the controlled variable during bipedal quiet standing (e.g. Clément et al. 1984; Horstmann and Dietz 1990; Winter et al. 1998). The latter, in addition to demonstrating a certain proportionality with the horizontal acceleration communicated to the CoG_v (Brenière et al. 1987; Gage et al. 2004; Winter et al. 1998), is assumed to express the ankle joint stiffness (Caron et al. 2000; Winter et al. 1998) and to be linked to the level of neuromuscular activity (Rougier et al. 2001). Thus, by decomposing the CoP trajectory into two elementary motions, this first method of analysis allows to determine to which extent a modification of the global CoP displacements can arise from either a single exaggerated elementary motion or both of them.

A further step in understanding how each of these CoG_v and CoP-CoG_v variables is controlled for the purpose of equilibrium was made by applying mathematical concepts such as fractional Brownian motion (fBm) (Mandelbrot and van Ness 1968) to these motions. Through this model and the resort to the so-called ''stabilogram-diffusion analysis'', initially used for interpreting CoP data (e.g. Collins and De Luca 1993; Vuillerme and Vincent 2006), the temporal organisation of various control mechanisms involved in controlling upright posture can be revealed in the sense that two distinct control mechanisms, persistent and anti-persistent operate in continual succession. Interestingly, this method of analysis allows the determination of the spatio-temporal coordinates of the transition point, i.e. for how long and to what extent a corrective (anti-persistent) process succeed on average to a non-corrective (persistent) one. In addition, by assessing the gap from a completely stochastic uncontrolled process, this method of analysis also allows determining the degree of control with which these mechanisms operate (e.g. Rougier and Caron 2000). Overall, previous studies evidenced that partially deterministic controls successively operate initially on CoP-CoG_v and then on CoG_v displacements through persistent and anti-persistent mechanisms, respectively. In other words, the CoP displacements have a tendency to drift away from the CoG_v during the shortest time intervals (Δt), inferring an increased difference CoP-CoG_v, whereas the CoG_v tends to return to an equilibrium point during the longest Δt.

On the whole, in light of the CoP displacements dissociation into two elementary CoP-CoG_v and CoG_v displacements and resort to the fBm framework through the stabilogram-diffusion analysis, the present experiment should indicate to which extent the decreased CoP displacements, recently observed when the plantar pressure-based, tongue-placed tactile biofeedback, was in use relative to when it was not (Vuillerme et al. 2006a, 2007), could be explained by (1) a modification of the respective contributions of CoP-CoG_v and/or CoG_v motions in the global CoP trajectories on one hand and/or (2) by the subjects' ability to control these elementary motions in a more or less precise manner on the other hand. It was hypothesized that the biofeedback would yield a reduction of the correction thresholds and an increased efficiency of the corrective mechanism involving CoG_v displacements.

Materials and Methods

Subjects

Sixteen young university students (age: 24.8 ± 3.2 (21.5–31.0) years; body weight: 71.4 ± 15.0 (50.0–96.0) kg; height: 177.3 ± 11.8 (160.0–192.0) cm; mean ± SD (range) participated in the experiment. They gave their informed consent to the experimental procedure as required by the Helsinki declaration (1964) and the local Ethics Committee, and were naive as to the purpose of the experiment. None of the subjects presented any history of motor problem, neurological disease or vestibular impairment.

Task and procedures

Subjects stood barefooted, feet together, hands at the sides and eyes closed. They were asked to sway as little as possible in two No-biofeedback and Biofeedback conditions. The No-biofeedback condition served as a control

condition. In the Biofeedback condition, subjects performed the postural task using a plantar pressure-based, tongue-placed tactile biofeedback system. A plantar pressure data acquisition system (FSA Inshoe Foot pressure mapping system, Vista Medical Ltd.), consisting of a pair of 2 mm thick flexible insoles instrumented with an array of 8×16 pressure sensors per insole (1 cm^2 per sensor, range of measurement: 0–30 PSI), was used. The pressure sensors transduced the magnitude of pressure exerted on each left and right foot sole at each sensor location into calculation of the positions of the resultant ground reaction force exerted on each left and right foot, referred to as the left and right foot centre of foot pressure, respectively (CoP_{lf} and CoP_{rf}). The positions of the resultant CoP were then computed from the left and right foot CoP trajectories through the following relation (Winter et al. 1996):

$$CoP = CoP_{lf} \times R_{lf}/(R_{lf} + R_{rf}) + CoP_{rf} \times R_{rf}/(R_{rf} + R_{lf}),$$

where R_{lf}, R_{rf},CoP_{lf}, CoP_{rf} are the vertical reaction forces under the left and the right feet, the positions of the CoP of the left and the right feet, respectively.

CoP data were then fed back in real time to a recently developed tongue-placed tactile output device (Vuillerme et al. 2006a, b, c, 2007). This so-called Tongue Display Unit (TDU), initially introduced by Bach-y-Rita et al. (1998), comprises a 2D array (1.5×1.5 cm) of 36 electrotactile electrodes each with a 1.4 mm diameter, arranged in a 6×6 matrix. The matrix of electrodes, maintained in close and permanent contact with the front part of the tongue dorsum, was connected to an external electronic device triggering the electrical signals that stimulate the tactile receptors of the tongue via a flat cable passing out of the mouth. The underlying principle of our biofeedback system was to supply subjects with supplementary information about the position of the CoP relative to a predetermined adjustable ''dead zone'' (DZ) through the TDU. In the present experiment, antero-posterior and medio-lateral bounds of the DZ were set as the standard deviation of subject's CoP displacements recorded for 10 s preceding each experimental trial. A simple and intuitive coding scheme for the TDU, consisting of a ''threshold-alarm'' type of feedback rather than a continuous feedback about the ongoing position of the CoP, was then used. (1) When the position of the CoP was determined to be within the DZ, no electrical stimulation was provided in any of the electrodes of the matrix. (2) When the position of the CoP was determined to be outside the DZ, electrical stimulation was provided in distinct zones of the matrix, depending on the position of the CoP relative to the DZ. Specifically, eight different zones located in the front, rear, left, right, front-left, front-right, rear-left, rear-right of the matrix were defined; the activated zone of the matrix corresponded to the position of the CoP relative to the DZ. For instance, in the case that the CoP was located towards the front of the DZ, a stimulation of the anterior zone of the matrix (i.e. stimulation of the front portion of the tongue) was provided. Finally, in the present experiment, the frequency of the stimulation was maintained constant at 50 Hz across participants, ensuring the sensation of a continuous stimulation over the tongue surface. The intensity of the electrical stimulating current was adjusted for each subject, and for each of the front, rear, left, right, front-left, front-right, rear-left, rear-right portions of the tongue, given that the sensitivity to the electrotactile stimulation was reported to vary between individuals (Essick et al. 2003), but also as a function of location on the tongue in a preliminary experiment (Vuillerme et al. 2006b). Several practice runs were performed prior to the test to ensure that subjects had mastered the relationship between the position of the CoP relative to the DZ and lingual stimulations.

Note that the foot insole system was put beneath the feet and the TDU was inserted in the oral cavity of all the subjects over the duration of the experiment (i.e. in both the No-biofeedback and Biofeedback conditions), ruling out the possibility that the postural improvement observed in the Biofeedback relative to the No-biofeedback condition is due to enhanced plantar cutaneous facilitation and mechanical stabilization of the head in space, respectively.

A force platform (AMTI model OR6-5-1), which was not a component of the biofeedback system, was used to measure the displacements of the centre of foot pressure (CoP), as a gold-standard system for assessment of balance during quiet standing. Signals from the force platform were sampled at 100 Hz (12 bit A/D conversion) and filtered with a second-order Butterworth filter (10 Hz low-pass cut-off frequency).

Three 30 s trials for each experimental condition were performed. The order of presentation of the two experimental conditions was randomized.

Estimation of the CoG_v and CoP-CoG_v displacements

CoG_v and CoP-CoG_v displacements were determined from the CoP trajectories computed from the force platform. A relationship between the amplitude ratio of the CoG_v and CoP motions (CoG_v/CoP) and sway frequencies allowed determining the CoG_v and consequently the CoP-CoG_v motions. Body sways being particularly reduced, standing still can therefore theoretically be modelled as a one-link inverted pendulum (e.g. Winter et al. 1998; Gage et al. 2004), where CoG_v and CoP behave as periodic functions in phase with each other. The method, initially proposed by Brenière (1996) for gait and then extended to standing

posture by Caron et al. (1997), is given by the following formula:

$$CoG_v/CoP = \Omega_0^2/(\Omega_0^2 + \Omega^2),$$

where $\Omega = 2\pi f$ is the pulsation (rad s^{-1}) and $\Omega_0 = [mgh/(I_G + mh^2)]^{1/2}$ (Hz), termed as 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 CoG to the ground, and moment of body inertia around the medio-lateral (ML) or antero-posterior (AP) axis with respect to the CoG).

The CoG_v estimation 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 (e.g. Bernard-Demanze et al. 2006; Genthon and Rougier 2005; Rougier et al. 2001; Rougier and Caron 2000; Vuillerme and Rougier 2005).

Data analysis

CoP-CoG_v and CoG_v displacements were processed through two different analyses.

(1) A frequency-domain analysis, issued from the FFT process, included the calculation of (*i*) the root mean square (RMS) and (*ii*) the mean power frequency (MPF) parameters aimed at characterising the mean spectral decompositions of the sway motions on specific bandwidths (0–0.5 Hz for CoG_v and 0–3 Hz for CoP-CoG_v). These bandwidths were chosen to give these indices the larger sensitivity since the modifications occurring on the frequency spectra intervene generally inside these bounds.

(2) A stabilogram-diffusion analysis (Collins and De Luca 1993) as described initially by Mandelbrot and van Ness (1968) enabled the assessment of the degree to which a trajectory is controlled. The principle of this analysis is that the aspect of a trajectory, expressed as a function of time, can be quantified by a fractional, i.e., a non-finite integer space dimension. This fractional dimension D is linked to a scaling exponent H (necessarily ranged between 0 and 1) since $D = 1\text{-}H$ for a point displaced through a single direction. This scaling regime graphically corresponds to the half slope of the line portions constituting a variogram depicted bi-logarithmically. This latter, in fact, expresses the mean square displacements $<\Delta x^2>$ as a function of increasing times intervals Δt and is given by the formula:

$$<\Delta x^2> = \Delta t^{2H}.$$

On the one hand, a median value of $H = 0.5$ indicates a lack of correlation between past and future increments and suggests that a pure random walk or stochastic process operates. On the other hand, i.e. if H differs from 0.5, positive ($H > 0.5$) or negative ($H < 0.5$) correlations can be inferred, indicating the greater probability for a material point to continue along or to turn back from a given direction, respectively. As the scaling regimes move away from the 0.5 median value, the contribution of deterministic mechanisms is therefore increased. The different necessary steps have been detailed in previous reports (e.g. Rougier and Caron 2000). For each of the two elementary motions and for each of the ML and AP axis, the stabilogram-diffusion analysis included the calculation of (i) the temporal (Δt) and spatial ($<\Delta x^2>$) co-ordinates of the transition point and (ii) the two scaling exponents, indexed as short (H_{sl}) and long latencies (H_{ll}), as reported in previous studies.

Statistical analysis

Data from both No-biofeedback and Biofeedback conditions were compared through t tests, the first level of significance being set at 0.05.

Results

Before presenting the results, it is important to emphasis that no statistical differences have been noticed regarding the mean positioning of the CoP between the two conditions of No-biofeedback and Biofeedback along both the ML and AP axes ($Ps > 0.05$), ruling out the possibility of the observed results to be confounded by a possible effect of leaning (Rougier et al. 2001) or asymmetrical postures (Genthon and Rougier 2005).

Frequency-domain analysis

Analysis of the CoP-CoG_v displacements showed (1) larger RMS in the Biofeedback than in the No-biofeedback condition along both the ML and AP axes ($T = 2.22$, $P < 0.05$, Fig. 1a and $T = 4.96$, $P < 0.001$, Fig. 1b, respectively), and (2) larger MPF in the Biofeedback than in the No-biofeedback condition along both the ML and AP axes ($T = 2.33$, $P < 0.05$, Fig. 1c and $T = 3.20$, $P < 0.01$, Fig. 1d, respectively).

Analysis of the CoG_v displacements showed (1) smaller RMS in the Biofeedback than in the No-biofeedback condition along both the ML and AP axes ($T = 4.88$, $P < 0.001$, Fig. 1e and $T = 3.89$, $P < 0.01$, Fig. 1f, respectively), and (2) larger MPF in the Biofeedback than in the No-biofeedback condition along both the ML and AP axes ($T = 4.48$, $P < 0.001$, Fig. 1g and $T = 3.66$, $P < 0.01$, Fig. 1h, respectively).

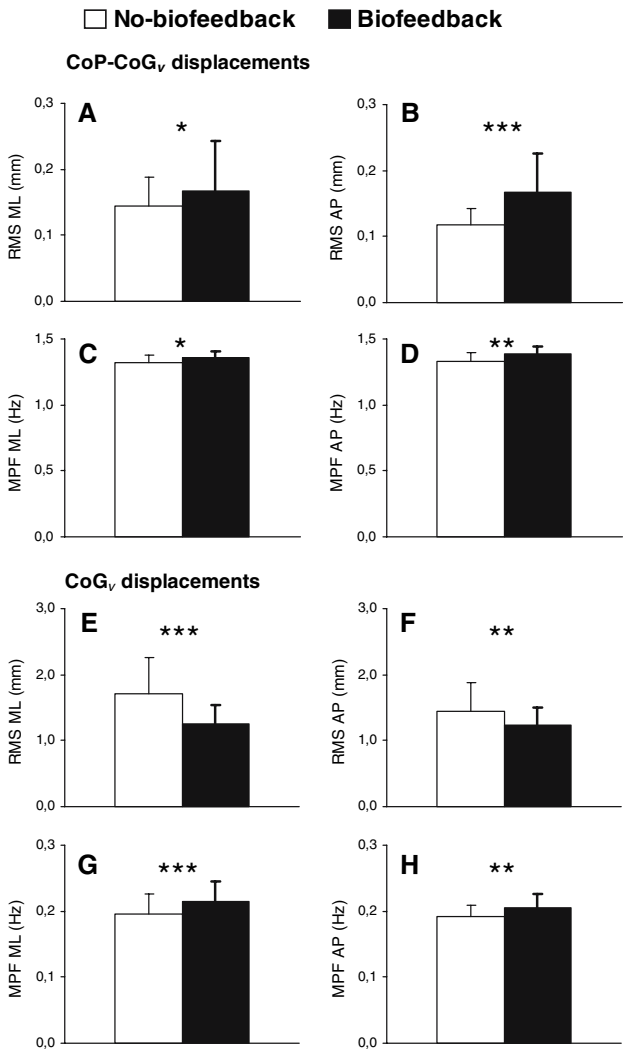

Fig. 1 Mean and standard deviation of the root mean square (RMS) along the ML (**a**, **e**) and AP (**b**, **f**) axes and mean power frequencies (MPF) along the ML (**c**, **g**) and AP (**d**, **h**) axes for CoP-CoG$_v$ and CoG$_v$ displacements obtained in the No-biofeedback and in the Biofeedback conditions. These two experimental conditions are presented with different symbols: No-biofeedback (*white bars*) and Biofeedback (*black bars*). *Upper* and *lower* panels represent CoP-CoG$_v$ and CoG$_v$ displacements, respectively. The significant *P* values for comparisons between No-biofeedback and Biofeedback conditions also are reported (* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$)

Stabilogram-diffusion analysis

Transition point co-ordinates

Analysis of the time intervals Δt of the transition point showed decreased values in the Biofeedback relative to the No-biofeedback condition along both the ML and AP axes ($T = 2.16$, $P < 0.05$, Fig. 2a and $T = 4.82$, $P < 0.001$, Fig. 2b, respectively).

Analysis of the mean square distances $<\Delta x^2>$ of the transition point showed (1) increased values for the CoP-CoG$_v$ displacements in the Biofeedback relative to the No-biofeedback condition along both the ML and AP axes ($T = 2.31$, $P < 0.05$, Fig. 2c and $T = 4.31$, $P < 0.001$, Fig. 2d, respectively), and (2) decreased values for the CoG$_v$ displacements in the Biofeedback relative to the No-biofeedback condition along both the ML and AP axes ($T = 2.63$, $P < 0.05$, Fig. 2i and $T = 2.17$, $P < 0.05$, Fig. 2j, respectively).

Scaling regimes exponents

Analysis of the CoP-CoG$_v$ displacements showed larger short latency scaling regimes exponents H_{sl} in the Biofeedback than in the No-biofeedback condition along both the ML and AP axes ($T = 2.81$, $P < 0.05$, Fig. 2e and $T = 3.62$, $P < 0.01$, Fig. 2f, respectively), suggesting an increased persistent behaviour in the short-term region during the shortest time intervals in the Biofeedback relative to the No-biofeedback condition.

Analysis of the CoG$_v$ displacements showed smaller long latency scaling regimes exponents H_{ll} in the Biofeedback than No-biofeedback condition along both the ML and AP axes ($T = 7.65$, $P < 0.001$, Fig. 2m and $T = 4.28$, $P < 0.001$, Fig. 2n, respectively), suggesting an increased anti-persistent behaviour in the long-term region during the longest time intervals in the Biofeedback relative to the No-biofeedback condition.

Finally, as generally observed in this kind of investigation, for both experimental conditions, the results of long latency scaling regimes exponents H_{ll} for CoP-CoG$_v$ displacements (Figs. 2g, 2h) and those of short latency scaling regimes exponents H_{sl} for CoG$_v$ displacements (Figs. 2k, 2l) were close to 0.5, hence indicating a behaviour solely stochastic in nature (e.g., Bernard-Demanze et al. 2006; Genthon and Rougier 2005; Rougier et al. 2001; Rougier and Caron 2000; Vuillerme and Rougier 2005).

Discussion

The purpose of this study was to determine the effects of a plantar pressure-based, tongue-placed tactile biofeedback on postural control mechanisms during quiet standing. To this aim, sixteen young healthy adults were asked to stand as immobile as possible with their eyes closed in two conditions of No-biofeedback and Biofeedback. Centre of foot pressure (CoP) displacements, recorded using a force platform, were used to compute the horizontal displacements of the vertical projection the centre of gravity (CoG$_v$) and those of the difference between the CoP and the vertical projection of the CoG (CoP-CoG$_v$). These displacements were processed through frequency-domain

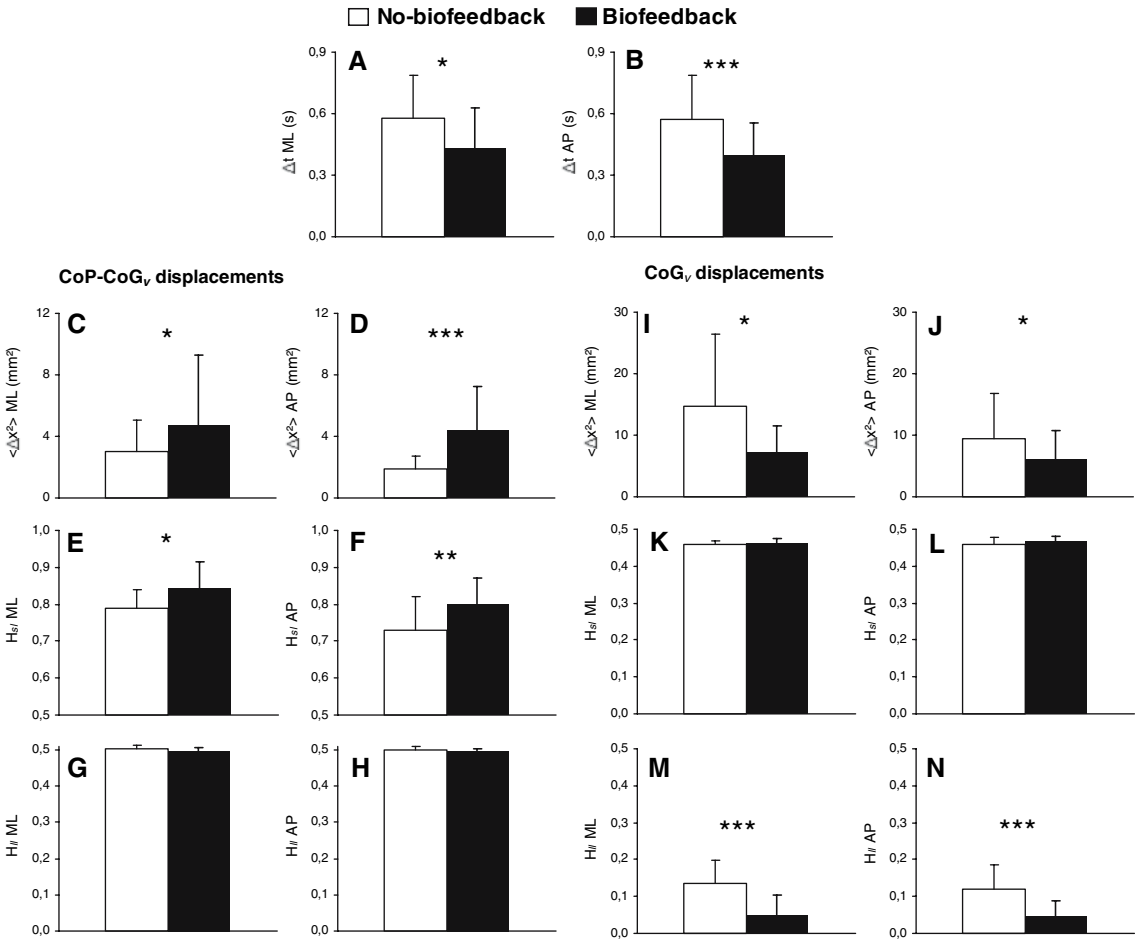

Fig. 2 Mean and standard deviation of the temporal co-ordinates of the transition point (Δt) along the ML (**a**) and AP axes (**b**), the spatial co-ordinates ($<\Delta x^2>$) of the transition point along the ML (**c**, **i**) and AP axes (**d**, **j**), the short latency scaling exponents (H_{sl}) along the ML (**e**, **k**) and AP axes (**f**, **l**), and the long along latency scaling exponents (H_{ll}) along the ML (**g**, **m**) and AP axes (**h**, **n**) for CoP-CoG$_v$ and CoG$_v$ displacements obtained in the No-biofeedback and Biofeedback conditions. These two experimental conditions are presented with different symbols: No-biofeedback (*white bars*) and Biofeedback (*black bars*). *Upper* and *lower* panels represent CoP-CoG$_v$ and CoG$_v$ displacements, respectively. The significant P values for comparisons between No-biofeedback and Biofeedback conditions also are reported (* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$)

and stabilogram-diffusion analyses to assess their spatio-temporal linkage and their degree of control.

Effect of biofeedback on CoP-CoG$_v$ displacements

Analysis of the CoP-CoG$_v$ displacements showed increased RMS (Figs. 1a, 1b) and MPF (Figs. 1g, 1h) along both the ML and AP axes in the Biofeedback and No-biofeedback condition. Complementary to the frequency-domain analysis, modelling the CoP-CoG$_v$ displacements as fBm through the stabilogram diffusion analysis provided additional insight into the nature and the temporal organisation of the control mechanisms involving the CoP-CoG$_v$ displacements called into play in the Biofeedback condition.

On one hand, the increased CoP-CoG$_v$ RMS (Fig. 1a, 1b) observed in the Biofeedback condition were likely to be related to (1) spatial parameters, since increased spatial co-ordinates of the transition point ($<\Delta x^2>$) were observed along both the ML and AP axes in the Biofeedback relative to the No-biofeedback condition (Figs. 2c, 2d), and (2) an increased persistent behaviour of CoP-CoG$_v$ displacements in the short-term region during the shortest time intervals, since increased short latency scaling exponents H_{sl} were observed along both the ML and AP axes in the Biofeedback relative to the No-biofeedback condition (Figs. 2e, 2f).

On the other hand, the increased CoP-CoG$_v$ MPF observed in the Biofeedback condition (Figs. 1c, 1d) means, by definition, that a diminution of the period needed for the CoP-CoG$_v$ to return to a similar position occurred. This result could hence be related to temporal parameters, since reduced temporal co-ordinates of the transition point Δt

were observed along both the ML and AP axes in the Biofeedback relative to the No-biofeedback condition (Figs. 2a, 2b).

Finally, it is important to keep in mind that, from a biomechanical point of view, increasing the amplitudes of CoP-CoG_v displacements in the Biofeedback condition, seen as an expression of the initial horizontal acceleration communicated to the CoG_v (Brenière et al. 1987; Gage et al. 2004; Winter et al. 1998), would negatively affect the relative facility for the subjects to handle CoG_v displacements in this condition due to the lower forces they would have to counteract.

Effect of biofeedback on CoG_v displacements

Analysis of the CoG_v displacements showed decreased RMS (Fig. 1e, 1f) and increased MPF (Fig. 1g, 1h) along both the ML and AP axes in the Biofeedback relative to the No-biofeedback condition. At this point, considering the increased CoP-CoG_v amplitudes observed in the Biofeedback relative to the No-biofeedback condition (Figs. 1a, 1b), determining larger initial horizontal accelerations communicated to the CoG_v (Brenière et al. 1987; Gage et al. 2004; Winter et al. 1998), it was hypothesized that these decreased CoG_v amplitudes observed with Biofeedback (Figs. 1e, 1f) to stem from a modification of the control characteristics of the CoG_v displacements set by the CNS, involving (1) a reduction in the correction thresholds and/or (2) an increased efficiency of the corrective mechanisms. Accordingly, modelling the CoG_v displacements as fBm through the stabilogram diffusion analysis allowed providing additional insight into (1) the spatio-temporal coordinates of the transition point at which the corrective process CoG_v displacements is initiated ($<\Delta x^2>$ and Δt) and (2) the extent to which the CoG_v is controlled (H_{ll}).

On one hand, results showed reduced spatio-temporal co-ordinates of the transition point ($<\Delta x^2>$ and Δt) along both the ML and AP axes in the Biofeedback relative to the No-biofeedback condition (Figs. 2a, 2b, 2i, 2j), suggesting that the distance covered by the CoG_v and the time spent before the onset of a corrective process were reduced in the Biofeedback relative to the No-biofeedback condition.

On the other hand, results showed decreased long latency scaling exponents (H_{ll}) in the Biofeedback relative to the No-biofeedback condition (Fig. 2m, 2n), suggesting an increased probability that CoG_v away from a relative equilibrium point will be offset by corrective adjustments back towards the equilibrium position, once a threshold in sway has been reached, with Biofeedback.

These shorter distances ($<\Delta x^2>$) associated with shorter time intervals (Δt) before a corrective mechanism begin to operate, and the improved determinism in this corrective process aimed at returning the CoG_v to its initial position (H_{ll}) observed along both the ML and AP directions in the Biofeedback relative to the No-biofeedback condition, could be explained by the specificity of the biofeedback provided to the subjects. Indeed, as above-mentioned, the plantar pressure-based, tongue-placed tactile biofeedback used in this study presented the particularity of supplying the subjects with (1) supplementary sway-related cues that could have allowed them to decrease spatio-temporal thresholds from which the postural corrections were set (Figs. 2a, 2b, 2i, 2j), and (2) a constant reference position (''dead zone'') in which they were required to stay (or, at least return regularly), that could have allowed them to increase the degree to which CoG_v displacements were controlled (Figs. 2m, 2n). Interestingly, with regard to the provision of enhanced sensory information from the plantar soles to the postural control system, our results replicate those of two recent studies investigating, with the same analysis method, the effects of an increased sensitivity of the plantar mechanoreceptors on postural control mechanisms during quiet standing (Bernard-Demanze et al. 2006). Indeed, plantar soles massages have been shown to induce, along both the ML and AP axes, reduced spatio-temporal co-ordinates of the transition point at which the corrective process involving CoG_v displacements is initiated (as indicated by decreased mean square distances $<\Delta x^2>$ and time intervals Δt) and an improved determinism in this corrective process aimed at returning the CoG_v to an equilibrium point (as indicated by decreased diminished long latency scaling exponents H_{ll}). The magnitude of these effects on CoG_v displacements was reported to increase with increasing the duration of the plantar soles massage (Bernard-Demanze et al. 2006). Along theses lines, it is possible that modifying the size of the predetermined adjustable ''dead zone'' of the biofeedback also would affect postural control mechanisms during quiet standing observed in the present study. An experiment is currently being performed to address this issue.

Conclusion

In light of the CoP displacements dissociation into two elementary CoP-CoG_v and CoG_v displacements and the recourse to fBm modelling through the stabilogram-diffusion analysis, the present findings suggest that the reduced territories covered by the CoP trajectories, recently observed during upright quiet standing when the plantar pressure-based, tongue-placed tactile biofeedback was in use (Vuillerme et al. 2006a, 2007) are the result of both a reduction of the correction thresholds and an increased efficiency of the corrective mechanism involving CoG_v displacements.

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