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The effects of a plantar pressure-based, tongue-placed tactile biofeedback system on the regulation of the centre of foot pressure displacements during upright quiet standing: a fractional Brownian motion analysis

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Abstract

A 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 for improving balance. The purpose of this study was to unravel the underlying control mechanisms involved in the regulation of the centre of foot pressure (CoP) displacements during upright quiet standing with this biofeedback system. Ten young healthy adults were asked to stand as immobile as possible with their eyes closed in two conditions of No-biofeedback and Biofeedback. CoP displacements, recorded using a force platform, were processed through a space-time-domain analysis and modeled as fractional Brownian motions according to the procedure of stabilogram-diffusion analysis (SDA). The space-time domain analysis showed decreased CoP displacements in the Biofeedback relative to No-biofeedback condition. Complementary, the SDA showed decreased spatio-temporal threshold at which corrective mechanisms are called into play and an increased degree of control of the CoP displacements in the Biofeedback relative to No-biofeedback condition. The present findings evidence that the effectiveness of the biofeedback in decreasing the CoP displacements during upright quiet standing stems from an increased contribution and efficiency of anti-persistent mechanisms (feedback control) involved in the regulation of the CoP displacements.

Key-words: Balance; Biofeedback; Tongue Display Unit; Centre of foot pressure; Stabilogram-diffusion analysis.

1. Introduction

Maintaining an upright stance represents a complex task, which is achieved by integrating sensory information from the visual, vestibular and somatosensory systems (e.g. Massion 1994). 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 (CNS) via an alternative sensory modality. Following this train of thought, a 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 (Tongue Display Unit) (Bach-y-Rita *et al.* 1998) was recently developed (Vuillerme *et al.* 2007a) (Figure 1). We have demonstrated the effectiveness of this biofeedback system in improving balance during upright quiet standing in young healthy adults by showing reduced spatial displacements of the centre of foot pressure (CoP) (Vuillerme *et al.* 2007a,b).

The purpose of the present study was to unravel the underlying control mechanisms involved in balance control with this biofeedback system, by modeling CoP displacements as fractional Brownian motions (Mandelbrot and van Ness 1968) according to the procedure of "stabilogram-diffusion analysis" (SDA) proposed by Collins and De Luca (e.g. Collins and De Luca 1993, 1994, 1995; Collins *et al.* 1995). This analysis suggests that CoP fluctuations are structured rather than random, with the structure dependent upon the time scale of observation. Over intervals less than about 1 s (short-term region), CoP samples are positively correlated, meaning that the CoP moves continuously in one particular direction. This type of behavior is known as "persistence" and interpreted in terms of "feed-forward" control. Over longer time intervals (long-term region), CoP samples are negatively correlated, meaning that displacements tend to be reversed. This type of behavior is known as

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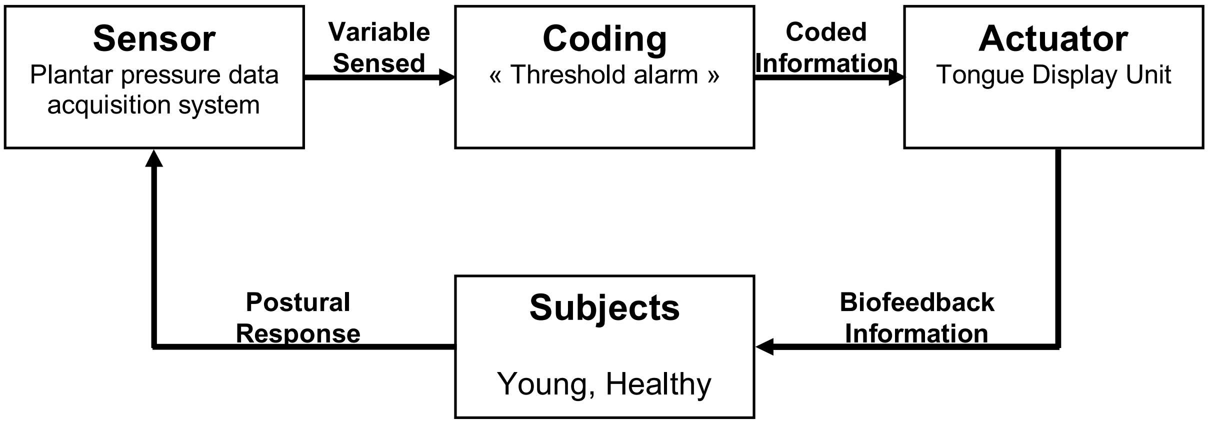

Figure 1. Architecture of the plantar pressure-based, tongue-placed tactile biofeedback system.

"anti-persistence" and interpreted in terms of "feedback" control. Interestingly, SDA has successfully been used to evaluate postural control strategies in different populations (e.g. Collins *et al.* 1995; Laughton *et al.* 2003; Maurer *et al.* 2004; Mitchell *et al.* 1995; Norris *et al.* 2005; Priplata *et al.* 2003; Raymakers *et al.* 2005; Rocchi *et al.* 2004; Tanaka *et al.* 2002), postural tasks (e.g. Cholewicki *et al.* 2004; Nolan and Kerrigan 2004; Schiffman *et al.* 2006; Silfies *et al.* 2003), sensory conditions (e.g. Collins and De Luca 1995; Meyer *et al.* 2004; Priplata *et al.* 2003; Raymakers *et al.* 2005; Riley *et al.* 1997; Silfies *et al.* 2003; Tanaka *et al.* 2002) and cognitive contexts (Raymakers *et al.* 2005; Vuillerme and Vincent 2006).

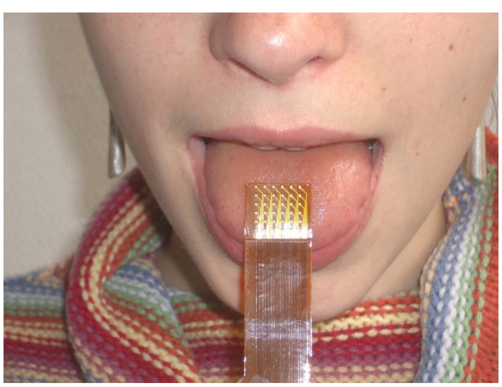

Figure 2. Photograph of the Tongue Display Unit used in the present experiment. It comprises a 2D electrode array (1.5 × 1.5 cm) consisting of 36 gold-plated contacts each with a 1.4 mm diameter, arranged in a 6 × 6 matrix.

2. Methods

2.1. Subjects

Ten young healthy adults (mean age: 25.2 ± 3.1 years; mean body weight: 70.5 ± 12.2 kg; mean height: 179.8 ± 10.2 cm; mean ± S.D.) 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.

2.2. Task and procedure

Subjects stood barefoot, feet together, their hands hanging at the sides, with their 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 (1cm² 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 the calculation of the positions of the resultant ground reaction force exerted on each left and right foot, referred to as the left and right CoP, respectively (CoP_{lf} and CoP_{rf}). The positions of the resultant CoP were then computed from the left and right 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.

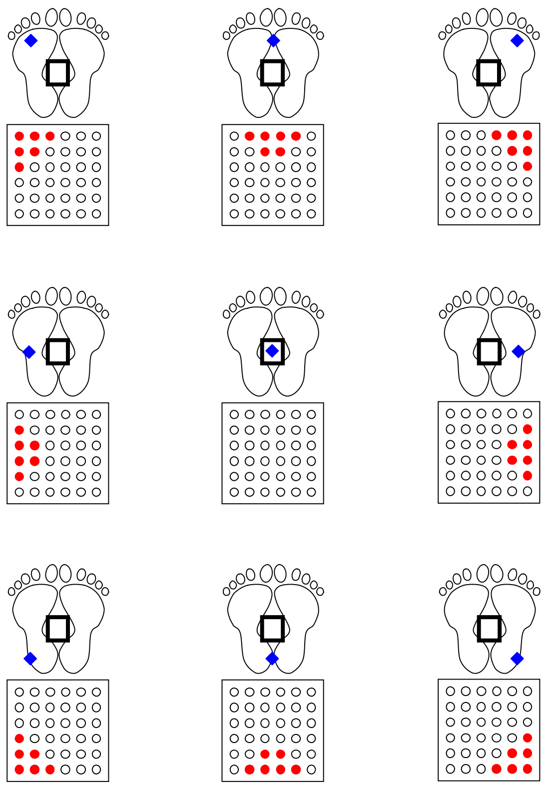

Figure 3. Sensory coding schemes for the Tongue Display Unit (TDU) as a function of the position of the centre of foot pressure (CoP) relative to a predetermined dead zone (DZ). Blue diamonds, white rectangles and red dots represent the positions of the CoP, the predetermined dead zones and activated electrodes, respectively. There were 9 possible stimulation patterns of the TDU. On the one hand, no electrodes were activated when the CoP position was determined to be within the DZ (*central panel*). On the other hand, 6 electrodes located in the front, rear, left, right, front-left, front-right, rear-left, rear-right zones of the matrix were activated when the CoP positions were determined to be outside the DZ, located towards the front, rear, left, right, front-left, front-right, rear-left, rear-right of the DZ, respectively (*peripheral panels*). These 8 stimulation patterns correspond to the stimulations of the front, rear, left, right, front-left, front-right, rear-left, rear-right portions of the tongue dorsum, respectively.

CoP data were then fed back in real time to a tongue-placed tactile output device (Vuillerme *et al.* 2006a,b, 2007a,b). 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 (Figure 2).

The underlying principle of this 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 (AP) and medio-lateral (ML) 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 in a "threshold-alarm" type of feedback was used (Figure 3). (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, 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.* 2006a). 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 all of the subject over the duration of the experiment (i.e. in both the No-biofeedback and

Biofeedback conditions), ruling out the possibility the postural improvement observed in the Biofeedback relative to the No-biofeedback condition to be 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 CoP displacements, as a gold-standard system for assessment of balance during upright 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 30s trials for each experimental condition were performed. The order of presentation of the two experimental conditions was randomized.

2.3. Data analysis

CoP displacements were processed through two different analyses:

(1) A space-time domain analysis included the calculation of (*i*) the ranges (in mm) and (*ii*) the variances (in mm²) of the CoP displacements along the AP and ML axes.

(2) A stabilogram-diffusion analysis (e.g. Collins and De Luca 1993, 1994, 1995; Collins *et al.* 1995), as initially described by Mandelbrot and van Ness (1968), enabled the assessment of the degree to which the CoP trajectory is controlled. The principle of this analysis is that the CoP 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 (necessary ranged between 0 and 1) since D=1-H for a point displaced through a single direction. This scaling exponent H 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. Depending on how H is positioned with respect to the median value 0.5, it can be inferred that the trajectory is more or less controlled: the closer H is to 0.5, the lesser the control. The different steps necessary in this data analysis have been detailed and illustrated by Fig. 1 from a previous report of Rougier (1999). The SDA 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}).

2.4. Statistical analysis

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

3. Results

3.1. Space-time domain analysis

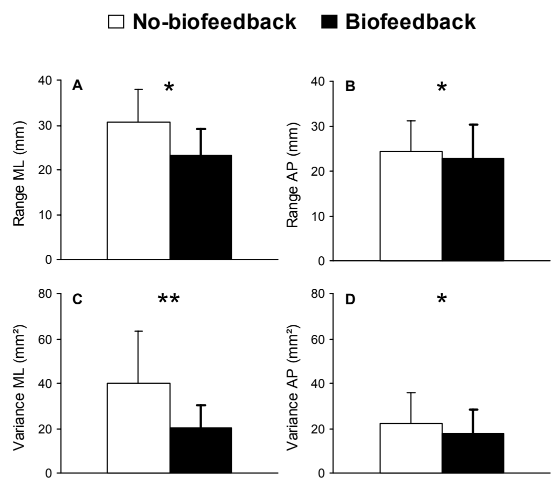

Figure 4. Mean and standard deviation of the range (A,B) and the variance of the displacements of the centre of foot pressure (CoP) (C,D) along the medio-lateral (ML) and antero-posterior (AP) axes obtained in the No-biofeedback and Biofeedback conditions. These two experimental conditions are presented with different symbols: No-biofeedback (*white bars*) and Biofeedback (*black bars*). The significant *P* values for comparisons between No-biofeedback and Biofeedback conditions also are reported (*: $P<0.05$; **: $P<0.01$).

The space-time domain analysis showed (1) decreased ranges (T=3, $P<0.05$, Fig. 4A and T=4, $P<0.05$, Fig. 4B, respectively) and (2) decreased variances (T=0, $P<0.01$, Fig. 4C and T=3, $P<0.05$, Fig. 4D) of the CoP displacements in the Biofeedback relative to the No-biofeedback condition along both the ML and AP axes. These results confirm the ability of the CNS to efficiently integrate an artificial plantar-based, tongue-placed tactile biofeedback for controlling posture during upright quiet standing (Vuillerme *et al.* 2007).

3.2. Stabilogram-diffusion analysis

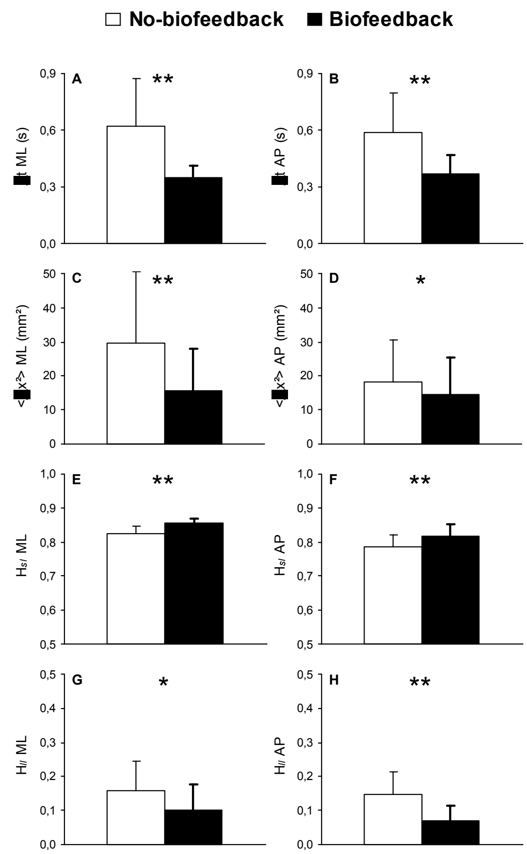

Figure 5. Mean and standard deviation of the temporal (Δt) (A,B) and the spatial co-ordinates ($<\Delta x^2>$) (C,D) of the transition point, the short (H_{sl}) and long latency scaling exponents (H_{ll}) along the medio-lateral (ML) and antero-posterior (AP) axes obtained in the No-biofeedback and Biofeedback conditions. These two experimental conditions are presented with different symbols: No-biofeedback (*white bars*) and Biofeedback (*black bars*). The significant *P* values for comparisons between No-biofeedback and Biofeedback conditions also are reported (*: $P<0.05$; **: $P<0.01$).

On the one hand, analysis of the transition point co-ordinates showed (1) decreased time intervals Δt (T=0, $P<0.01$, Fig. 5A and T=0, $P<0.01$, Fig. 5B) and (2) decreased mean square distances $<\Delta x^2>$ (T=0, $P<0.01$, Fig. 5C and T=6, $P<0.05$, Fig. 5D, respectively) in the Biofeedback relative to the No-biofeedback condition along both the ML and AP axes. These results suggest that anti-persistent corrective mechanisms (feedback control) were called into play after (1) shorter delays (Δt) and (2) smaller drifts in position ($<\Delta x^2>$) with than without the use of the biofeedback.

On the other hand, analyses of the scaling regimes exponents first confirmed that, for the two experimental conditions, the CoP trajectories are characterized by a persistent behavior over the short-term region ($H_{sl}>0.5$) and an anti-persistent behavior over the long-term region ($H_{ll}<0.5$), in accordance with previous results (e.g. Collins and De Luca 1993, 1994, 1995; Collins *et al.* 1995). More interestingly, results also showed (1) increased short latency scaling regimes exponents (H_{sl}) (T=0, $P<0.01$, Fig. 5E and T=2, $P<0.01$, Fig. 5F) and (2) decreased long latency scaling regimes exponents (H_{ll}) (T=8, $P<0.05$, Fig. 5G and T=0, $P<0.01$, Fig. 5H) in the Biofeedback relative to the No-biofeedback condition along both the ML and AP axes. These results suggest a greater degree of control of the CoP displacements during the (1) shorter (H_{sl}) and (2) longer time intervals (H_{ll}) with than without the use of the biofeedback.

4. Discussion

A 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 for improving balance (Vuillerme et al., 2006) (Figure 1). The purpose of this study was to unravel the underlying control mechanisms involved in the regulation of the centre of foot pressure (CoP) displacements during upright quiet standing with this biofeedback system. To achieve this goal, ten young healthy adults were asked to stand as immobile as possible with their eyes closed in two conditions of No-biofeedback and Biofeedback. CoP displacements, recorded using a force platform, were processed through a space-time-domain analysis and modeled as fractional Brownian motions according to the procedure of stabilogram-diffusion analysis (SDA).

The space-time domain analysis confirmed decreased CoP displacements in the Biofeedback relative to No-biofeedback condition (Vuillerme et al., 2007a,b) (Figure 4). Complementary to the space-time domain analysis, the SDA provided further insight into how the CNS used the biofeedback for regulating CoP displacements. The SDA showed decreased spatio-temporal threshold at which corrective mechanisms are called into play and an increased degree of control of the CoP displacements in the Biofeedback relative to No-biofeedback condition (Figure 5). Taken together, the present findings evidence that the effectiveness of the biofeedback in decreasing the CoP displacements during upright quiet standing stems from an increased contribution and efficiency of anti-persistent mechanisms (feedback control) involved in the regulation of the CoP displacements.

Finally, although this study has been conducted in young healthy individuals, i.e., in individuals with intact sensory, motor, cognitive capacities, it could be interesting to investigate the effects of the plantar pressure-based, tongue-placed tactile biofeedback system on the regulation of the CoP displacements during upright quiet standing in people showing less accurate postural capacities (e.g., older adults, patients with stroke, persons with lower limb amputation) for whom the consequences of an impaired postural control could be more dramatic.

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