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Human balance control during cutaneous stimulation of the plantar soles

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Abstract

Previous work on human postural control of upright stance, performed in the absence of visual and vestibular orientation cues, suggests that somatosensory cues in the feet enable subjects to maintain equilibrium during low-frequency platform tilts. Here we confirm earlier studies which indicated that stimulation of plantar cutaneous mechanoreceptors can lead to postural responses. Yet, this stimulation did not modify considerably the postural reactions of normal subjects and vestibular loss patients during platform tilts. We therefore suggest that it is necessary to differentiate between (i) cues from plantar cutaneous receptors involved in exteroceptive functions, like the evaluation of the support structure or of relative foot-to-surface motion, and (ii) cues from deep receptors which subserve proprioceptive functions like the control of center of pressure shifts within the limits of the foot support base.

Keywords: Human; Posture control; Plantar soles; Mechanoreceptors; Somatosensory graviception; Vestibular loss

Human sensory control of upright stance is known to involve, in addition to visual, vestibular, and proprioceptive cues, also somatosensory inputs from mechanoreceptors at the body site where support forces have impact. Clinically, distal sensory neuropathy in the feet is known to impair postural control [5]. Experimentally, cooling or anaesthetising the plantar soles of upright standing human subjects leads to increased postural sway [8,11]. Furthermore, responses to support perturbations change after ischaemically blocking afferent fibers above the ankles [2,10]. Additionally, limiting the foot support surface from a broad base to a narrow beam changes the intersegmental coupling [4]. However, it is not clear to date, which of the foot mechanoreceptors are providing the different pieces of information that are relevant for the various aspects of postural control.

Recent studies pointed to cutaneous receptors in the plantar sole. It was found that varying the pressure under the supporting points of the soles modifies postural responses to sudden toes-up rotation [13]. Furthermore, high-frequency (100 Hz) low-amplitude vibration of the plantar soles has been shown to produce postural reactions, the directions of which depend on the areas stimulated [6] and on the difference in vibration frequency when two sites are stimulated simultaneously [7].

In previous work we showed that patients with chronic bilateral vestibular loss (Ps) can successfully balance on a tilting platform in the absence of visual orientation cues at low tilt, unlike at high frequencies [9]. This ability was attributed to a 'somatosensory graviception' from receptors in the feet, which complements vestibular graviception in normal subjects (Ns). In the present study, we investigated whether the input used for somatosensory graviception stems from the aforementioned cutaneous receptors. We proceeded in two steps. First, we evaluated the postural reactions to mechanical stimulation of the plantar soles, using frequencies in the range of natural postural sway (≈ 0.2 Hz). Second, we evaluated the effect of this plantar stimulation on responses to platform tilts.

The experiments were performed in eight healthy subjects (six men and two women, age 36 ± 9 years; mean $\pm$ SD) and four male Ps (35 ± 3 years). Vestibular loss in Ps was due to meningitis and ototoxic medication in childhood. Apart from deafness, they showed no other neurological symptoms. The diagnosis of vestibular loss was based on conventional electronystagmographic and clinical criteria (see [9]). Subjects gave their informed

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consent to the experimental procedures as required by the Helsinki declaration (1964) and the local Ethics Committee.

For mechanical stimulation of the plantar soles, subjects were standing barefoot, feet side by side at a distance of 5 cm, with their forefeet on a fixed pin matrix and their heels on a fixed plate. Each pin matrix (6×8 pins) covered an area of 75×105 mm (pin diameter, 3 mm; rounded tops; equal distances of 15 mm). The pins protruded 1.5 mm through holes of a movable plate. The plate was driven up and down by an eccentric shaft of a servomotor, thereby reducing and enlarging, respectively, the distance between the surface of the plate and that of the fixed grid (see Fig. 1). Plate stroke was adjusted to ± 1.2 mm; this changed the relative indentation of the pins into the plantar skin, without yet evoking an observable movement of the feet. When performed smoothly and slowly (sinusoidally; $f = 0.05$, 0.1, 0.2, and 0.4 Hz), the enlarging and reducing of the indentation depth evoked a feeling of increasing and decreasing pressure under the feet, respectively. The stimulator was mounted on a custom-made tilt platform which was kept stationary (first experiment; see below) or was tilted sinusoidally in the sagittal plane, with the tilt axis through subjects' ankle joints (second experiment). Stimulus presentations were always in random order.

During the experiments, subjects stood with their hands at their sides, looking through goggles at a homogenous blue surface (no visual reference). They were instructed to stand relaxed and to keep their bodies upright in space. Antero-posterior body displacement in space was measured with the help of an opto-electronic device (Optotrack 3020; markers fixed at the level of hip and shoulders). Centre of pressure (COP) was measured using a force platform (Kistler, 9865B; corrected for stimulator thickness of 2.5 cm). The responses were analyzed using FFT, extracting stimulus-related amplitude and phase of hip and shoulder angular displacements and COP displacement as well as stimulus-response coherence values for these data [1]. Center of mass (COM) angular displacement and coherence was calculated from these signals according to anthropometric data of Winter [12]. Below we give grand averages and inter-individual SD values for each subject group.

First experiment. This experiment tested the effect of the plantar foot stimulation alone. For each stimulus frequency subjects performed two trials which consisted of a sequence of several stimulus cycles (ranging from $n = 4$ at 0.05 Hz to $n = 16$ at 0.4 Hz). COP displacement of Ns and Ps is shown in Fig. 2A as polar plot, with 0° phase corresponding to maximum of plantar forefoot indentation (by lowering forefoot plate; tantamount to maximum of subjective pressure under forefoot; phase lag, clockwise). Note that the COP response is essentially in counter-phase; at 0.05 Hz Ns' response slightly preceded a compensatory response, which would have a phase of 180° if it were ideal, and at 0.4 Hz it slightly followed. This frequency dependent time relation is reflected in Fig. 2A by the phase shift from 130 to 230°. The amount of COP shift always was very small (<0.5 cm). Stimulus-response coherence ranged from 0.77 to 0.92. The COP shifts were associated with an equally small counter-phase angular displacement of the hip, while the shoulders (upper body) remained stationary in space or were moved slightly in-phase with the stimulus (Fig. 2B; coherence hip: 0.76–0.92, shoulder: 0.79–0.94). Thus, with the maximum of skin indentation under the forefoot, for instance, Ns moved the hip slightly backwards and simultaneously were bending the upper body forwards (response unnoticed by subjects). COP, hip and shoulder responses of Ps (Fig. 2A,B) closely corresponded to those of Ns, apart from a slightly larger phase shift with lower frequencies,

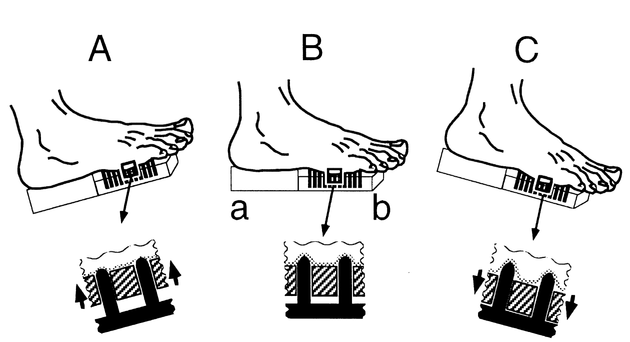

Fig. 1. (A–C) Schematic representation of plantar foot stimulation ('in-phase' run, second experiment). Skin indentation by pin matrix was increased during platform tilt forward (C) and was decreased with backward tilt (A, B, intermediate state; see insets). Indentation was increased/decreased by lowering/lifting a plate with holes through which the pins protruded (plate driven by servomotor). In the first experiment the stimulus consisted of plantar skin stimulation alone. (a) Stable heel board. (b) Forefoot board with stable pin matrix (black bars in insets) and mobile plate (hatched).

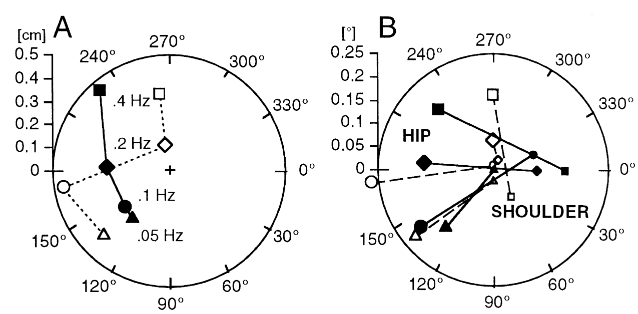

Fig. 2. (A,B) Results of plantar skin stimulation alone (first experiment). Mean responses of Ns (full symbols, solid lines) and Ps (open symbols, dashed lines), in terms of COP shift (A) and hip and shoulder angular excursion (B) are given in polar plots (space coordinates). 0° phase corresponds to maximum of plantar skin indentation. Note that there is a small shift of the COP roughly counter to maximum indentation, with the phase depending on stimulus frequency (indicated by different symbols). This COP shift is associated with a similar hip excursion (B, large symbols), while the upper body (shoulders, small symbols) remains essentially stationary in space or shows an in-phase excursion.

and COM values of Ns and Ps (not shown) closely resembled the just described hip responses.

Second experiment. This experiment tested how the effects observed with the plantar skin stimulation might affect subjects‘ responses to sinusoidal platform tilt (same frequency as sole stimulation, 0.05, 0.1, 0.2, and 0.4 Hz). Three runs were performed for each stimulus frequency: (i) maximum of forefoot indentation coinciding with that of forward tilt (‘in-phase’ run), (ii) maximum occurring with backward tilt (‘counter-phase’ run), and (iii) indentation remaining unchanged at the primary value of 1.5 mm (‘constant’ run). Peak tilt amplitude was always ±2°. Data analysis focused on gain, phase and coherence measures of COP and COM in relation to the tilt stimulus (gain: ratio of response to stimulus fundamentals of FFT; phase: response phase minus stimulus phase of fundamentals).

The results for COM are shown in Fig. 3 as polar plots with two superimposed coordinate systems, one representing space (SC), the other platform coordinates (PC; compare [9]). In each panel the results of the three runs are superimposed, giving mean values and SD areas (ellipses fitted to x and y ± SD values). The responses of Ns (Fig. 3A) were essentially in counter-phase to the platform tilt, with a gain that ranged from 0.61 at 0.05 Hz to 0.82 at 0.4 Hz, on average (if one views subjects’ tilt responses in platform coordinates). They were similar to those of a previous study in which no plantar stimulation was used (subjects were standing on the flat surface of the Kistler platform [9]).

There were no significant differences across the three runs ($P = 0.93$; ANOVA). Results were virtually identical and independent of whether plantar skin indentation remained constant during tilt or covaried with tilt in an in-phase or counter-phase manner. Coherence of responses (0.65–0.89) also was essentially the same across the three runs, as was the COP (not shown; at low frequency approximately equal to COM).

The responses of Ps (Fig. 3B) also were similar to those of our previous study with flat surface [9]. They differed from those of Ns, in that COM was kept approximately stationary with respect to the platform at 0.2 Hz (i.e. Ps‘ COM tilted together with platform) and even became inclined into the direction of platform tilt at 0.4 Hz, which typically caused Ps to ‘fall’ (Ps grabbed security handles in a rescue reaction; therefore, no data are given for 0.4 Hz in Fig. 3B). In contrast, at 0.1 Hz, and even more so at 0.05 Hz, Ps successfully counteracted gravitational pull during tilt, by producing a small COM shift. The peak of this shift occurred clearly later than that of Ns ≈ 270°; corresponding to

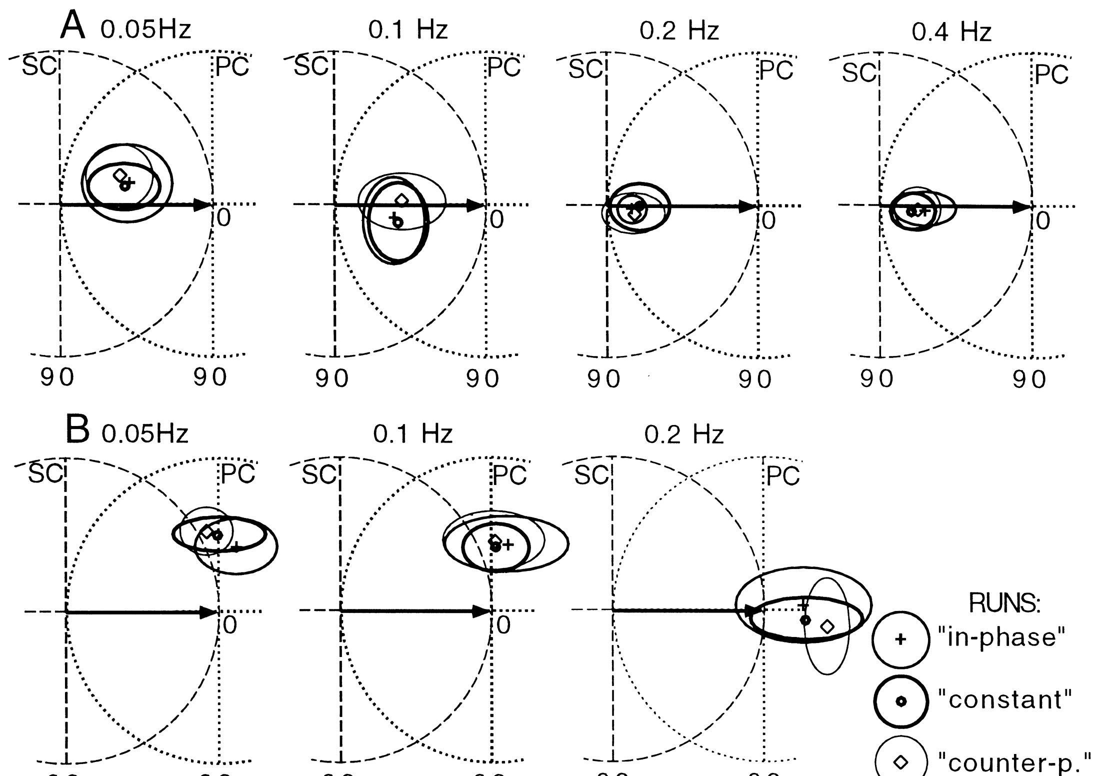

Fig. 3. (A,B) Results of combined plantar skin stimulation and platform tilt (second experiment). Mean gain and phase values (±SD, ellipses) of COM angular excursion in polar plots of space coordinates (SC, phase lag, clockwise). Platform tilt stimulus (±2°) is given by arrows (representing gain of unity and phase of 0°). Arrowheads point to center of superimposed coordinate system of tilted platform (PC). (A) Results of Ns for the indicated frequencies. (B) Data from Ps (not 0.4 Hz; Ps were falling). Results from the indicated three runs (different plantar skin stimulations) essentially coincide, both in Ns and Ps.

$\approx 90°$ lag with respect to almost ideal $\approx 180°$ compensatory responses of Ns. As mentioned before, we had attributed the latter responses in Ps mainly to a 'somatosensory graviception' from the feet [9] and focused here on the effects of concurrent plantar skin stimulation. The different foot sole stimulations, noticeably, did not scale or shift Ps' tilt responses to a significant degree ($P = 0.62$; similar for coherence measures, which ranged between 0.80 and 0.94).

From these findings we conclude that plantar skin indentation, applied at frequencies well within the range of normal body sway and performed locally in a differential way (on forefoot pads, not heel pads), produces small, but consistent postural responses, similarly in Ns and Ps. However, it does not change considerably the response to platform tilt in both Ns and Ps. Actually, we were surprised to find that Ps did not profit from the additional somatosensory cues which we provided them in the 'in-phase' runs, for instance. We therefore assume that the plantar skin receptors are mainly involved in exteroceptive tasks, like the evaluation of the texture and quality of the support surface when standing or placing the foot, rather than contributing to the continuous control of COM and COP under the constraint to maintain body equilibrium.

This notion would be in line with Ns and Ps subjective experience that the skin stimulation produced a clear sensation of changing pressure under the soles, but hardly any sensation of a change in body lean. The small active postural response we observed with skin stimulation alone likely represents a protection response to reduce pressure under the forefoot when the skin indentation increased (and became slightly unpleasant, but not yet painful). Such a reaction may normally occur, for instance, when we are standing with the forefeet on rough stones and the heels on soft grass. Yet, when body equilibrium becomes endangered by some external perturbation, like with the platform tilt in Ps, the control of posture may shift from a weighting of the sole protection mechanism by somatosensory exteroception more towards one of an equilibrium control by proprioception ('somatosensory graviception').

We justify this concept of a somatosensory exteroception versus proprioception by previous work [3] which suggests that postural control involves a mechanism that scales the magnitude of postural responses depending on load information, presumably from Golgi tendon organs, a mechanism which should be essentially independent of the structure and quality of the support surface. In the present context, we take Ps' tilt responses at low frequency as evidence for a related, but functionally different proprioceptive mechanism, i.e. one that controls for COP shifts, which occur with passive and actively, produced torques in the ankle joints. Torque information from the ankle joint alone, conceivably, would not suffice to control COP such that it always remains within the limits of the foot support base. Since the mechanism fails with tilt stimuli >0.2 Hz in Ps, unlike in Ns (see above), we assume that its dynamics are normally improved by fusion with vestibular information. Below 0.2 Hz, the somatosensory graviception allowed the patients to compensate for the platform tilt (Fig. 3B) and to show an essentially normal response to plantar stimulation alone (Fig. 2A,B).

Admittedly, further evidence is required to corroborate this concept. For instance, it remains to be elucidated from which sites in the foot the mechanism originates and which types of receptors contribute to it. One could argue that the CNS can extract COP shift information from cutaneous inputs by some spatial and temporal integration. However, we hold that this information can be derived more directly from receptors in deeper structures of the foot and that the main task of the cutaneous input would be to contribute information about the properties of the support surface and of the contact between foot and support.

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