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COMPREHENSIVE REVIEW

How can the stimulation of plantar cutaneous receptors improve postural control? Review and clinical commentary

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Summary Postural control requires constant and subconscious postural sway to manage balance and achieve postural stability. These movements of regulation are based in particular on cutaneous plantar information. The foot constitutes a functional whole that participates in the mechanisms of postural control and regulation. It represents the direct interface between the body and the ground during quiet standing, and plantar cutaneous information contributes to postural control. Upright balance mechanically depends on the gravitational torque produced by the forces of gravity and reaction of the ground. In this context, the foot behaves like a sensory system for postural regulation whose objective is to maintain a state of stability within a changing and constraining environment. There is a relation between balance improvement and the facilitation of sensory feedback related to the activation of the plantar cutaneous mechanoreceptors. From a clinical point of view, the application of additional tactile cues may have therapeutic benefits in relation to fall prevention, or to improve specific types of chronic pain.
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Introduction

Postural control requires constant and subconscious postural sway to manage balance and achieve postural stability. These regulatory movements are based in particular on cutaneous plantar information. Several studies have been devoted to investigating effects of cutaneous plantar stimulation for postural control and balance performance. Specifically, it has been proposed that increased plantar cutaneous information [5,22,39,58,59] could improve balance control by facilitating plantar sensory cues detection and enhancing postural responses [16,45,46]. The aim of this article was to focus on plantar skin afferents and to examine evidence of their stimulation on postural control and stability.

Plantar cutaneous receptors help us balance and stand upright

The foot constitutes a functional whole that participates in the mechanisms of postural control and regulation. It represents the direct interface between the body and the ground during quiet standing and plantar cutaneous information contributes to postural control [22]. Plantar skin afferents transmit spatial and temporal information concerning the pressure variations exerted under the foot [22,64]. This cutaneous feedback is provided by four classes of low-threshold mechanoreceptors that innervate the glabrous skin of the foot (Fig. 1) [1,17,24]. These mechanoreceptors are highly sensitive to the forces applied to the sole of the foot [17,24]. Each afferent class demonstrates adaptive and receptive field properties. They are activated by moderate mechanical stimuli [36,62], and encode the reversible deformations of the skin induced by pressure, vibration or stretching [22,23]. For example, fast adapting type I (Meissner) and type II (Pacinian) afferent fibers are sensitive to dynamic stimuli; their activation can evoke the perception of fluttering and vibration [26]. In contrast, slowly-adapting type I (Merkel discs) and type II (Ruffini endings) afferents respond to sustained indentation and stretching of the skin. Their activation allows for the perception of pressure and movement at the skin [26]. Cutaneous afferences may thus provide detailed spatial and temporal information about contact pressures from the foot plantar surface [55]. In addition to these myelinated A afferent fibers, mechanoreceptive innervation of the skin also includes unmyelinated C afferents [48,56]. Tactile C fibers are a class of unmyelinated sensory axon in the skin [27] which conduct impulses as slowly as 1 m/s [48,56]. The sensory terminals of these fibers are free nerve endings. They respond in a slowly-adapting fashion to very small forces applied to the skin such as stimuli that are in the ''light touch'' range [27,56]. In response to this sensory perception, the action of the plantar muscles will allow a corrective postural reaction to be initiated [46,52,53]

What about activating cutaneous receptors of foot sole?

Cutaneous mechanoreceptors in the soles of the feet are at the interface between the body and the ground. Their distribution and density vary according to the cutaneous areas considered [17] and they may play an important role in control of balance [23]. In this context, different conditions can be used to investigate the influence of the plantar cutaneous inputs on postural control. For example, sensory feedback may be facilitated by specific plantar stimulation or by focal additional thickness.

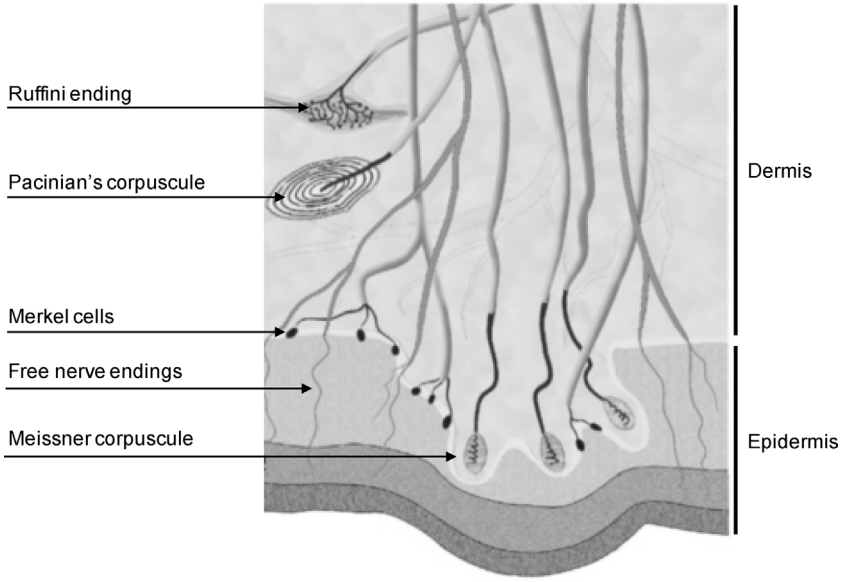

Figure 1 Organization of cutaneous mechanoreceptors from the foot sole. According to Abraira and Ginty, 2013 (With permission of Abraira). Four classes of low-threshold mechanoreceptors innervate the glabrous skin of the feet. They inform the central nervous system via large diameter Aβ myelinated afferents.
Abraira VE, Ginty DD. The sensory neurons of touch. Neuron. 2013;79(4):618—39

Activation by specific plantar stimulation

Vibration

Applications of vibration are commonly used to activate low-threshold cutaneous afferents [21,22,40,51,55]. More precisely, the use of vibrations has been experimentally associated to microneurography techniques to identify the characteristics of the mechanoreceptors in the hand [21,55] and foot [17,24,40]. In addition, these mechanical stimulations of the plantar skin during quiet stance were used to evoke postural sway [22] and to investigate the specific role of the cutaneous plantar information in the control of upright balance. For example, Kavounoudias et al., [22] stimulated cutaneous receptors in different plantar areas. They applied superficial low amplitude and high-frequency vibrations to the forefoot and rear foot zones of both soles. In this way, they induced cutaneous sensory messages simulating variation of pressure usually associated with body displacements. Their results showed spatially oriented whole-body tilts. A posterior displacement of centre of pressure (CoP) was induced by the specific vibration of each forefoot and anterior displacement of CoP was induced by the specific vibration of each rearfoot. Finally, the direction of the tilts depended on the foot areas stimulated and was always opposite to the vibration-stimulated pressure increase.

Interestingly, the application of subthreshold foot sole vibration has been shown to improve standing balance in healthy people, elderly adults [14] and subjects with diabetic neuropathy [15,36—38], as evidenced by reductions in postural sway [25,38]. Otherwise, suprathreshold foot sole vibration has been shown to modulate postural sway, where the magnitude and velocity of sway increases with higher frequencies [23].

More recently, Strzalkowski et al. [51] hypothesized that low-threshold cutaneous mechanoreceptor feedback from glabrous skin on the foot was able to modulate peripheral sympathetic outflow to skeletal muscle. Indeed, the results of this study showed that applying vibration to the foot produced small but consistent reductions in muscle sympathetic nerve activity burst occurrence. These results provide support for a link between cutaneous afferent feedback from glabrous skin and autonomic efferent sympathetic outflow involved in cardiovascular regulation. Such tactile feedback from plantar cutaneous afferents could play an important role in modulating efferent autonomic responses during postural challenges or exercise [51]. Authors suggested a contributory role from cutaneous afferent feedback in the regulation of efferent sympathetic outflow to skeletal muscle.

In conclusion, activation of cutaneous receptors by mechanical vibration of localized areas of the foot:

- induces specific and predictable postural reactions [22,23];
- improves balance control by reducing postural sway [15,37], and;
- modulates efferent autonomic responses during postural challenges [51].

Electrical stimulation

Plantar cutaneous reflexes play an important role in maintaining upright stance [6]. They are obtained by stimulating nerves of afferents from specialize cutaneous mechanoreceptors [65]. These reflexes are characterized by a stereotyped and distinct neural response evoked by a peripheral stimulus [65]. They appear to be organized in a highly location specific manner [9,10,34,63,64] and depend on intensity of stimulation [8]. More precisely, activation of plantar cutaneous mechanoreceptors by using electrical stimulation, induced a potent reflex modulation of the electromyographic activity of upper [4] and lower [2,9,32,62—65] limb muscles. The functional muscular organization (excitatory or inhibitory) of cutaneou reflexes also has been demonstrated [10,32]. For example, Nakajima et al. [34] showed that electrical cutaneous stimulation to the heel resulted in inhibitory afferents to the tibialis anterior muscle, whereas stimulation to the hallux area induced excitatory afferents. In the same way, electrical cutaneous stimulation of the metatarsal heads promoted the inhibition of the soleus muscle, whereas stimulation of the heel promoted its excitation [47]. Furthermore, a change in the magnitude of the reflex followed by an inversion of this reflex was observed when the cutaneous stimulation was moved gradually from the toes to the heel [34].

In conclusion, electrical stimulation of plantar cutaneous afferents produces highly organised topographic reflex effects in the muscular activity of both upper and lower limbs in humans. Localisation [9,10,34,63,64] and intensity [8] dependences were observed in the muscular responses, and offer additional evidence that non-noxious cutaneous perturbations applied under the foot provide important tactile information for balance.

Non-electrical stimulation

Sensory feedback from the foot may also be facilitated by non-electrical stimulation of plantar mechanoreceptors such skin indentation [28,60], plantar massage [54,61], or use of textured surface [5,39]. Several studies showed that change of pressure under the supporting points of the soles can modify postural responses [28]. For example, Watanabe and Okubo [60] used three types of shotgun ball plates to induce delicate pressure changes under the feet. The authors suggested that plantar cutaneous input influenced directly or indirectly muscle rhythm control at the cerebral basal ganglia level. In the same way, a movable plate with pins protruding 1.2 mm was driven up and down in order to change the indentation of the pins into the plantar skin without evoking an observable movement of the feet [28]. Results of this study showed that plantar skin indentation, applied at frequencies within the range of normal body sway and performed locally on forefoot pads, produced small but consistent postural responses. The skin stimulation by indentation induced a sensation of changing pressure under the feet but no sensation of body position change. The authors suggested that the small postural response observed represented a protection response to reduce pressure under the foot when the skin indentation increased. In consequence, information derived from cutaneous receptors of the foot

could contribute information about the properties of the support surface and the contact between foot and support [28]. More recently, some studies investigated the effects of textured insoles on postural stability [5,39]. It was suggested that the use of textured surface could increase postural stability in both young and elderly people in the eye closed condition [5,39] but not in the eye open condition [5].

Finally, the material [42], thickness [43,44] and hardness [42,44] of shoe soles could also influence postural control.

Activation by focal additional thickness

Since tactile plantar sensations are important for maintaining upright balance, specific sole stimulation could exert a significant effect on postural control. In addition to specific stimulations, several authors have used focal additional thicknesses to facilitate cutaneous sensory feedback from the foot [11—13,18,19,57]. For example, an anterior bar of small thickness (3 mm) placed behind the metatarsal heads of the feet induced a significant posterior displacement of the CoP in the sagittal plane [11,19]. In the same way, a mechanical facilitation of sensation that was produced with a coin-shaped piece of aluminum placed approximately at the junction of the anterior third and posterior two thirds of the plantar sole caused a decrease in the velocity and amplitude of movement of the CoP [58]. More recently, Viseux et al. [57] showed that very small degrees (0.8 mm) of additional thickness placed under the toes are sufficient to changes CoP measures widely employed in clinical practice, namely sagittal mean position of CoP and variance of speed of CoP. In addition to these postural reactions induced by additional thicknesses placed under both feet, Janin and Dupui [18] showed that an additional thickness (3 mm) placed under the medial part of the right foot induced a shift of the CoP in the sagittal plane towards the left, and conversely when the same additional thickness was placed under the medial part of the left foot. Furthermore, Forth and Layne [12,13] stimulated the lateral aspect of the foot sole using a 3 mm thick mechanical stimulus. Based on surface electromyography, they showed that the low mechanical stimulus induced increased activation of the plantar flexor musculature. They suggested that their small depression of the lateral aspect of the plantar surface stimulated both type I and II cutaneous mechanoreceptors units [17,23,24]. All of these results support that low mechanical stimulation of the plantar surface of the foot can enhance neuromuscular activity [4,9,12,13,34,47]. They also confirm the specific and predictable postural reactions induced by low mechanical stimulation of localized areas of the foot [12,13,18,19]. Their findings are in agreement with those of Kavounoudias et al. [22,23], who showed the same results using mechanical vibration.

In addition, and interestingly, Foisy et al. [11], demonstrated a systemic effect related to the activation of cutaneous receptors by focal additional thickness. Indeed, in addition to the improvement of postural control, the results showed that focal additional thicknesses (3 mm) placed under the medial or the lateral part of both feet, induced an effect on ocular vergence, especially modification of amplitude. They also emphasized the fact that the observed modifications are different depending on the stimulated foot zone.

Implications for clinical practice

In different pathological conditions, cutaneous sensitivity can be altered. For instance, patients with diabetic neuropathy present deficit of cutaneous information and perturbation of postural stability [49] compared to healthy people. Plantar electrical stimulation [33], textured insoles [35], or vibration applied under the foot [3], may be practical means to change static balance, enhance motor performance, and possibly decrease the risk of ulceration in patients with diabetes and peripheral neuropathy. In the same way, a decrease in plantar cutaneous sensitivity is observed in older adults [29]. Ageing can lead to a degradation of postural control and contributes to the increased incidence of falls in the elderly [29]. In this context, cutaneous plantar stimulations have been reported as an important therapeutic intervention to improve balance and to increase somatosensory input [7]. Facilitate sensory feedback from the soles can reduce postural sway in elderly, particularly during more challenging tasks [39]. Interestingly, another study showed that facilitation of plantar sensory feedback by activating cutaneous mechanoreceptors produced significant improvement in gait pattern and stability in patients with Parkinson's disease [20].

Finally, athletes could benefit from the use of plantar devices, since cutaneous input from the foot can modulate proprioception at the ankle joint [30]. Additional tactile cues may improve movements that require rapid changes in direction [31], or increase the awareness of ankle positioning and decrease the chance of ankle injury [50]. In addition, cutaneous plantar stimulation has been shown to have a positive effect on balance in subjects with functional ankle instability [41].

Conclusion

Cutaneous information arising from the feet plays an important role in controlling posture. This review showed that several possibilities can be used to facilitate sensory feedback from the soles. Indeed, specific plantar stimulations (electrical and non-electrical) or local use of additional thickness can induce predictable and specific postural reactions. The results of these different studies highlight the relationship between improvements of balance and facilitation of sensory feedback related to the activation of plantar cutaneous mechanoreceptors.

The application of additional tactile cues may therefore have therapeutic benefits in relation to the development of novel clinical practice to improve balance. In particular, the use of additional focal thickness seems to be an interesting way of facilitating the sensory feedback of plantar receptors. Indeed, from a clinical point of view, it is quite simple and inexpensive to insert a low plantar thickness on a customized sole. This provides interesting perspectives in the context of management of patients with risk of falling, with balance disorders or with specific chronic pain syndromes, complementing validated therapeutic strategies.

Disclosure of interest

The authors declare that they have no competing interest.

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