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The Lasting Effects of Spike Insoles on Postural Control in the Elderly

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The purpose of the present study was to explore the lasting effects of a tactile sensitivity enhancement induced by spike insoles on the control of stance in the elderly. Healthy elderly subjects ($n = 19$, mean age = 68.8) and young adults ($n = 17$, mean age = 24.3) were instructed to stand or to walk for 5 minutes with sandals equipped with spike insoles. Postural control was evaluated four times during unperturbed stance: (1) before putting on the sandals equipped with spike insoles, (2) 5 minutes after standing or walking with them, (3) immediately after placing thin, smooth, and flexible insoles (no spike insoles) into the sandals to avoid the cutaneous contact with the spikes, and (4) after a sitting rest of 5 minutes with the no spike insoles. Sway parameters such as surface area, mean speed and root mean square were recorded. The present results suggest that (1) whatever the session (i.e. standing or walking) and the population, the artificial sensory message elicited by the spikes improved postural sway and, (2) the elderly were particularly perturbed when the tactile sensitivity enhancement device was removed. Whatever the age, the enriched sensory context provided by this tactile sensitivity enhancement device led to a better postural control; its suppression entailed a reweighting of the plantar cutaneous information. The difficulty that the elderly had to adjust the relative contribution of the different inputs probably reflected their poorer central integrative mechanisms for the reconfiguration of the postural set. A reduced peripheral sensitivity may also explain these postural deficits.

Keywords: elderly, postural control, foot sole stimulation, spike insoles, plantar cutaneous information

A variety of sensory sources, including visual, proprioceptive, and vestibular information, contributes to the overall control of posture and gait in humans. Plantar cutaneous inputs also contribute to balance control during standing (Kavounoudias, Roll, & Roll, 2001; Palluel, Nougier, & Olivier, 2008), walking (Nurse & Nigg, 1999; Palluel et al., 2008; Perry, Santos, & Patla, 2001), running (Nurse & Nigg, 1999), or compensatory stepping evoked by balance perturbation (Maki, Perry, Norrie, & McIlroy, 1999; Perry, McIlroy, & Maki, 2000). A large number of neurophysiological studies in monkeys (Johnson, Ferraina, Bianchi, & Caminiti, 1996; Jones, Coulter, & Hendry, 1978; Jones & Powell, 1970) and in humans (Wolpert, Goodbody, & Husain, 1998) demonstrated the crucial role of the superior parietal lobe for receiving and integrating proprioceptive, motor, tactile, and visual information about the body. This cerebral region is able to represent the spatial configurations of body parts as well as their relative positions across modalities. The integration of the different sensory information is reweighted according to the sensory environment (Horak, 2006): when located on a firm base of support, healthy individuals rely mostly on somatosensory cues (70%), but the dependence on these inputs decreases as the surface becomes unstable (Peterka, 2002a). The foot soles are well innervated by mechanoreceptors with a majority of fast adapting ones: 14.4% are slow adapting I (SA I) receptors, 15.4% are slow adapting II (SA II) receptors, 56.7% are fast adapting I (FA I) receptors, and 13.5% are fast adapting II (FA II) receptors (Kennedy & Inglis, 2002). The density of fast adapting receptors is lower in elderly people (Perry, 2006). All mechanoreceptors are involved in postural control because they represent the direct interface between the body and the ground (Kennedy & Inglis, 2002).

Kavounoudias et al. (1998) investigated the effects of vibration applied to the forefoot and demonstrated that the mechanoreceptors are able to code each static pressure exerted on the skin as well as their dynamic changes (Kavounoudias et al., 1998; Nurse & Nigg, 1999). For example, backward tilts were observed while the forefeet were stimulated: this artificial message gave an impression of pressure increase under the forefeet and led to an opposite-directed compensation. Another experiment was carried out in cats and showed that stimulation of localized skin areas of the toe pads involved highly specialized reflexes that are very important for adjusting the position of the toes and ankles relative to the support surface in order to stabilize the paw during posture and gait (Hongo, Kudo, Oguni, & Yoshida, 1990). The input from plantar mechanoreceptors also causes reflex modulation of the ongoing activity in ankle muscles in humans (Fallon, Bent, McNulty, & Macefield, 2005). Therefore, these results reinforce the relevance of cutaneous afferent messages for the control of balance. Nevertheless, as suggested by Welch and Ting (2009), the underlying

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neural mechanisms of balance control still remain unknown. These authors suggested that an invariant feedback law was used to generate the entire time course of muscle activity across a variety of postural disturbances.

On one hand, reducing or suppressing the plantar cutaneous inputs by hypothermia (Eils, Behrens, Mers, Thorwestern, Völker, & Rosenbaum, 2004; Eils, Nolte, Tewes, Thorwestern, Völker, & Rosenbaum, 2002; Stal, Fransson, Magnusson, & Karlberg, 2003), anesthesia (Meyer, Oddsson, & De Luca, 2004a, 2004b) or ischemia (Diener, Dichgans, Guschlbauer, & Mau, 1984) lead to a degradation of postural control. This increase of postural sway is also observed in neuropatic patients (e.g., diabetics) and in elderly people; it can be partially explained by a loss of tactile sensation. In fact, both vibratory and touch detection thresholds decline with age (Perry, 2006). Kenshalo (1986) also mentioned changes in receptors morphology, a reduction of receptors density, elasticity, and a slower nerve conduction with age. This decrease of plantar-surface sensitivity contributes to the increased incidence of falls and injuries in elderly people (Lord, Ward, Williams, & Anstey, 1994; Menz, Morris, & Lord, 2006; Robbins, Waked, & McClaran, 1995). On the other hand, stimulating the foot sole by applying subsensory vibration (Priplata, Niemi, Harry, Lipsitz, & Collins, 2003; Priplata, Patritti, Niemi, Hughes, Gravelle et al., 2006) or rotary plantar massages (Bernard-Demanze, Burdet, Berger, & Rougier, 2004) enhances balance control both in young adults or in elderly people. The role of tactile signals has also been explored by changing the characteristics of the supporting surface. For example, standing on an array of ball bearings (Watanabe & Okubo, 1981), on pins (Maurer, Mergner, Bolha, & Hlavacka, 2001), or on a tubing located on the plantar-surface boundaries (Maki et al., 1999) was found to facilitate sensation and to reduce postural sway. In addition, a textured insole involves a more accurate foot positioning in young athletes (Waddington & Adams, 2003). Previous findings also provided evidence that a tactile sensitivity enhancement induced by spike insoles can contribute, at least temporarily, to the improvement of unperturbed stance in elderly people with relatively intact plantar cutaneous sensation (Palluel et al., 2008). Its effectiveness was observed on different postural variables (center of foot pressure [CoP] surface area, CoP mean speed, root mean square [RMS] on the anterior-posterior and medial-lateral axes) in most elderly subjects and young adults (Palluel et al., 2008). These results suggested that the spikes provided relevant tactile information about body position in reference to verticality. As daily activities include standing, walking, and resting periods, we examined whether the benefits were lost immediately after the tactile sensitivity enhancement was removed or whether they remained over a longer period of time. A previous experiment indicated that a 10-min massage of the foot soles resulted in a better distribution of the body weight. The artificial sensory message elicited by a pressure increase under particular foot areas reinforced the capacity to detect body motion. However, these effects disappeared after about 8 minutes (Bernard-Demanze, Rougier, & Berger, 2002). In the present experiment, which is a follow-up study of Palluel et al. (2008), the indented surface provided by the spike insoles was intended to artificially increase the pressure under the plantar areas that were directly in contact with the spikes. Stimulation of the mechanoreceptors enhanced the likelihood of exceeding the sensitivity threshold and thus the activity of the associated neurons. We hypothesized that the benefits may not remain after a long period of time after taking off the spike insoles, suggesting that the cutaneous inputs from the foot sole and the sensory reweighting mechanisms are temporary and mainly activated online by the central nervous system for reconfiguring the postural set and controlling balance regulation.

Experimental Procedures

Participants

Nineteen healthy elderly (8 men and 11 women; mean age = 68.8, range: 61–80 years; mean height = 165 ± 2 cm; mean weight = 73.8 ± 1.4 kg) and 17 healthy young adults (7 men and 10 women; mean age = 24.3, range 21–32 years; mean height = 172 ± 2 cm; mean weight = 66.8 ± 1.3 kg) volunteered for this study. Informed consent was obtained from each participant as required by the Helsinki declaration and the Local Ethics Committee. All elderly subjects were ambulatory and lived at home. They were free from (1) any diagnosed neurological or musculoskeletal diseases (all of them were able to feel the 5.07 Semmes-Weinstein monofilament at four different foot sole locations [great toe, first metatarsal head (MT), fifth MT, heel]), (2) any history of falls for the last 6 months, (3) any known balance impairment, and (4) any current use of medication that could affect their plantar-surface sensitivity or their balance.

Procedures

Each participant was exposed to *standing* and to *walking* sessions that were counterbalanced across participants. In both sessions, postural responses were assessed during unperturbed stance with participants standing on a force platform (Equi+, model PF01, Aix les Bains, France). They had the eyes closed, the arms at their sides, and the feet abducted at 30° with the medial borders of the heels separated by 5 cm. As vision is a predominant sensory system in elderly people (Perrin, Jeandel, Perrin, & Bene, 1997) and as no significant effect of plantar cutaneous inputs could be seen when vision was available (Meyer et al., 2004a), the visual information was suppressed in order to explore the influence of the cutaneous cues alone. Moreover, this blindfolded condition is close to situations with poor environmental lighting or with visual impairment that are often observed in elderly people. Participants were asked to sway as little as possible. The sampling frequency was 64 Hz.

The footwear consisted of sandals (see Figure 1). The entire insole (*spike* insoles) was covered with an array of spikes made with semi-rigid PVC (density: 4 spikes/cm^2; height of a spike: 5 mm; diameter: 3 mm) and uniformly distributed under the feet except on the medial arch where the spikes were bigger (density:

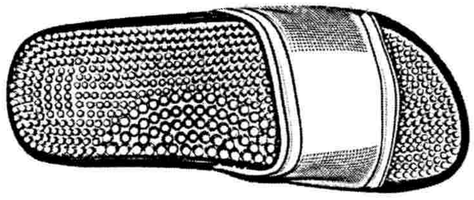

Figure 1. Spike sandals used for the study.

2 spikes/cm^2; height: 1 cm; diameter: 5 mm). Thin, smooth, flexible, and 3-mm-thick insoles (*no spike* insoles) were sometimes put into the sandals equipped with spike insoles and were used as control insoles. Three trials of 32 s with 15 s of standing rest in-between were performed four times in the *standing* and the *walking* sessions: (1) in a control condition, before wearing the *spike* insoles by covering them with *no spike* insoles (t_1) and (2) 5 minutes after standing in the *standing* session or 5 minutes after walking in the *walking* session with the *spike* insoles (t_2). The walk was performed indoor on flat ground at natural speed in the corridors of the medicine faculty. Before doing the postural measurement, 30 seconds of standing rest were allowed at the end of the *standing* and the *walking* sessions to rule out a possible effect of effort, especially in the *walking* session; (3) immediately after replacing the *no spike* insoles into the sandals, that is, approximately 3 minutes after the standing or walking session (t_3) and (4) after an additional sitting rest of 5 minutes (t_4) with the *no spike* insoles (see Figure 2).

As the trials were always performed with the sandals on, the *no spike* insoles were put into the sandals at t_1, at t_3, at t_4 and were kept between t_3 and t_4 to avoid the cutaneous contact with the spikes. *Spike* and *no spike* insoles were blocked together by surgical tape in order to suppress mechanical movements within this insoles superposition. Forty-five seconds of standing were imposed before the postural measurements at t_4 in order to avoid the effects due to the transition from a seated to a standing position. The 5-min duration used at t_2 was determined on the basis of a previous experiment which showed an improvement after 5 min of wearing the spike insoles (Palluel et al., 2008).

Dependent Variables

The center of foot pressure (CoP) motion was calculated through surface area (i.e., 90% confidence ellipse area, in mm^2), mean speed (mm.s^{-1}), root mean square on the antero-posterior (AP RMS) and medio-lateral (ML RMS) axes (mm). The mean of the three trials was calculated at t_1, t_2, t_3, and t_4 for the *standing* and the *walking* sessions, respectively. The surface area is a measure of the CoP spatial variability (Vuillerme, Chenu, Pinsault, Fleury, Demongeot, & Payan, 2008). The mean speed represents a good index of the amount of neuromuscular activity that is required to regulate postural control (Geurts, Nienhuis, & Mulder, 1993). The AP and ML RMS enabled us to estimate overall postural performance. The reliability and the validity of these parameters for the clinical quantification of postural control has already been demonstrated (Geurts et al., 1993; Piirtola & Era, 2006; Pinsault & Vuillerme, 2009). A reduction of at least one of these postural parameters has often been considered as an improvement of postural stability (Melzer, Benjuya, & Kaplanski, 2003; Priplata et al., 2003; Vuillerme et al., 2008).

Statistical Analysis

For two ages (young and old adults) × two sessions (standing and walking) × four times (t_1, t_2, t_3, and t_4), an analysis of variance (ANOVA) with repeated measures on the last two factors was used to determine whether the benefits of wearing spike insoles remained after the suppression of this tactile sensitivity enhancement. Adjustments of the p values for the violation of the sphericity assumption were made with a multivariate test (Hotelling-Lawley Trace). Post hoc analyses (Tukey's HSD) were used whenever necessary. The level of significance was set at $\alpha = .05$.

Results

The three-way interaction of age × session × time was significant for the CoP surface ($p = .028$) and the AP RMS ($p < .001$). In the elderly subjects, as expected (Palluel et al., 2008), post hoc analysis showed an improvement of the CoP surface and the AP RMS after standing for 5 minutes (t_2) with the spike insoles, compared to t_1 ($p < .001$ and $p = .048$, respectively). When the spike insoles were removed (t_3), the benefits were immediately lost for both variables ($p_s < .001$) with values returning to baseline. In the *walking* session, the decrease of the CoP surface and the AP RMS were not significant between t_1 and t_2 ($p = .26$ and $p > .99$, respectively), but higher values were observed immediately after removing the insoles (t_3; $p < .001$) and after a rest of 5 minutes (t_4) for the CoP surface, only ($p < .001$). In the young adults, post hoc analysis indicated a small improvement of postural stability in the *standing* session. There was no significant effect for the CoP surface ($p_s > 0.55$) and the AP RMS ($p_s > .99$). In the *walking* session, as expected, the decrease of the CoP surface area and the AP RMS were significant between t_1 and t_2 ($p = .028$, $p = .030$, respectively), but the benefits disappeared at t_3 and t_4 with values returning to baseline ($p_s < .001$).

A main effect of age was observed for the mean speed and the ML RMS ($p < .001$ and $p = .006$, respectively) with the lower values observed in the young adults. The analysis also indicated a main effect of time for the ML RMS ($p < .001$): whatever the age or the session, an improvement of the ML RMS (i.e., lower values)

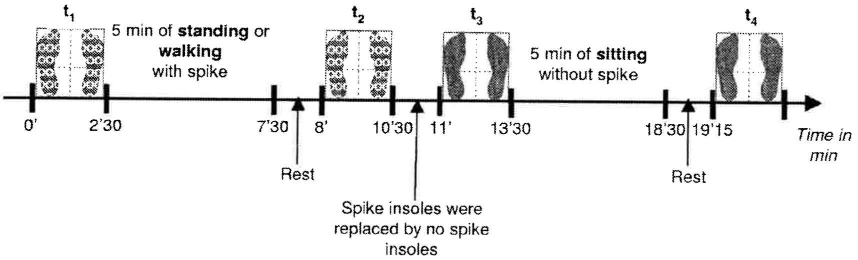

Figure 2. Experimental procedure. t_1 and t_2: Measures of postural stability with the sandals equipped with spike insoles. t_3 and t_4: Measures of postural stability with the sandals. The spike insoles were covered with thin and flexible insoles that avoided the cutaneous contact with the spikes.

was obtained after wearing the sandals for 5 minutes (t_2; $p = .045$). But the benefits were lost immediately after taking them off (t_3; $p < .001$) and after a rest of 5 minutes (t_4; $p < .001$; see Figure 3).

At the end of the experiment, participants were asked whether they preferred the *spike* or the *no spike* insoles: 9 elderly and 2 young adults preferred the spike insoles, 0 elderly and 8 young adults preferred the no spike insoles and 10 elderly and 7 young adults had no preference. Moreover, eight young adults reported a slight discomfort while wearing these spike insoles. However, they did not exhibit a large degradation of postural control.

Discussion

The purpose of the present experiment was threefold: (1) to validate the fact that standing or walking for 5 min with spike insoles entailed a postural improvement in elderly people and young adults, (2) to determine the lasting effects of this plantar-surface mechanical stimulation, and (3) to provide further insight in how the central nervous system reconfigures the postural set for balance control. A previous experiment of Palluel et al. (2008) already demonstrated that the improvement of postural stability was actually due to the spikes and not solely to the action of standing or walking. The novel finding of the present study is that the benefits observed on postural control in young adults and elderly subjects after wearing the spike insoles for 5 minutes disappeared at the offset of the tactile stimulation, whatever the session (standing or walking). These findings confirmed previous ones suggesting that whatever the nature of the spike stimulation—standing or walking with the spikes—it enhanced the somatosensation, the spatial representation of the pressure distribution under the foot soles and postural stability (Palluel et al., 2008). In fact, the young adults and the elderly subjects took a postural advantage of this indented surface and were destabilized immediately after the tactile sensitivity enhancement device was removed: At t_3, they exhibited a larger CoP surface area, AP and ML RMS than at t_1 or t_2. This degradation of stability was more pronounced in elderly subjects and has already been observed by Teasdale and Simoneau (2001), Teasdale, Stelmach, and Breunig (1991a), and Teasdale, Stelmach, Breunig, and Meeuwsen (1991b) when visual and proprioceptive inputs from the ankles were removed or perturbed and suddenly reintroduced. They highlighted the inability of elderly people to rapidly reconfigure the postural set when the sensory context was modified and suggested a deficit of the central integrative mechanisms responsible for the reconfiguration of the postural set. Moreover, they argued that the process of reweighting sensory inputs could lead to a perturbation of postural stability in elderly people because it requires additional attentional resources. Woollacott, Shumway-Cook, and Nashner (1986) reported that the elderly were more affected by visual or proprioceptive conflicting conditions than young adults. They proposed that reduced peripheral acuity may be another possibility to explain their limited capacity to reorganize the hierarchy among the sensory inputs.

In the present experiment, the enriched sensory context provided by the spike insoles had a stabilizing effect in elderly people and young adults. The difference observed between both populations during the *standing* and the *walking* sessions could be due to the nature of the stimulation. The stimulation while standing on the spike insoles was continuous and had always the same intensity. It was discontinuous when the subject was walking with the spike insoles because the stance and the swing phases involved a modulation of the pressure applied onto the spikes. As the young adults have a better plantar-surface sensitivity than the elderly do (Perry, 2006), the continuous stimulation in the *standing* session may have been too strong for them. A continuous stimulation seems to be more appropriate for people that generally exhibit a loss of tactile sensation. Conversely, a discontinuous stimulation may be too weak for the elderly but may be more suitable for young adults.

There is also evidence that the suppression of this supplementary information entailed a degradation of postural control in both populations during the transition between the *spike* and *no spike* conditions. We suggest that this transition involved a reorganization of the sensory information hierarchy and thus a reweighting of the sensory inputs (Peterka, 2002b), that is, a reconfiguration of the postural set. The central nervous system continuously adjusts the relative contribution of the different sensory inputs according to the sensory context and the neuromuscular constraints (Vuillerme et al., 2008). This adaptive capacity of the central nervous system has been described in many articles (Peterka, 2002b; Vuillerme et al., 2008). It contributes to a more stable and flexible control of upright stance. For example, an alteration of the proprioceptive inputs can be compensated for by the visual, vestibular, or haptic information (Vuillerme, Burdet, Isableu, & Demetz, 2006). In this study, the spikes probably enhanced the subjects' reliance on cutaneous inputs. The elderly particularly exhibited some difficulties in being able to immediately adjust the relative contribution of the different sensory cues. It probably reflected their poorer central integrative mechanisms for the reconfiguration of the postural set (Teasdale et al., 1991b). This integration deficit might be due to the regional deterioration (i.e., parietal lobe) of brain structure that is a typical feature of aging (Raz & Rodrigue, 2006). A reduced peripheral sensitivity may also explain these postural deficits (Woollacott et al., 1986). As the degradation was immediate, we can conclude that the cutaneous inputs from the foot sole were used online for balance regulation.

There is a considerable regional variation in sensitivity thresholds (Kekoni, Hämäläinen, Rautio, & Tukeva, 1989) and therefore in the density of the mechanoreceptors. As the SA I receptors are the most sensitive to maintained indentation (Fallon et al., 2005), we can suggest that these mechanoreceptors may be important and particularly activated by the spikes. Nevertheless, they are mostly located on the borders of the sole and represent just 14.4% of the mechanoreceptors on the foot soles in young adults (Kennedy & Inglis, 2002). Thus, the SA II, FA I, and FA II may also have been implicated and stimulated efficiently by the spikes to detect the CoP shift. Further research will be necessary to examine (1) the effects of a partial stimulation of the foot sole (e.g., a stimulation of the forefoot, the midfoot or the heel) on the somatotopic representation of the foot sole in the brain, (2) what kind of stimulation is more appropriate (since the spikes had unknown modulus of bending or stiffness), and (3) what is the specific function of each kind of mechanoreceptors in the regulation of postural sway. Additionally, as 8 young adults out of 36 subjects reported a slight discomfort after wearing the spike insoles for 5 min, it remains to be determined whether it is possible to walk with these insoles for a longer period of time without pain or discomfort.

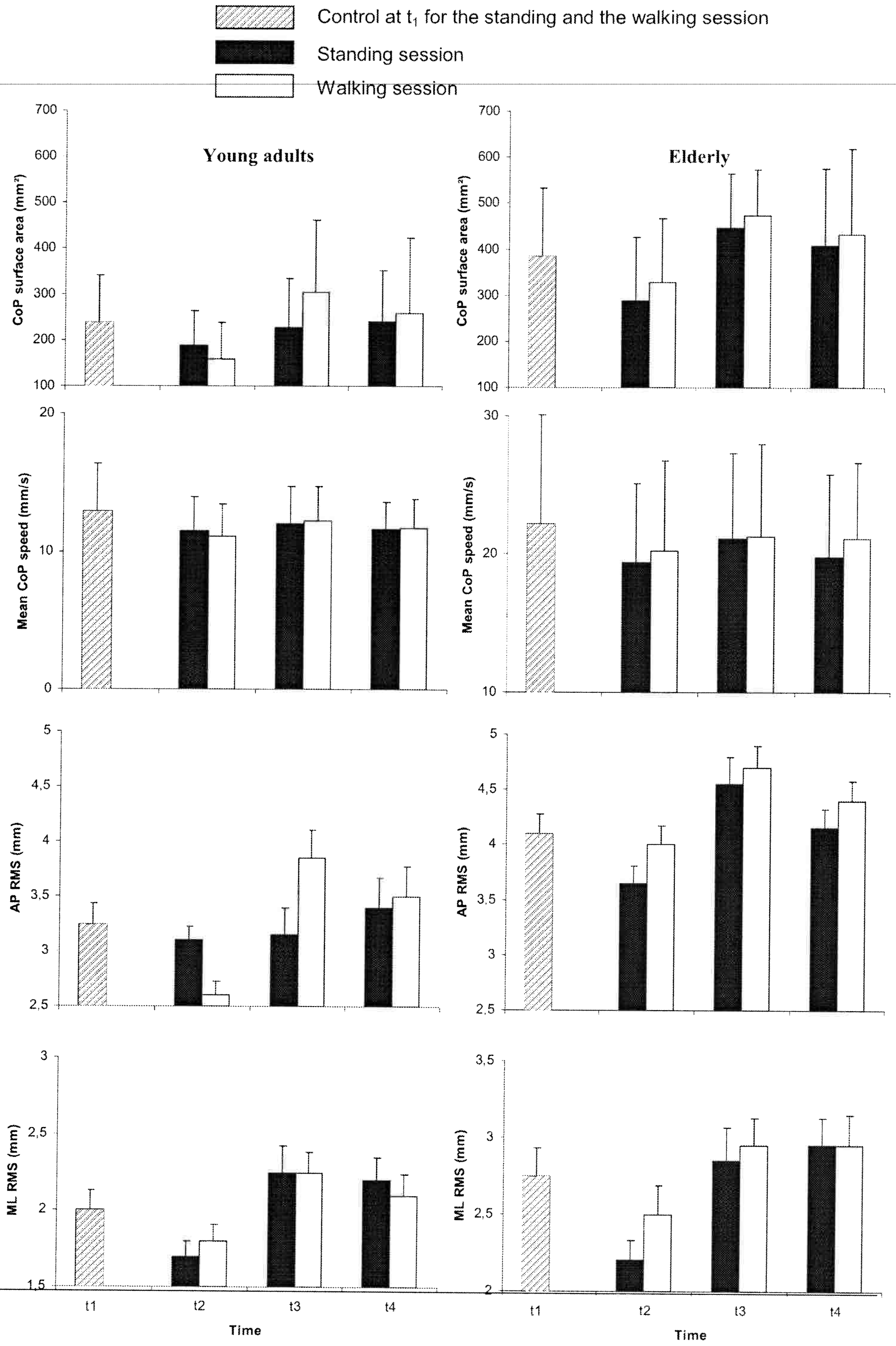

Figure 3. Mean and standard deviation of the surface area (mm^2), mean speed (mm/s), AP and ML RMS (mm) as a function of time: (1) before wearing the spike insoles by putting the *no spike* insoles on the sandals (t_1), (2) 5 minutes after standing or walking with the spike insoles (t_2), (3) immediately after putting the no *spike* insoles on the sandals (t_3), and (4) after a sitting rest of 5 minutes with the *no spike* insoles (t_4) and as a function of session (standing and walking) in young adults and elderly. Refer to text to see significant effects or interactions. For illustration purposes, the ordinate scale of the graphs has been adapted so that its amplitude remains the same for both populations.

Conclusion

Our results confirmed a reorganization of hierarchy of the sensory inputs and the inability of elderly people to rapidly reconfigure the postural set when the sensory context is modified. In addition to its relevance for the field of neuroscience, the enriched sensory context provided by the spikes is an original method of stimulation that may be appropriate for subjects suffering from balance problems. Further research is needed to find the best compromise between the duration, the intensity, the frequency of the stimulation, and the comfort of the insoles.

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