



Effects of experimentally induced pain of the plantar soles on centre of foot pressure displacements during unperturbed upright stance

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ABSTRACT

Background: Although impaired balance control during quiet standing has repeatedly been reported in persons suffering from foot pain, a better understanding of the effect of foot pain on unperturbed postural control is needed in order to propose and implement efficient podiatry treatments/interventions into clinical practice. The present study was hence designed to address this issue.

Methods: Ten young healthy adults were asked to stand upright, eyes closed, as still as possible in three experimental conditions: (1) a no-pain condition, (2) a condition when a painful stimulation was applied to the plantar surfaces of both feet, and (3) a condition in which painful stimulation was applied to another body part, the palms of both hands. The centre of foot pressure displacements was recorded using a force platform. **Findings:** For the same perceived intensity of the pain, the severe painful stimulation applied to the plantar surfaces of both feet increased centre of foot pressure displacements, whereas the severe painful stimulation applied to the palms of both hands did not.

Interpretation: These results reveal the deleterious effect of experimentally induced pain on the plantar soles on unperturbed bipedal postural control. At this point, it is conceivable that these effects of experimental pain could generalise to the effects of pain in patients. Accordingly, the present findings suggest that clinical and/or instrumental interventions designed to mitigate pain in patients suffering from plantar foot pain (e.g., podiatry treatments/interventions) could improve postural control.

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1. Introduction

Among the multiple sensory cues involved in the control of upright posture, somatosensory information from the sole of the foot is recognised as playing a major role (e.g., Kavounoudias et al., 1998; Meyer et al., 2004). Plantar cutaneous mechanoreceptors could potentially provide detailed spatial and temporal information about contact pressures under the foot and shear forces resulting from body movement that constitute valuable feedback to the postural control system. When sensory information from the plantar soles is improved either with therapeutic manipulation of the feet (e.g., Bernard-Demanze et al., 2006, 2009), footwear interventions such as textured (Corbin et al., 2007) or vibrating insoles (e.g., Priplata et al., 2002, 2003), or the use of plantar-based biofeedback (Vuillerme et al., 2007a, 2007b, 2008), bipedal postural control generally improves. Conversely, when sensory information from the plantar soles is deteriorated, either by changing the characteristics of the supporting surface on which individuals were standing (e.g., Isableu and

Vuillerme 2006; Fransson et al., 2007; Vuillerme and Pinsault, 2007, Vuillerme et al., 2008), anaesthetising (e.g., Meyer et al., 2004), or cooling (e.g., Magnusson et al., 1990; Hong et al., 2007; McKeon and Hertel, 2007) the soles of the feet, postural control generally deteriorates. Further evidence for the strong influence of plantar cutaneous cues on postural control further comes from the example of diabetic neuropathy in which this sensory input is altered (e.g., Simoneau et al., 2004; Bernard-Demanze et al., 2009). Impaired balance control during quiet standing also has repeatedly been reported in persons suffering from foot pain (Menz and Lord, 2001; Menz et al., 2006). However, a better understanding of the effect of foot pain on unperturbed postural control is needed in order to propose and implement effective podiatry interventions in clinical practice. Indeed, causality cannot be determined in clinical cross-sectional studies since any confounding effect of foot pain with age and/or with an underlying pathology and/or adaptive adjustments of motor control strategies (Latash and Anson, 1996; Vuillerme et al., 2001) cannot be a priori excluded (Bennell and Hinman, 2005).

Furthermore, although recent studies have reported deleterious effects on postural control when a painful stimulation is applied cutaneously or to the muscles of the ankle (Blouin et al. 2003; Hirata et al., 2010), feet (Corbeil et al. 2004) or neck (Vuillerme and Pinsault,

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2009), to the best of our knowledge, the effects of experimentally induced pain of the plantar soles on postural control during quiet stance have not yet been investigated. The present experiment was designed to address this issue by comparing centre of foot pressure (CoP) displacements recorded in a condition when a painful stimulation was applied to the plantar surfaces of both feet with CoP displacements during a no-pain condition and also with CoP displacements recorded in a condition in which painful stimulation was applied to another body part (Corbeil et al., 2004): the palms of both hands.

2. Methods

2.1. Subjects

Ten young healthy adults (mean age = 26.0 (SD 3.7) years; mean body weight = 68.6 (SD 7.5) kg; mean height = 174.8 (SD 5.1) cm) voluntarily participated in the experiment. They gave informed consent to the experimental procedure as required by the Helsinki declaration (1964) and the local Ethics Committee. None of the subjects presented any history of injury, surgery, or pathology to either lower extremity that could affect their ability to perform the experiment.

2.2. Experimental procedures

Subjects stood barefoot on a force platform (Dynatronic, France; sampling frequency 40 Hz) in a natural but standardised position (feet abducted at 30°, heels 3 cm apart), their arms hanging loosely by their sides and their eyes closed. They were asked to stand as still as possible during three experimental conditions: no pain, plantar pain, and palmar pain.

Two 1-cm rigid square pyramid shapes (polyurethane, hardness shore A110) were used to experimentally induce the painful stimulation. In the plantar-pain condition, to apply the pain on the sole of the feet, one rigid pyramid was placed, under each foot, at the centre of the plantar surface at the intersection between a line drawn through the centre of the heel and the second metatarsal, and a transversal line that divides the plantar surface (but not the toe) in two equal parts (see Fig. 1). In the palmar-pain condition, one pyramid was placed at the centre of the palm of each hand with clamps to induce pain in the palms of both hands.

Three 25.6-s trials for each experimental condition were performed. The order of presentation of the three experimental conditions was randomised.

2.3. Pain intensity assessment

At the end of each trial, subjects were asked to rate their perception of the intensity of the pain induced by the stimulation by indicating the level on a 10-cm visual analog scale where 0 cm indicated “no pain” and 10 cm, “intolerable pain”. Use of visual analog scales to measure experimental pain has been validated (Price et al., 1983).

2.4. Postural analysis

The surface area, mean velocity, and standard deviation of the CoP displacements along the medio-lateral (ML) and antero-posterior axes (AP) were used to describe the subject's postural behaviour. The calculation of the surface area and standard deviation of the signal provide measures of amplitude variability of CoP around the mean position. The mean velocity represents the total distance covered by the CoP (total sway path) divided by the duration of the sampled period and constitutes a good index of the amount of activity required to maintain stability (Maki et al., 1990; Geurts et al., 1993).

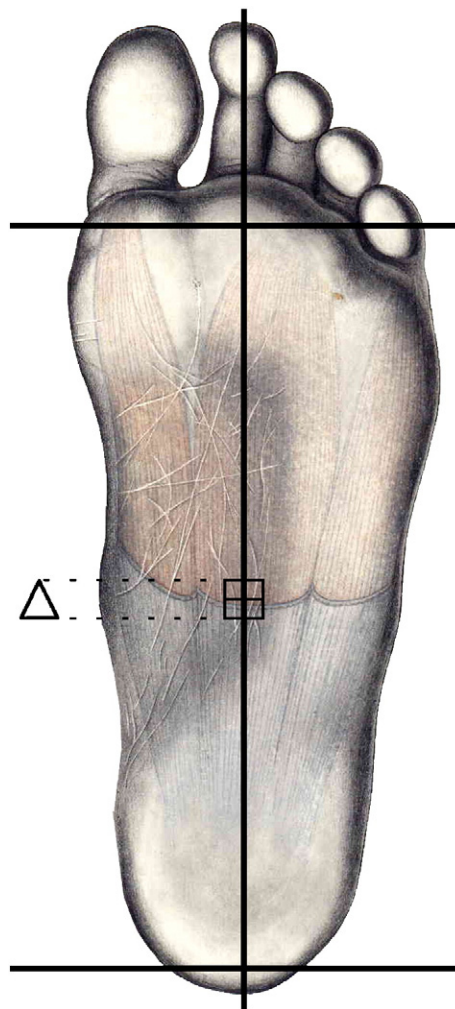


Fig. 1. Positioning and shape of the objects placed under the feet in the Plantar-pain condition.

2.5. Statistical analysis

For each dependent variable, a 3×3 trials (Trial1 vs. Trial2 vs. Trial3) \times Pain (no pain vs. plantar pain vs. palmar pain), analyses of variance with repeated measures on both factors were performed.

Post hoc analyses (Scheffé Test) were used whenever necessary. The level of significance was set at 0.05.

3. Results

3.1. Perceived pain intensity

Analysis of the visual analog scores showed a main effect of Pain ($F(2,18) = 364.84, P < 0.001$). Post hoc analyses indicated that the plantar-pain and the palmar-pain conditions result in higher values of perceived pain intensity relative to the no-pain condition ($P < 0.001$), whereas there was no statistical difference between VAS scores for plantar-pain and palmar-pain conditions ($P > 0.05$) (0.0, 7.2, and 7.2 cm, for no-pain, plantar-pain, and palmar-pain conditions, respectively). There was no significant interaction between Trials \times Pain ($F(4,36) = 0.40, P > 0.05$), or a significant main effect of trials ($F(2,18) = 0.84, P > 0.05$).

3.2. Postural analysis

Analysis of the CoP surface area showed a main effect of pain ($F(2,18) = 19.94, P < 0.001$). Post hoc analyses indicated that the

plantar-pain condition results in a wider surface area relative to the no-pain and the palmar-pain conditions ($P_s < 0.001$), whereas there was no statistical difference for the CoP surface area between the palmar-pain and no-pain conditions ($P > 0.05$) (Fig. 2A). There was no significant interaction between trials \times pain ($F(4,36) = 0.23, P > 0.05$), or a significant main effect of trials ($F(2,18) = 0.18, P > 0.05$).

Analysis of the CoP mean velocity showed a main effect of pain ($F(2,18) = 12.92, P < 0.001$). Post hoc analyses indicated that the plantar-pain condition resulted in a higher CoP mean velocity relative to the no-pain and the palmar-pain conditions ($P_s < 0.01$), whereas there was no statistical difference for the CoP mean velocity between the palmar-pain and no-pain conditions ($P > 0.05$) (Fig. 2B). There was no significant interaction between trials \times pain ($F(4,36) = 0.39, P > 0.05$), or a significant main effect of trials ($F(2,18) = 0.83, P > 0.05$).

Analysis of the ML CoP standard deviation showed a main effect of pain ($F(2,18) = 15.37, P < 0.001$). Post hoc analyses indicated that the plantar-pain condition resulted in a larger ML CoP standard deviation relative to the no-pain and the palmar-pain conditions ($P_s < 0.001$), whereas there was no statistical difference for the ML CoP standard deviation between the palmar-pain and no-pain conditions ($P > 0.05$) (Fig. 2C). There was no significant interaction between trials \times pain ($F(4,36) = 0.55, P > 0.05$), or a significant main effect of trials ($F(2,18) = 1.60, P > 0.05$).

Analysis of the AP CoP standard deviation showed a main effect of pain ($F(2,18) = 8.95, P < 0.01$). Post hoc analyses indicated that the plantar-pain condition yielded larger AP CoP standard deviation relative to the no-pain and the palmar-pain conditions ($P_s < 0.01$), whereas there was no statistical difference for the AP CoP standard deviation between the palmar-pain and no-pain conditions ($P > 0.05$) (Fig. 2D). There was

no significant interaction between trials \times pain ($F(4,36) = 0.61, P > 0.05$), or a significant main effect of trials ($F(2,18) = 0.69, P > 0.05$).

4. Discussion

Before considering the effects on postural behaviour, it is important to mention that there was no difference in pain intensity between the plantar-pain and palmar-pain conditions. In both conditions, the pain was perceived as severe.

Analyses of the CoP displacements suggest that a painful stimulation applied to the plantar surfaces of both feet impaired upright postural control, as indicated by the increased surface area (Fig. 2A), mean velocity (Fig. 2B), and standard deviation along both axes (Fig. 2C and D) in the plantar-pain condition relative to both the no-pain and the palmar-pain conditions. In addition to the absence of significant interactions between trial \times pain, these results indicate that the destabilizing effects of Plantar-pain were consistent across all trials. What is more, an individual analysis revealed that all subjects demonstrated postural control impairments in the palmar-pain condition relative to the no-pain condition. Considering the functional significance of these CoP-based parameters (Maki et al., 1990; Geurts et al., 1993; Prieto et al., 1996), these results suggest that the painful stimulation applied to the plantar surfaces of both feet degraded the effectiveness of the postural control system and increased the amount of postural regulatory activity required to control unperturbed bipedal posture. Furthermore, if one agrees with the suggestion that “leaning too far or too fast can result in a situation where it is not possible to recover balance” (Patton et al., 1999), the observed increase in CoP data in the plantar-pain condition could potentially increase the risk of falls. Conversely, further analyses of the CoP

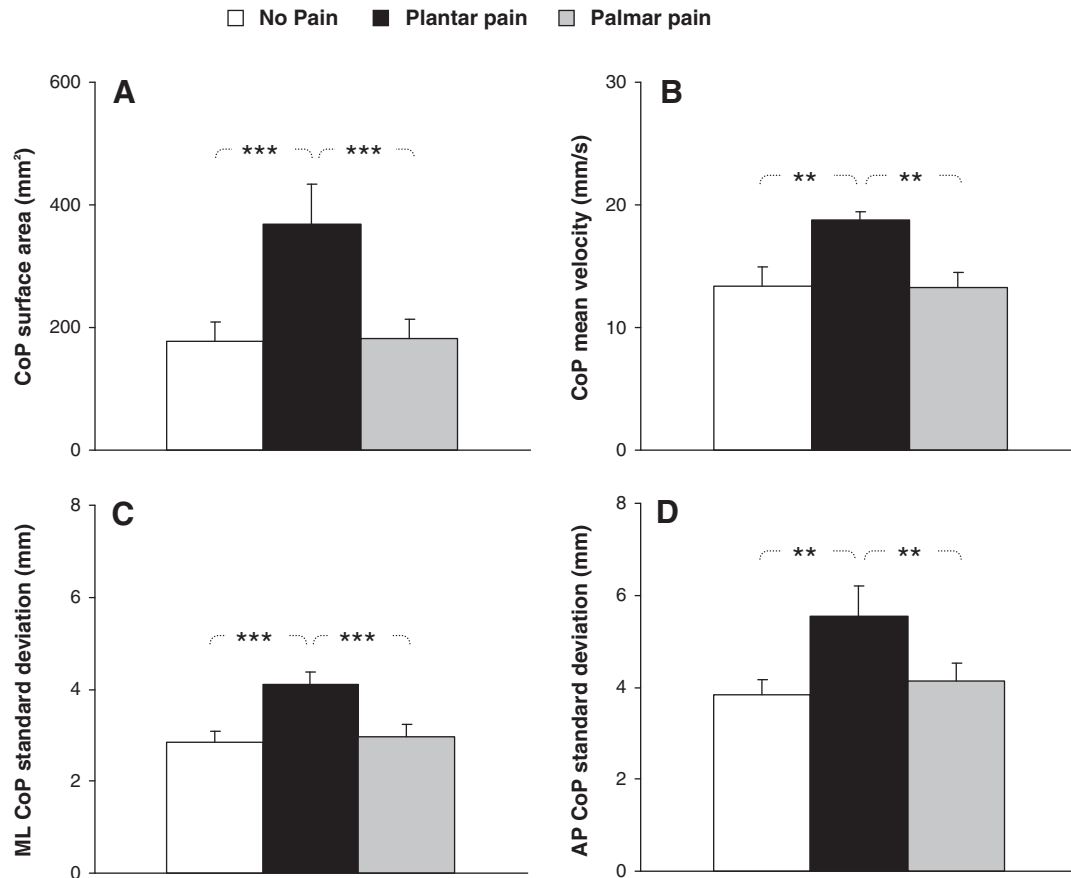


Fig. 2. Mean and standard error of the mean of the surface area (A), the mean velocity (B), and the standard deviation of the CoP displacements along the mediolateral (ML) (C) and anteroposterior (AP) (D) axes obtained in the three conditions of No-pain, Plantar-pain, and Palmar-pain. Each of the three experimental conditions is presented with a different symbol: No-pain (white bars), Plantar-pain (black bars), and Palmar-pain (grey bars). The significant P values are reported for comparison (* $P < 0.05$).

displacements showed no significant difference between the CoP displacements measured in the palmar-pain condition and those measured in the no-pain condition.

Taken together, these results indicate that, for the same perceived intensity of the pain, the severe painful stimulation applied to the plantar surfaces of both feet degraded upright postural control, whereas the severe painful stimulation applied to the palms of both hands did not. Although the location of the painful stimulation was different (dorsum of the first tarso-metatarsal joint of both feet and of the first and second metacarpal heads of both hands), these results are in line with those previously reported by Corbeil et al. (2004).

At this point, a potential limitation of the present study pertains to the experimental design used in the present experiment to induce pain of the plantar soles. It is indeed possible that the pyramids used in the plantar-pain condition of the present experiment may have had a mechanical, rather than sensory, effect that led to postural control impairment observed in this condition relative to the no-pain condition. To address this issue, a small control experiment was performed on four young healthy subjects to assess if a non-painful plantar mechanical stimulation also increased CoP displacements during upright stance. Two 1-cm rigid square pyramid shapes (polyurethane, hardness shore A110), identical to those used in the present experiment except that the point was not sharp, were used to experimentally induce the non-painful mechanical stimulation. These objects were placed at the same location than those used in the plantar-pain condition (Fig. 1). Results showed that the non-painful plantar mechanical stimulation resulted in *decreased* CoP displacements. This result hence suggests that the *increased* CoP displacements observed in the plantar-pain condition relative to the no-pain condition did not stem from the mechanical stimulation or “hyper-sensation” associated with our experimental design. Rather, the painful plantar stimulation could have altered balance control through several neurophysiological mechanisms (Blouin et al., 2003; Corbeil et al., 2004; Vuillerme and Pinsault, 2009) including changes in motor cortex excitability (Le Pera et al., 2001) and/or in the accuracy and/or reliability of the integration of somatosensory information (e.g., Rossi and Decchi, 1997; Weerakkody et al., 2002) induced by nociceptive afferents from the plantar sole, which could have impaired estimation of the whole body position in space (Gandevia and Phegan, 1999). However, such a proposal is yet speculative, and further experiments, employing more valid methods such as the injection of hypertonic saline (Hirata et al., 2010) or painful electrical stimulus (Corbeil et al., 2004; Vuillerme and Pinsault, 2009), are warranted to investigate the postural effects of foot sole pain *per se* and to determine the exact locus of the observed effects of the painful plantar stimulation.

It is also important to mention that the present experiment was performed in the absence of vision, considering the dominant role played by visual information on postural control during quiet standing (e.g., see Redfern et al. 2001, for a recent review), and, specifically its effectiveness in compensating for alterations in plantar cutaneous information (e.g., experimentally induced by pharmaceutical (Meyer et al., 2004) or hypothermic anaesthesia of the feet (Magnusson et al., 1990; Hong et al., 2007; McKeon and Hertel, 2007), or by the interposition of a foam support surface beneath the feet (Fransson et al., 2007). The eyes-closed condition thus avoided visual information interfering with the induced postural behaviours and allowed specific evaluation of the effect of experimentally induced pain of the plantar soles on CoP displacements during unperturbed upright stance. To investigate the generalisation of the present findings, further investigations are currently being performed in different sensory environments (e.g., Hirata et al., 2010).

From a clinical point of view, our results show the destabilizing effect of plantar-pain on unperturbed bipedal postural control that could support the observations that persons suffering from foot pain exhibit balance deficits (Menz and Lord, 2001; Menz et al., 2006),

especially persons suffering from concomitant foot pain and sensory and cognitive deficits—i.e., posture-related functions, as can be seen in older adults or in patients with diabetic polyneuropathy, for instance. Along these lines, it is possible that clinical and/or instrumental interventions designed to mitigate pain in patients suffering from plantar foot pain (e.g., podiatry interventions) could improve postural control.

5. Conclusion

By showing differential effects of a painful stimulation applied to the plantar surfaces of both feet and to the palms of both hands on CoP displacements, the present findings provide evidence that, in order to degrade postural control, the painful stimulation must be applied to a limb, which is specifically involved in the control of unperturbed postural control. These results also reveal the deleterious effect of experimentally induced pain of the plantar soles on unperturbed bipedal postural control that had not yet been documented.

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