Increased postural sway and modified pressure distribution patterns following reduced plantar sensitivity

Eils E, Tewes M, Nolte S, Rosenbaum D
Funktionsbereich Bewegungsanalytik (Movement Analysis Lab), Orthopaedic Department, University of Muenster, Germany

Introduction
Human movement is controlled on the basis of afferent information of the visual, the vestibular and the somatosensory system. Whereas many investigations concern the effects of the visual and the vestibular system upon postural control (Dichgans and Diener 1989; Simoneau et al. 1992; Patla 1997) the contribution of the somatosensory system still remains unclear. Knowledge about how somatosensory signals trigger and modulate human balance or gait patterns has important implications for the rehabilitation of postural and gait disorders, and advances our understanding of normal interactions between these sensory systems. The somatosensory system consists of different cutaneous, joint and muscle mechano-receptors and appears to have the major influence on postural control (Simoneau et al. 1995; van Deursen and Simoneau 1999). The consequences of lost or reduced information of any of these mechano-receptors on balance or gait patterns is still unknown. Therefore, the aim of the present investigation was to selectively reduce the cutaneous information of the plantar surface of the foot using an ice immersion approach in order to study the changes in pressure distribution and postural control.

Methods

Pilot study: In a pilot study including nine subjects (25.9±3.2 years, 68.4±18.9 kg, 173.6±12.8 cm) the efficacy of the cooling procedure and its influence on the elastic properties of the plantar soft tissue were examined. Subjects placed one foot in ice water (0° C) so that only the plantar aspect of the foot was submerged. Different durations of cooling (10 and 25 minutes), sensation (using Semmes-Weinstein monofilaments) and indentation depths of a constant pressure (32N/qcm) after cooling were tested. Results showed that after ten minutes of cooling there was a significant reduction of sensation but no additional effect between 10 and 25 minutes and no significant differences in indentation depth of the plantar soft tissue between normal and iced conditions. Therefore, an influence of the cooling procedure on indentation depth could be excluded (Bennett and Ker 1990) and duration of the cooling procedure was set to ten minutes.

Main study: 40 healthy subjects with no history of sensory disorders participated in the study. Their mean age, mass and height was 25±3.3 years, 71±10.6 kg and 177±7.8 cm, respectively. Pressure distribution (PD) during walking and postural sway (PS) in single limb stance were measured using an EMED ST4 platform and a Kistler force plate. Six barefoot trials for both PD and PS were measured under normal conditions. The foot was then submerged in ice water. After 10 minutes of cooling, reduction of sensation for five areas was reported using Semmes-Weinstein monofilaments (Fig. 1) and after an additional cooling procedure of 10 minutes two trials of PD or PS were measured. The foot was then cooled down again and the procedure was repeated until six trials for each test were complete. For analysis, the sway of the center of pressure in the medio-lateral, antero-posterior direction and the sway distance as well as peak pressures, contact times and relative impulses (force-time integrals) for 10 selected areas of the foot (two areas for the heel and the midfoot, three areas for the forefoot, the hallux, first metatarsal head, fifth metatarsal head, central midfoot and central heel. Testing sensation threshold of the hallux is shown on the right side.

Fig. 1. The five sites of the pressure/sensation test of the sole of the foot shown on the left site (from top to bottom): hallux, first metatarsal head, fifth metatarsal head, central midfoot and central heel. Testing sensation threshold of the hallux is shown on the right side.
second toe and lateral toes) were used for analysis. Normal distribution of the extracted parameters was tested by the Kolmogoroff-Smirnoff one sample test. Differences between the two conditions were determined (i) using the parametric dependent Student t-test for normally distributed parameters or (ii) using the nonparametric dependent Wilcoxon signed rank test for not sufficiently normally distributed parameters. Most of the tested variables were normally distributed. The statistical level of significance was set at p<0.05. Effect size was calculated using the approach from Cohen (Cohen 1988). Power analysis revealed that intermediate and large effects were detectable with a power of 87% and 99%.

Results
The cooling procedure led to a significantly decreased plantar sensitivity for all tested areas. The size of the monofilament that was sensed under cooled condition increased significantly from 3.7±0.2 to 4.0±0.3 (p<0.0001) indicating a reduction of sensation. The analysis of center of pressure excursion showed a significant increase of postural sway under ice conditions in both the medio-lateral and the antero-posterior direction (p<0.0001, Tab. 1).

<table>
<thead>
<tr>
<th>Postural sway [mm]</th>
<th>Normal Mean ± SD</th>
<th>Ice Mean ± SD</th>
<th>P level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sway variance medio-lateral</td>
<td>5.6 ± 1.4</td>
<td>6.4 ± 1.7</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Sway variance antero-posterior</td>
<td>6.5 ± 1.7</td>
<td>8.1 ± 2.5</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Maximum sway medio-lateral</td>
<td>26.6 ± 6.4</td>
<td>30.2 ± 7.8</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Maximum sway antero-posterior</td>
<td>31.5 ± 7.8</td>
<td>39.1 ± 11.1</td>
<td>&lt;.0001</td>
</tr>
</tbody>
</table>

Tab. 1. Means and standard deviations for parameters of postural sway.

Peak pressures were reduced for all areas under ice conditions with significant changes under the toes and under the heel (p<0.001, Fig. 2, left).

The total contact time did not change significantly between normal and ice condition (814±111 ms vs. 823±91 ms, p>0.05). Significantly longer contact times, that are the result of an earlier and prolonged contact, were found under the medial forefoot (p<0.001), central forefoot (p<0.01), lateral forefoot (p<0.05), lateral midfoot (p<0.05) and lateral toes (p<0.05). The force-time integral for the whole foot (representing the loading of the foot) did not change significantly between both conditions (415.5±96.4 Ns vs. 405.9±89.7 Ns, p>0.05). For the different areas, a significant load shift from the heel and toes towards the central and lateral forefoot and the lateral midfoot was observed (Fig. 2, right).

![Fig. 2](image-url) Changes of peak pressure and relative impulse under normal and ice conditions. **"** indicated significant differences between both conditions.

Discussion
The results of the present study indicate the important input of afferent information from the sole of the foot to control posture. The reduction of the pressure/sensation threshold of the sole of the foot could clearly be shown using an ice water approach. It is well described that cold application leads to a decrease of nerve conduction velocity and also influences skin receptors (Lee et al. 1978). In single limb stance,
muscles of the shank, the thigh and the hip play a major role in maintaining stability. The muscles that stabilize the ankle joint are located in the lower leg and are not likely to be affected by the cooling procedure. Therefore, it can be concluded that the increased sway in both medio-lateral and antero-posterior direction may be attributed to the sensory attenuation of mechanoreceptors located in the glabrous skin of the sole of the foot. A reduced ability to detect the actual position of the center of pressure compared to normal conditions leads to a delayed correction of posture and therefore to an increase of postural sway.

The influence of reduced or altered information from the plantar surface on pressure distribution has been shown recently (Chen et al. 1995; Nurse and Nigg 1999). The results of the pressure distribution analysis in the present study revealed that there is a change in strategy in the roll-over process of the cooled foot compared to the normal foot. First, there is a reduction of peak pressures under the heel and the toes. The heel plays an important role in the initial foot to ground contact and the hallux in the push-off phase. It appears that subjects used a more cautious touch down and push-off to protect the foot from unexpected occurrences because of the reduced feedback. Second, the total force-time integral between normal and ice condition did not change significantly and therefore the differences in the relative impulse for all areas between both conditions can be attributed to a shift of load within one foot and not a shift to the contralateral leg. Within the foot, the load is transferred from the heel and the toes to the forefoot and the lateral part of the midfoot. This specific roll-over pattern can be described as follows: At heel strike, the load is shifted to the forefoot by an earlier ground contact of the forefoot under ice conditions. During the roll-over process, there is always more contact area of the foot than under normal conditions leading to the increased contact times for all areas (especially to the significant increase in the forefoot region) and a better load distribution over the whole foot. At push-off, the load under the forefoot is not transferred to the toes and push-off takes place from the central and lateral forefoot.

In general, it appears that subjects try to protect the foot from unexpected events by using an altered roll-over process that can be described by a reduction of peak pressures, a load shift to the lateral part of the foot and a more even load distribution over the whole foot by an early, prolonged foot-flat.

**Conclusion**

Short term reduced afferent information of the sole of the foot has a strong influence on the ability to control balance in single limb stance and modulates the roll-over process in walking. It has to be considered that long term loss of information like in diabetic neuropathy may lead to compensatory mechanisms of other sensory systems that counterbalance the actual results.

**References**


Lee JM, Warren MP, Mason SM (1978) Physiotherapy 64: 2-6


Patla AE (1997) Gait & Posture 5: 54-69

