Withdrawal Reflexes
Elicited by Electrical Stimulation of the Foot Sole during Gait
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Abstract
A technique of distributed surface electrical stimulation of the foot sole was used to elicit the withdrawal reflex in ankle flexors and extensors during gait. Tibialis anterior and soleus reflexes were recorded from 8 subjects during treadmill walking. The largest responses in tibialis anterior were evoked at the arch of the foot, while in soleus the largest responses were elicited at the heel/arch of the foot. Reflexes were elicited in four different phases of the gait cycle (after heel-contact, in the flat-foot phase, after heel-off and in the swing phase). The strongest tibialis anterior reflexes were obtained when stimulating after heel-contact. The soleus reflexes were minimum when stimulation was applied after heel-off. Spinal motor centers most likely modulate the withdrawal reflexes in order to secure balance and continuity of the movement. The reflex may have application for initiation of gait in paraplegic patients.

1. Introduction
Based on studies in rats, Schouenborg and Kaliomaki proposed a modular organization of withdrawal reflexes [7]. This concept involves an organization in which each muscle or group of muscles has a separate cutaneous receptive field that corresponds to the skin area withdrawn by a contraction of the particular muscle group. Grimby [5] found in 1963 the first indications of a modular organization of the human withdrawal reflex by observing dorsal flexion when stimulating the distal, medial plantar surface of the foot sole and plantar flexion when stimulating the skin area around the heel. Andersen et al. [1] confirmed studies in animals and provided evidence for a modular organization of the human withdrawal reflex for lower limb muscles when electrically stimulating the foot sole of healthy volunteers. Cutaneomuscular reflexes have been studied extensively during gait for stimulation intensities below [4], [8] and above the pain threshold [3], [2]. However, all of these reports used nerve trunk stimulation.

The purpose of this work was to study the organization and modulation of withdrawal reflexes in tibialis anterior (TA) and soleus (SOL) muscles during human gait, using a technique of distributed electrical stimulation applied in the sole of the foot. This may provide information useful for applying the reflex in rehabilitation.

2. Methods
Eight volunteers (5 men and 3 women; mean age 23.9 years, range 22-25 years) participated in the study. Informed consent was obtained from all subjects.

Electrical stimulation was delivered on the sole of the foot; 4 adhesive electrodes (15×15 mm, Ag-AgCl, Medicotest, Oelstykke, Denmark) were mounted as shown in Fig. 1. The common anode (10×14 cm electrode, Pals, Axelgaard Ltd., Fallbrook, California) was placed on the dorsum of the foot. For each electrode position, the electrode was moved slightly in case the evoked response indicated direct nerve stimulation (sensory and motor responses). The computer-controlled electrical stimulator (Neuromatic 2000 C, Disa, Skovlunde, Denmark) delivered a stimulus to 1 of the 4 electrodes according to a pre-programmed randomized sequence. Each stimulus consisted of a constant current pulse train of five individual 2 ms pulses delivered at 200 Hz. For each electrode position, the intensity of the stimulation was determined as a proportion of the pain threshold. A factor varying between 1.4 and 1.8 was used for the different volunteers. The pain thresholds were determined while the volunteer was standing.

The gait cycle was divided in 4 parts. The stimulation was delivered 10 ms after heel-contact; in the middle of the period between heel-contact and heel-off (flat-foot phase);
10 ms after heel-off; and at 80 % of the gait cycle, i.e. during the swing phase.

Fig 1. Placement of the stimulation electrodes on the foot sole: 1- medial, distal position; 2- lateral, distal position; 3- arch of the foot; 4- heel. The common anode was mounted on the dorsum of the foot.

The electromyogram (EMG) of TA and SOL muscles was recorded using Ag-AgCl surface electrodes in a bipolar configuration (2 cm interelectrode distance). The EMG signals were amplified, filtered (5–500 Hz, second order), sampled at 2 KHz, displayed and stored for later analysis.

The volunteers walked on a treadmill at a speed of 3 km/h while 5 reflex responses were obtained for each of the 4 electrode positions and 4 phases of the gait cycle.

The rectified and low pass filtered (Butterworth, 40 Hz, tenth order) EMG signals were averaged for each stimulation position. The reflex response was assessed by the difference between the area calculated in the 60-200 ms poststimulation interval and the corresponding area in the average EMG obtained during unperturbed gait.

Two–way repeated measure analysis of variance (ANOVA) was applied. Student–Newman–Keuls test was used for pairwise comparisons. P < 0.05 was considered as statistically significant.

### 3. Results

The largest reflexes in TA were elicited at the arch of the foot. When the stimulation was applied after heel-contact and during the swing phase, the TA reflex response elicited at the arch of the foot was significantly larger than at the other 3 stimulation positions (P < 0.05). But when stimulating during the flat-foot phase of the gait cycle and after heel-off, there was only a significant difference in the response evoked at the arch of the foot compared to the heel and lateral distal foot (P < 0.02).

Comparing responses during the phases of the gait cycle, a significantly larger TA reflex response was observed when stimulating after the heel-contact for the arch of the foot (P < 0.01) and the medial, distal stimulation site (P < 0.04). A significant difference was also found when comparing responses to stimulation after the heel-contact and the flat-foot phase of the gait cycle for the lateral, distal stimulation site (P < 0.025). However, there were no differences within the gait cycle when stimulating at the heel (see Table I).

<table>
<thead>
<tr>
<th>Electrode number</th>
<th>Heel-contact</th>
<th>Flat-foot</th>
<th>Heel-off</th>
<th>Swing</th>
</tr>
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<tbody>
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</table>

Magnitude is expressed as a percentage of the maximal TA evoked response (electrode 3, stimulation after heel-contact). * Indicates a significantly different reflex response compared with all the other phases. † Indicates a significantly different reflex response compared with the flat-foot phase.

The largest reflexes in SOL muscle were triggered at the arch of the foot and at the heel. These reflexes were significantly larger than the response evoked at the lateral, distal foot (P < 0.03, stimulation after heel-contact) and at the medial, distal foot (P < 0.05, stimulation after the heel-off). When the stimulation was delivered during the flat-foot phase of the gait cycle, there was only a significant difference between the SOL responses evoked at the heel and at the lateral distal foot (P < 0.015). There were no significant differences between the stimulation positions during the swing phase of the gait cycle.

Regarding the responses through the gait cycle, significantly larger responses (P < 0.05) were observed for heel-contact, flat-foot, and swing phases compared to heel-off, for the heel, the arch of the foot and the medial, distal stimulation sites (see Table II).

<table>
<thead>
<tr>
<th>Electrode number</th>
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<th>Heel-off</th>
<th>Swing</th>
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<td>51% *</td>
<td>86%</td>
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</tbody>
</table>

Magnitude is expressed as a percentage of the maximal SOL evoked response (electrode 4, stimulation in flat-foot phase). * Indicates a significantly different reflex response compared with all the other phases.
4. Discussion and Conclusions

Electrical stimulation is adequate to evoke reproducible reflexes. From the quality of the evoked sensations (sharp, pricking), Aδ afferent input was most likely part of the afferent inflow. The stimulus intensity was determined as a factor of the individual pain thresholds in order to obtain an equal afferent input for all four stimulation sites.

The modular organization of the human withdrawal reflex for lower limb muscles was confirmed. The reflex receptive fields (RRF) for TA and SOL muscles have the same shape and location along the gait cycle and were comparable to previous studies on subjects in sitting position [1]. The TA RRF is located in the arch of the foot. The SOL RRF presents two areas, the heel and the arch of the foot.

The withdrawal reflex was modulated during the gait cycle in both muscles. For all the stimulation positions except the heel, a maximal TA response was observed when stimulating immediately after the heel-contact. The reduction of the magnitude of the TA evoked reflexes during the stance phase is consistent with the preservation of the gait function. An increment of the reflexes during the swing phase was expected but not observed. No modulation was present when stimulating at the heel; the evoked reflex was weak all along the gait cycle.

The SOL reflexes presented a minimum when elicited after the heel-off for all the stimulation positions except the lateral distal site. Even though there is a reduction of the reflex response, the foot would be withdrawn from the noxious source due to the leg is being moved away by the ongoing movement.

Reflexes in ankle flexors and extensors were evoked depending on the stimulation position and the phase of the gait cycle, probably to ensure an appropriate withdrawal of the affected area. Further studies are necessary to determine the relationship between the biomechanical function of each muscle, their RRF and the modulation of the actual movement along the gait cycle. Spinal motor centers most likely modulate the withdrawal reflexes in order to secure balance and continuity of the actual movement [3], [6].

Results about modulation of the evoked response might be used to improve the control of FES assisted gait and in rehabilitation programs based on functional electrical therapy.

Acknowledgment

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5. References