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Sensitivity Mapping of The Human Foot: Thresholds at 30 Skin Locations

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ABSTRACT

Background: **Mechanoreceptors in the skin provide sensory input for the central nervous system about foot placement and loading. This information is used by the brain to actively control or regain balance and is important to establish memory traces for subsequent movement. A sensitivity map of the human foot could help to understand the mechanisms of the foot as a sensory organ for movement adjustment and balance control.** ***Materials and Methods:*** **Touch and vibration perception threshold values from 30 plantar and dorsal foot locations were determined in more than 40 women and men between 20 and 35 years. Semmes Weinstein monofilaments and a vibrotactile neurothesiometer were used for skin sensitivity threshold detection.** ***Results:*** **Large sensitivity differences were present between the 30 different foot sites. Gender effects were not present for touch but women had better sensitivities for vibration ($p < 0.01$), especially on the dorsal aspect of the foot. Age, in our cohort of 20- to 35-year-olds, did not have an influence on vibration or touch sensitivity. The heel had the highest detection thresholds for touch but was very sensitive for vibration stimuli. Compared to the dorsum, the plantar foot was substantially more sensitive, especially for vibration detection.** ***Conclusion:*** **The results suggest that primarily the fast adapting plantar mechanoreceptors are important in assisting balance control during human locomotion.** ***Clinical Relevance:*** **The sensitivity map of the foot will help in understanding the function of the foot as a sensory organ and could be useful in creating footwear for better balance control and for the design of comfortable shoes.**

Key Words: Foot Sensitivity; Mechanoreceptors; Touch; Vibration; Gender; Semmes Weinstein Monofilaments, Neurothesiometer; Footwear Design

INTRODUCTION

The human foot is an efficient structure to support the human body during standing and many kinds of movements. It is also an important source of sensory input. Various mechanoreceptors in the skin with slow, medium and fast adaptation speeds are able to detect displacement, velocity and acceleration of the skin surface. Merkel discs and Ruffini corpuscle end organs belong to the slowly adapting (SA) cutaneous mechanoreceptors whereas Meissner and Pacinian corpuscles are rapidly adapting (RA) receptors in the skin. Clinically, sensory malfunction of the foot may cause substantial problems, as present in diabetic patients with neuropathy. In recent years, more and more scientific evidence has been presented that demonstrates the importance of the foot as a sensory organ. The detection of mechanical stimuli by the foot has been shown to be an important factor for balance control during standing and walking in healthy subjects.[14] For standing balance control, especially under eyes-closed and unipedal stance conditions, foot-sole anesthesia increases the Center of Pressure length and velocity and thus influences mediolateral as well as anteroposterior posture control.[11]

It has been shown that touch threshold sensitivity values increase with age at the index finger[21] and under the foot.[19] The reduction in touch sensitivity cannot be explained by the changes in the mechanical properties of the skin, but are related to changes of the nervous system with increasing age.[26] A considerable reduction of sensitivity with age has also been reported for vibrotactile stimuli.[15] However, there is not yet a difference for skin vibration recognition between children (7 to 11 years) and young adults (21 to 27 years).[5] Guclu and Oztek[5] suggest that a loss of sensitivity with age occurs more suddenly at a later age. Including the factors age, gender and body height, Lin et al.[8] found that age is the primary factor in predicting sensory thresholds for vibration stimuli. The epidermal area occupied by nerve endings was

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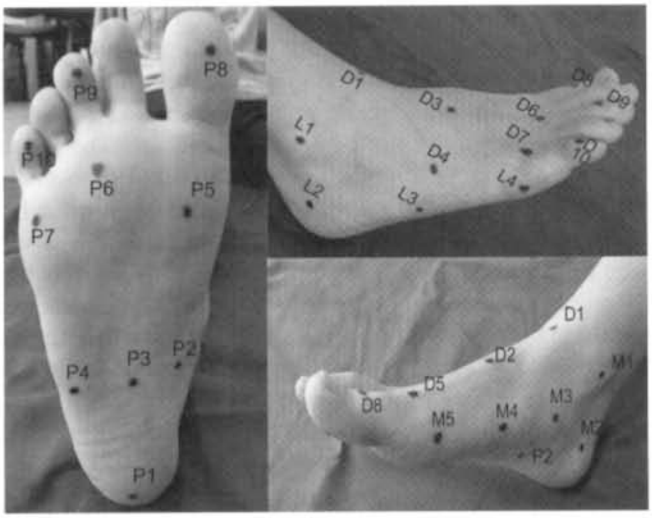

Fig. 1: Dorsal and plantar measuring sites for touch and vibration sensory threshold detection.

between subjects. Using the method by Dyck et al.[3] a 4, 2, and 1 stepping algorithm with null stimuli was used for threshold detection. As suggested by Mueller,[12] five repetitive stimuli, including null stimuli, were given with the same filament. If subjects gave right answers in four out of the five trials, the filament was considered recognized.

In the vibration sensation study 23 women (24.0 ± 3.1 years, 168,6 ± 5.7 cm, 62.0 ± 7.2 kg) and 24 men (26.5 ± 4.0 years, 185,0 ± 6.1 cm, 81.5 ± 10.3 kg) participated. The order of the anatomical sites was randomized between subjects. Vibration sensitivity thresholds were determined by using a modified Horwell Neurothesiometer (Scientific Laboratory Supplies Ltd., Nottingham, UK) with a vibration frequency of 50 Hz. Using an external 50 Hz sinusoidal wave generator the vibrator head amplitude was slowly increased (1 micrometer in 5 seconds) until the subjects hit a button as soon as they first recognized vibration. The neurothesiometer was calibrated using a high precision laser distance measuring system (Lase ODS, Wesel, Germany). To simulate the placement on the skin, the Horwell vibration head was placed with its mass of 497 gram (excitation unit plus head) on a stretched rubber membrane. From below the membrane the laser distance measuring system recorded the displacement of the membrane with increasing voltage amplitude of the sinusoidal wave generator. The response between voltage amplitude and head excursion on the membrane was nonlinear. From this calibration procedure a second order polynomial regression equation was established to correct for the nonlinearity of the vibration head displacement. This regression equation served to transform the recorded voltages from the experiments to vibration amplitudes. During the experiments, the vibration head was placed on an anatomical site and was carefully supported and balanced by one hand to avoid additional force on the skin except for the weight of the vibration unit. For improving the reliability of measurements all experiments were carried out by the same person, as suggested by Peters et al.[17]

In both studies the subjects did lie on a massage bed in a quiet room and were blindfolded, to improve the attentiveness for threshold recognition. To measure all the anatomical sites the subject had to change body positions on the bed. For the measurements of the plantar sites, the participants were prone and the foot was rested at a knee angle of approximately 90 degrees on a block of foam rubber. Room temperature was kept constant and an infrared lamp served to keep skin temperature at a comfortable level. From vibration measurements at the hand it was reported that at 20°C the detection thresholds were considerably higher than at 30 or 40°C.[4] However, only minor sensitivity differences were found in the same study between 30 and 40°C. In our experiments we used an infrared thermometer, to control for a skin temperature of well above 30°C.

Based on a test for normality (Shapiro-Wilk's W), parametric statistics were chosen for data evaluation. A two-way mixed design ANOVA was used for the touch as well as the vibration sensitivity experiments. Gender was chosen as the independent factor and the measuring sites across the foot as dependent factor. A type I error probability of less than 5% was selected as statitistical significance level. Furthermore, simple linear regression analyses were performed to compare the experimental data with anthropometric variables of the participating subjects.

RESULTS

Significant ($p < 0.0001$) touch sensitivity levels between the 30 anatomical sites were found but no gender effect. Therefore, the data of the women and men for touch sensitivity were combined. A linear regression analysis for the 44 subjects in our study did not show a correlation between age and the averaged touch threshold sensitivities across the 30 anatomical sites ($r^2 = 0.04$). The SWF (Semmes Weinstein Filament) scores in Figure 2 demonstrate that there were substantial sensitivity differences between the anatomical sites. The least sensitive touch regions were the heel (P1), followed by the most proximal site on the foot dorsum (D1), the medial and lateral malleoli (M1, L1), and the Achilles tendon (A1). The medial longitudinal arch location (P2) and the plantar (p8, P9, P10) as well as the dorsal (D8, D9, D10) toe regions had the best sensitivities for touch.

For the vibration sensitivity experiment significant differences were found ($p < 0.0001$) for vibration sensitivity levels between the 30 anatomical sites, a significant ($p < 0.01$) gender effect, and also a significant ($p < 0.01$) interaction. Regression analyses showed no correlation between age and the averaged vibration threshold sensitivities across the 30 anatomical sites for the women ($r^2 = 0.09$) and the men ($r^2 = 0.08$). The women showed considerably better sensitivities at all 30 foot sites (Figure 3).

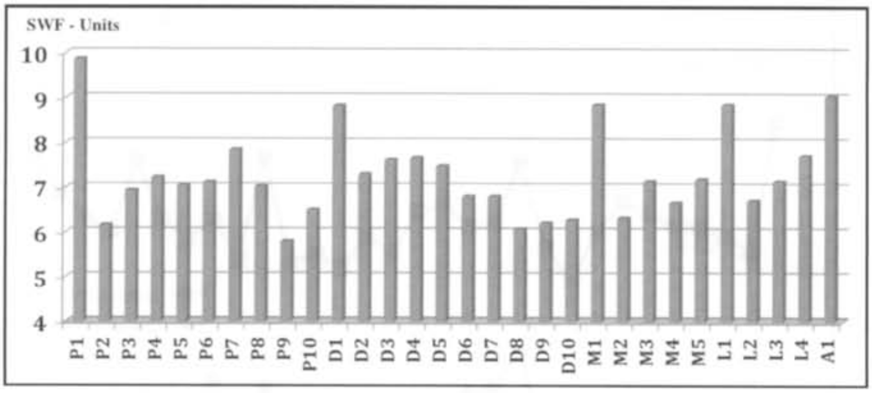

Fig. 2: Touch sensitivity threshold values in SWF units from 44 subjects at 30 anatomical locations.

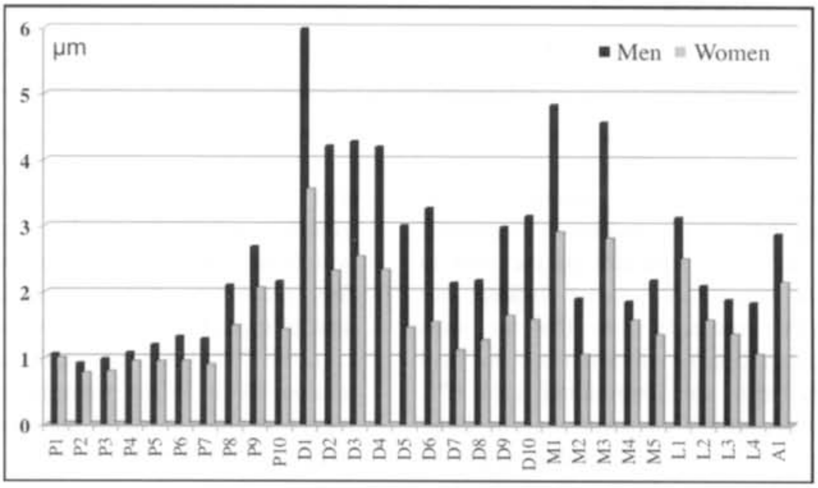

Fig. 3: Vibration (50 Hz) sensitivity thresholds in mikrometer from 24 men and 23 women at 30 anatomical locations.

Twenty-three of our subjects participated in both the touch as well as the vibration threshold studies. Although those subjects with a better touch sensitivity also demonstrated an improved skin vibration sensitivity, this relationship was weak ($r^2 = 0.19$). Figure 4 shows the direct comparison of the touch and vibration threshold results from our 23 subjects. With few exceptions a similar pattern can be seen across the 30 anatomical sites. However, there was a large sensitivity difference between the touch and vibration sensitivities under the heel.

DISCUSSION

In our study no reduction of touch and vibration sensitivities was found with increased age. For the comparison of touch sensitivity with age, the coefficient of determination was only $r^2 = 0.04$ and for the age related vibration sensitivity only $r^2 = 0.09$ for the women and $r^2 = 0.08$ for the men. It could be that this is a consequence of the narrow age range between 20 and 35 years of our subjects. This finding would agree with the statements of Guclu and Oztek[5] that the loss of sensitivity with age occurs at a later age.

It is interesting that there was a clear gender effect for the vibration but not the touch sensitivities across the foot. For touch stimuli with Semmes Weinstein filaments, Birke et al.[2] also found no difference and Tremblay et al.[22] only marginal tactile sensitivity differences between women and men at the foot and fingertip. For the plantar locations, especially for P1 to P7, there were only very small differences between the male and female vibration threshold values. The plantar region of the foot is especially important for placement recognition of the foot and should therefore be of equal importance for both women and men. However, at all dorsal locations the men show considerably higher vibration detection threshold values.

The least sensitive touch regions are the heel (P1), followed by the most proximal site on the foot dorsum (D1), the medial and lateral malleoli (M1, L1), and the Achilles tendon (A1). The medial longitudinal arch location (P2) and the plantar (P8, P9, P10) as well as the dorsal (D8, D9, D10) toe regions showed the best sensitivities for touch. Nurse and Nigg,[13] measuring the plantar foot at five different locations, also reported that the heel was the least sensitive site for touch stimuli, whereas under the

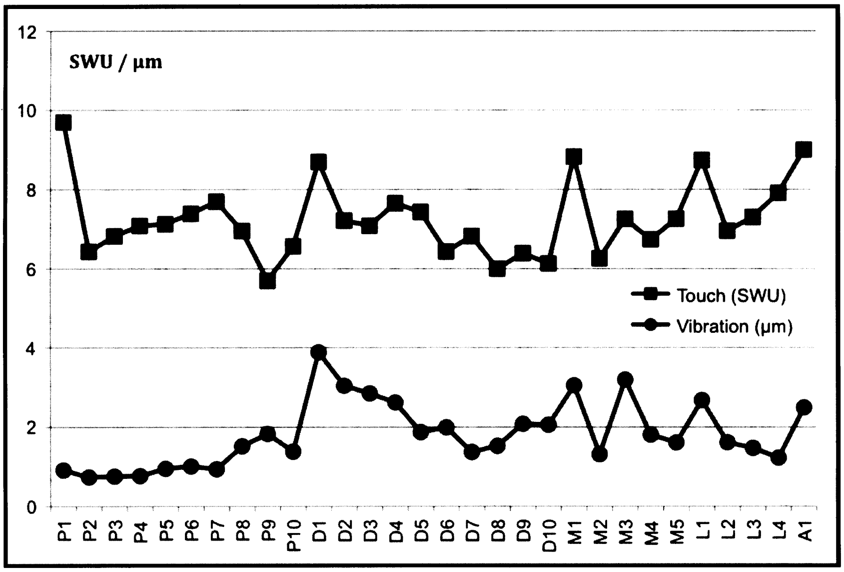

Fig. 4: Comparison of touch sensitivity in Semmes Weinstein Units and vibration sensitivity in μm for 23 subjects.

medial longitudinal arch best sensitivity was found. The high touch detection threshold under the heel appears surprising, because the heel is an important structure of the foot to recognize disturbances at initial foot contact. Indeed, our vibration threshold results (Figure 3) show that the most sensitive sites for the recognition of vibration are the heel and medial midfoot area below the longitudinal arch (P1, P2, P3). Recognition of the initial foot strike may be more suited to the fast adapting mechanoreceptors that would be particularly sensitive to sudden skin displacement changes. This is supported by data from Kennedy and Inglis[7] who reported a lower density of the slowly adapting SA I as compared to the fast adapting FA I mechanoreceptors in the heel region. The vibration sensitivities (Figure 3) of all plantar locations, except for the toes, did show the lowest threshold values. These are the structures that are needed for recognition of foot placement throughout the contact phase on the ground. Unevenness of the ground and unexpected slips can be detected by fast adapting mechanoreceptors of the skin and will serve as a feedback mechanism for balance maintenance and/or recovery. Kennedy and Inglis[7] reported that 70 % of the mechanoreceptors under the foot belong to the fast adapting types. The recognition of sudden load and displacement changes under the foot seem to play a major role in neuromotor adjustment and learning.

When combining the touch and vibration results of the present study with data from the literature, it appears that vibration threshold sensitivity and thus the function of the fast adapting mechanoreceptors is important in assisting balance control and movement adjustment during human locomotion. The importance of the plantar region for the neuromotor adaptation of human gait may also be derived from the fact that there is no gender effect in this area of the foot. Men and women are equally dependent on this feedback information from the periphery. From the vibration sensitivity results, it appears that those structures which provide the least mechanoreceptor information about foot placement during ground contact, show the lowest sensitivities. These are the medial and lateral malleolus (M1, L1), the dorsal area above the ankle (D1), and the Achilles tendon (A1). When wearing shoes, even the dorsal skin receptors provide useful information about foot position and behavior during ground contact.

Interestingly, the toe regions P8, P9, and P10 are less sensitive for vibration but are more sensitive for touch stimuli compared to the remaining plantar sites. For most locomotor activities, the grip function of the toes is not very important for balance control because the foot is already leaving the ground when the toes come into action. The better touch sensitivity of the toes perhaps remains from when our ancestors still used their feet and toes for grasping and handling activities. The least important sites for sensory feedback during ground contact D1, M1, L1, A1 show the highest threshold values for the touch as well as vibrotactile stimuli. These anatomical locations have little functional importance for foot placement recognition.

A translation of the above findings into recommendations for footwear design and clinical applications is speculative and needs confirmation by future studies. Nevertheless, knowing the more and less sensitive skin sites around the foot, shoe comfort may benefit from extra padding at very sensitive sites of the foot. For some sports, a reduction in shoe weight improves performance. Therefore, less shoe material for foot bedding could be used in foot areas that show reduced skin sensitivity. On the clinical side, studies have shown[16,9] that footwear design can have a positive influence on dynamic balance control and may be used for decreasing the risk of falls for the elderly. The idea behind these shoe designs is an attempt to provide additional sensory feedback by an increase in mechanical stimulation of the skin during contact of the foot with the ground. Based on a sensitivity map of the foot, a more systematic footwear modification approach could be chosen to provide additional peripheral sensory feedback to the brain for better balance control during standing and locomotion.

CONCLUSION

Large sensitivity differences were found at different sites of the foot surface. Especially at the dorsal aspect of the foot women have lower vibration sensitivity thresholds. Age did not have an influence on vibration or touch sensitivities in our age group from 20 to 35 years. Compared to the dorsal foot, the plantar foot is substantially more sensitive, especially for vibration detection. The function of the plantar cutaneous mechanoreceptors seems to be particularly important in assisting balance control during human locomotion. The sensitivity map of the foot will help to understand the function of the foot as a sensory organ. It can also be useful in creating footwear for better balance control or for the design of comfortable shoes.

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