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Presentation of plantar tactile illusions to the midfoot and hindfoot through vibratory stimulation of the dorsal foot and tarsal tunnel

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***Abstract*— In this study, we induced illusory tactile feedback in the midfoot and hindfoot by applying vibratory stimulation to three specific sites: the navicular tuberosity, the fifth metatarsal tuberosity, and the tarsal tunnel. While illusions were successfully elicited at the navicular and fifth metatarsal sites, the responses from the tarsal tunnel varied considerably, thereby necessitating individualized calibration.**

I. Introduction

Recent advances in virtual reality technology have given rise to an increased interest in methods that enhance user immersion by providing haptic feedback in response to body movements. The plantar surface has attracted particular attention among the various stimulation sites, as tactile information from the sole is essential for perceiving ground surfaces and maintaining postural stability [1]. Haptic feedback applied to the sole holds significant promise for diverse applications, including enhancing immersion in VR environments, simulating the sensation of walking while seated, and supporting older adults who experience age-related declines in plantar tactile sensitivity that affect balance. The majority of plantar tactile feedback systems depend on the direct vibration of the sole via platforms embedded in the floor or actuators embedded in insoles. However, floor-mounted devices are bulky, while insole actuators dampen natural ground cues and may increase the risk of falling. Consequently, a method that preserves authentic ground contact without restricting mobility is highly desirable.

In order to address these challenges, a novel method of eliciting illusory tactile feedback on the plantar surface without direct stimulation has been explored (Fig. 1). This technique facilitates the introduction of novel tactile experiences without disrupting the perception of actual ground textures. In our previous work, we confirmed that illusory sensations on the sole can be elicited by applying vibratory stimuli to the toenail or to the dorsal aspects of the first and fifth metatarsal heads [2][3]. Furthermore, evidence was provided that combining these stimuli produces a wide-range illusory tactile presentation across the forefoot region [3]. However, during actual locomotion, the midfoot and rearfoot regions also come into contact with the ground, thereby contributing to overall tactile perception. Consequently, a focus exclusively on the forefoot is inadequate for achieving comprehensive tactile augmentation. The present study aims to extend the spatial range of illusory tactile feedback on the plantar surface by investigating whether such sensations can also be evoked in the midfoot and rearfoot regions. This paper reports on our efforts to identify effective stimulation sites and determine optimal vibration intensity conditions for eliciting illusory tactile feedback in these new target areas.

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II. Experiment

In this experiment, we aimed to extend the range of the illusory tactile sensation by administering vibratory stimulation to several regions of the midfoot and hindfoot where the induction of such an illusion on the sole was anticipated, and we evaluated the probability of its occurrence.

A. Vibration stimulation sites

In the present experiment, several candidate stimulations were selected based on the distribution of sensory receptors across the plantar surface, the nerves extending to the sole, and the potential for vibration transmission via bone conduction. Preliminary experiments verified that three locations (the tuberosity of the navicular, the tuberosity of the fifth metatarsal, and the tarsal tunnel) were identified as the vibration positions to be employed in this study (Fig. 2).

B. Setups

A vibrator (Nidec, LD14-002) and an audio amplifier (Adafruit, Stereo 3.7W Class D Audio Amplifier – MAX98306), controlled by a microcontroller (Espressif Systems: ESP32), delivered a 150 Hz rectangular-wave stimulus to the foot dorsum (Fig.3(a)(b)).

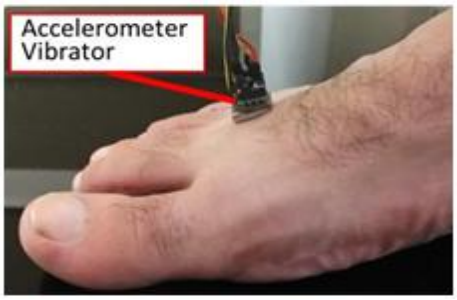


Figure 1. Presentation of plantar tactile illusion

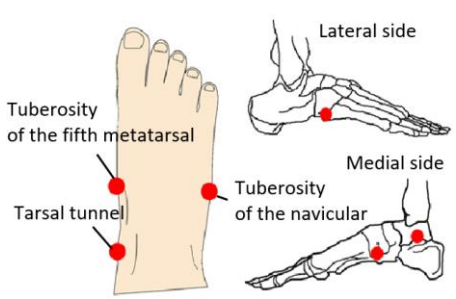


Figure 2. Vibration stimulation sites

C. Method

In the present investigation, vibratory stimuli with a range of intensities from 1.5 G (14.7 m/s²) to 3.0 G (29.4 m/s²) in 0.5 G (4.9 m/s²) increments were applied to each of the stimulation sites previously described in 10 male participants (mean age ± SD: 22.1 ± 0.3,). The probability of eliciting an illusory plantar tactile sensation was then assessed. The intensity range was selected based on the perceptual thresholds identified in the preliminary experiment. At each intensity level, twenty trials were conducted with vibration conditions randomly sampled from the defined set. The total number of trials was thus eighty, and the occurrence probability of the illusion was calculated from these data. The experimental procedure is shown below.

i) With the participant standing, a vibrator was attached to the designated stimulation site (Fig.3(b)). Subsequently, participants donned headphones and an eye mask to eliminate auditory and visual cues, respectively, while continuous white noise was played through the headphones.

ii) Vibrations were presented for 7 seconds. During each presentation, participants continuously adjusted their plantar load to distribute pressure evenly across the sole.

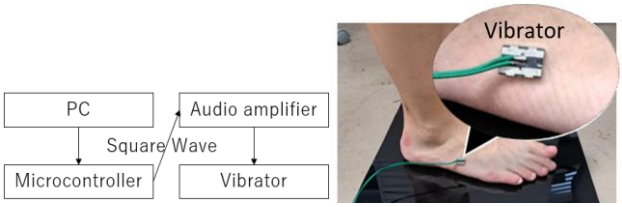
iii) Immediately after the vibration ceased, participants reported whether they had perceived it on the sole of the foot.

Steps ii) and iii) were then repeated. After 40 trials, a three-minute interval was observed. Thereafter, stimulation was applied to the next site.

D. Result

The elicitation probabilities of illusory plantar tactile sensations at each stimulation site are shown (Fig. 4). The horizontal axis represents vibration intensity, and the vertical axis represents elicitation probability. In the navicular-tuberosity region, the probability peaked at 85.0 % at 2.0 and 3.0 G. In the fifth-metatarsal-tuberosity region, the probability reached 87.5 % at 2.0 G. In the tarsal-tunnel region, the elicitation rate was 77.5 % at 3.0 G, but marked inter-subject variability was observed. Participants who showed high elicitation rates maintained those high rates across all vibration intensities, whereas those with low elicitation rates remained low regardless of intensity.

Moreover, individual analyses revealed that the elicitation intensity of each participant exhibited a distinct pattern of variation. Some participants showed a monotonic increase in intensity with increasing stimulation, while others showed a decline once the intensity surpassed their optimal level.



(a) (b)

Figure 3. Apparatus Setup(a), Mounting of the vibrator (b)

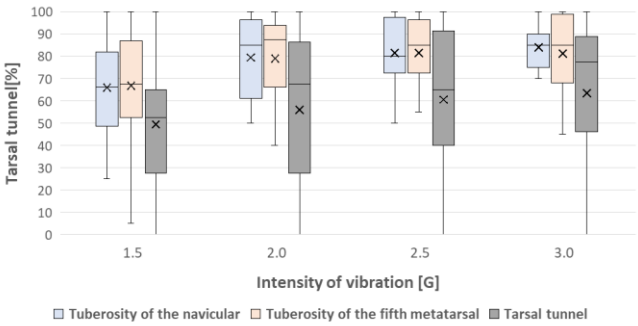


Figure 4. Probability of inducing a tactile illusion on the sole of the foot

III. Discussion

The navicular and fifth metatarsal tuberosities yielded consistent tactile illusions at vibration intensities of 2.0 G and above, exceeding the 75 % threshold cited in prior studies [3][4]. However, optimal intensity varies across individuals. Strong dorsal perception may mask plantar illusions, suggesting that individual calibration is key to effective feedback.

While the tarsal tunnel showed promise for some participants, results were highly individual. This may be due to imprecise stimulation positioning. Follow-up trials, in which the stimulation site was adjusted between the medial malleolus and the heel, resulted in the induction of a successful illusion in one participant. Consequently, Precise targeting and participant-specific mapping may be necessary for this site.

IV. Conclusion

We investigated new stimulation sites to extend illusory tactile feedback to midfoot and rearfoot. Vibratory stimulation to the navicular and fifth metatarsal tuberosities successfully evoked plantar illusions. The tarsal tunnel showed high individual variability, requiring further study. Personalized intensity calibration was shown to enhance effectiveness. Future work will examine load conditions and illusory tactile sensations during walking. We will also explore multi-point stimulation to induce phantom sensations or apparent motion.

References

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