Investigation of Sensitivity of Foot Soles to Vibrational Stimuli: First Results for Developers of Information Interfaces

Stefan Lutherdt(✉), Eva Kaiser, Tim Kirchhofer, Philipp Wegerich, and Hartmut Witte

Technische Universität Ilmenau, Ehrenbergstr 29, 98693 Ilmenau, Germany
stefan.lutherdt@tu-ilmenau.de

Abstract. This paper gives the first results of basic researches to identify parameters and requirements for the development of a vibrational interface in shoe soles. This interface is an integral part of a system to support orientation and navigation of elderly in new and/or unfamiliar environments. To meet the requirements of the later users it is necessary to know the restrictions, basics and needs of this new technology. For these analyses a test bench was developed to examine the sensitivity of the user's foot sole to vibrational stimuli, and to determine the amount of information which could be transmitted. Another result of first test runs is the possibility to decrease the number of vibrational actuators beneath the foot sole.

Keywords: Foot sole · Vibro-tactile stimuli · Mechanoreceptors · Vibrational interface for orientation · Elderly

1 Motivation

The change in the demographical pyramid is one reason for the increasing number of age caused diseases. Therefore it is reasonable to develop new devices to help the elderly to obtain quality of life and independence.

In the last years researches more and more focused on vibro-tactile stimulation, especially in the field of interface design. Throughout the years more improvements were achieved due to different studies on the devices used, the target group and the application area on the human body. Initially, the actuators were embedded in a belt [1, 2]. This stimulation zone provides a large contact area with the actuator, and consecutively the capability to realize a high information load. Due to the density of receptors this solution delivers a usable device for many target groups, but not for elderly people.

Another area for the application of vibro-tactile stimuli has been considered to be helpful, the foot sole. In the study of [3] a vibro-tactile prototype shoe was designed for examination of navigational skills, only with the aid of those stimuli. The addressed group described in [3] mainly were blind people. The LECHAL shoe (shown in Fig. 1 [4]), a commercial solution for navigation by vibrational stimulation, was also first dedicated to blind people, now it can be used for sports and wellness, for tracking activities and vital parameters.

J. Zhou and G. Salvendy (Eds.): ITAP 2015, Part II, LNCS 9194, pp. 290–299, 2015.
DOI: 10.1007/978-3-319-20913-5_27

Fig. 1. LECHAL (Hindi for "bring me home"), left: version as a whole shoe with integrated vibration sole; right: sole-only version to integrate vibration stimuli into any kind of shoe [4].

The present study concentrates on the interface in the foot sole. The main reason is the familiarity with the device. For the target group of elderly people, who may have a starting memory disorder, it is important to use a device which they are already familiar to, and which is used on a daily basis. To realize the given requirements the implementation of the interface in a shoe sole was the best option to ensure the usage for elderly people. To realize a user fitted device it is necessary to research the basics.

The aim of the study was the fundamental research concerning the vibro-tactile sensibility of the foot sole in loaded condition and the possible transmittable information for an user fitted device.

2 Propaedeutics

The human skin is not only the largest organ but also the largest sensory system of the human body. It integrates four different senses with the responsible receptors: thermal perception (heat and cold) are sensed by thermoreceptors; perception of pain (nociceptors), and mechanoreceptors, sensitive for mechanical stimuli (necessary for haptic and tactile perception). Tactile perception mainly is aroused by vibration and/or pressure and shear forces. Haptic perception beyond that always has an active component and additionally uses kinesthetic receptors (proprioceptors) in muscle fibers and tendons (e. g. Golgi tendon organ).

As vibrational stimulation is a mechanical stimulation we focus on the mechanoreceptors embedded in the skin, valuable for tactile perception. There are four types of mechanoreceptors, each has its own anatomical structure and physiological function. They are classified in two categories. The first is their adaptivity to the stimulus, the second is the size of the receptive field [3, 6–8].

The receptors are fast or slow adapting. The fast adapting receptors are sensitive for texture and vibration, and the slow ones for dynamic pressure. The size of the receptive field is defined as that skin area which is allocated to one receptor. There are two types of mechanoreceptors with different receptive fields called type I and II. Receptors of type I are small and have defined boundaries, while type-II receptors have large receptive areas with diffuse boundaries. In summary four types of mechanoreceptors can be found: fast adapting I (FA I), fast adapting II (FA II), slow adapting I (SA I), slow adapting II (SA II). The FA I and FA II receptors are sensitive for vibration within different frequency ranges. FA I are mainly aroused between 10 Hz and 100 Hz, while the FA II mechanoreceptors are most sensitive in the range of 100 Hz–300 Hz [7, 8].

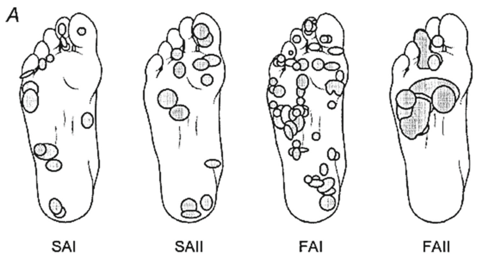

Fig. 2. Position of the receptive fields of the four different receptors on human foot sole [6]

Figure 2 shows, that there is no exact border between the main zones of different types of mechanoreceptors at the foot sole, which makes it difficult to define a receptive field for an exclusive stimulus. In conclusion there always more than one type of receptor is aroused by a given stimulus, and it is difficult to directly arouse a specific receptive field.

To develop an interface which gives adequate stimuli to the foot sole it is necessary to know the range of frequencies as well as the allocation of receptors in the foot sole skin. The following tests focus to provide corresponding data.

3 Design of Experiment

In dependence on anatomical and physiological conditions we used a flexible design of vibro-tactile actuators shown in Fig. 3. The four vibro-tactile actuators used in the study can be arranged in order to anatomical varieties of the volunteers (foot length and width). Additionally they are aligned in those areas which are in ground contact during rolling motion of the foot. The actuators can stimulate the mechanoreceptors in the range between 100 Hz and 225 Hz, because the addressed receptors are of FA II type.

3.1 Design of the Test Bench

The test bench (shown in Fig. 4) is a base body made from alloy with 14 holes for the embedding of the actuators, so the foot is placed plantar on the base body of test bench. It is possible to adapt the test bench for each foot size from 36 to 45 (European Sizes) by switching of alloy distance plates. A back stopper ensures that each subject takes the same and adequate position above the actuators.

The control of the actuators has been realized via USB-6008 from National Instruments®, and by LabView®. The current work bench is controlled by an Arduino Mega™ and an electronic conductor board with drivers for each actuator. The controller gets its program from a PC-based software with internal database via I^2C bus.

The vibration actuators used are eccentric rotating mass (ERM) motors in coin format (pancake motors Pico Vibe 10 mm) from Precision Microdrives™ [9]. The working range is given by the performance characteristics according to Fig. 5.

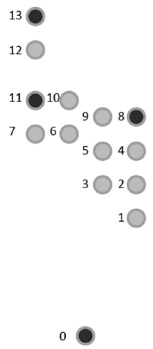

Fig. 3. Schematic array of the 14 actuator positions with the four actuators used marked in black.

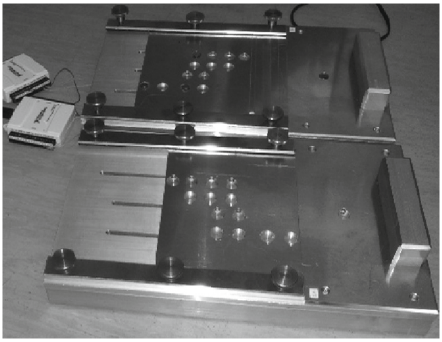

Fig. 4. Test bench with four actuators on right foot, two NI USB-6008 for each side; left side has no foot size adaptation (that means size 36), right sight is adapted for size 40.5

To validate these characteristics we also determined the real vibration frequencies by a measurement of the resulting noise, and a following frequency analysis. The main spectral part in FFT was the vibration frequency of the motors evoked by the rotating mass.

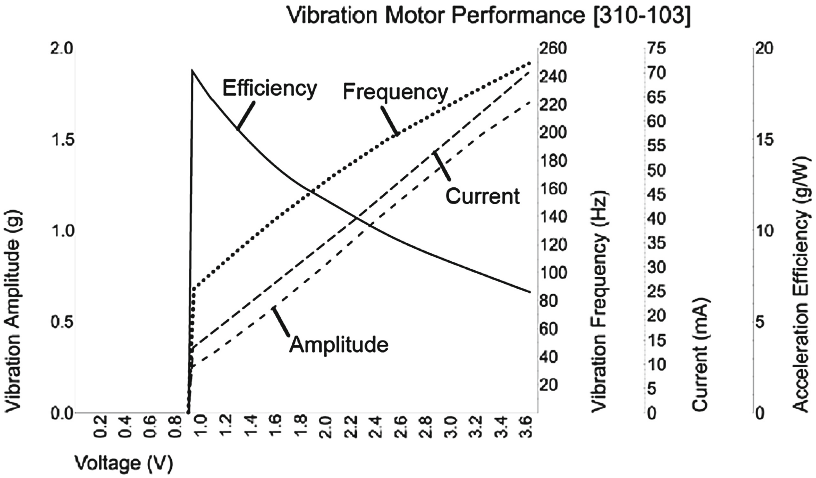

Fig. 5. Performance characteristics of the used ERM coin motors (own image after [9])

For a better control of the test bench and also a better administration of the later experiments a software program with a graphical user interface (GUI) shown in Fig. 6 was developed and tested. With this program it is possible to change all the parameters of each actuator, to combine them to sequences and save this combination for later experiments. If a special set-up of parameters already exists the user will give a hint. By that it is possible to execute a broad variety of tests within a short time.

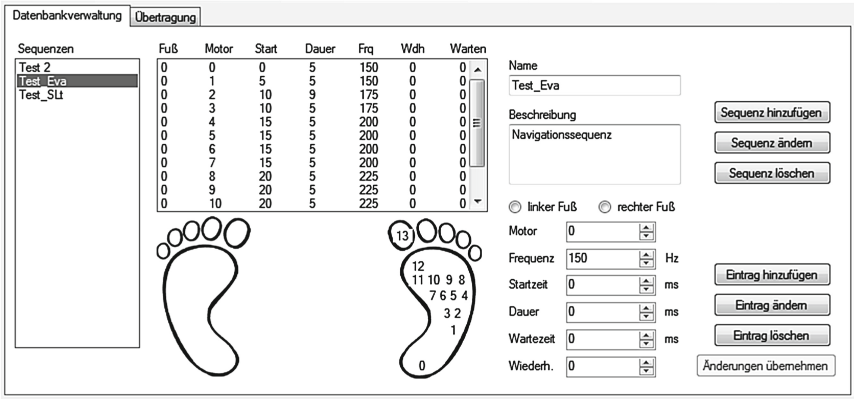

Fig. 6. Screenshot of GUI of software to control the test bench

Pretests had shown that actuators placed directly next to another had a poor spatial resolution, so we reduced the number of actuators in the final tests to only four. These four actuators used were placed, as shown in Figs. 3 and 4, beneath the *Hallux* (pos. 13), right and left side of the ball (pos. 8 and 11) and under the heel (pos. 0).

3.2 Participants

To prevent results from other effects all test persons had to use thin socks which do not damp vibrational stimuli. In all tests only the right foot was stimulated. No information about handedness was surveyed, but in references no information about any correlation between handedness and sensitivity is given.

The psychophysical experiments were participated by 25 volunteer students, 10 females and 15 males with an average age of 23.8 years. The group was chosen with some criteria. Inclusion: the availability at the university, age between 20 years to 30 years; exclusion: no known neuropathic diseases or diabetes. Also subjects with very hard skin on foot soles were excluded from the experiments.

We chose that small variability within the group to eliminate varieties in anatomy and physiology or aging factors, which could possibly cover the results. To ensure the requested criteria each participant had to complete a form which retrieved the necessary information.

3.3 Sensitivity Tests

With regard to the development of the information interface it was primarily important to get a better knowledge of the spatial resolution of the sensitivity of vibro-tactile stimulation of the foot sole. Therefor three experimental tests were designed and performed. All data underlay tests of normal distribution (Kolmogorov-Smirnoff-test) and tests of significance (Student's t-test) performed.

Experiment 1. The purpose of this first test was to examine the spatial resolution of the foot sole. One actuator stimulated the corresponding receptive field at a frequency of 150 Hz. The participant had to recognize at which position the mechanoreceptors were arousen.

To apply the stimulation the test person had to place both feet on the test bench, so its weight was equally applied at both feet. After its verbal answer another motor was started, while the first shut down. The experiment was repeated three times for each actuator. The main questions to be answered through this experiment were, if there are differences between males and females, and how do the volunteers feel the arousal at their foot soles. The focus of interest here is, if they are able to differentiate the diverse stimuli (spatial and time discrimination).

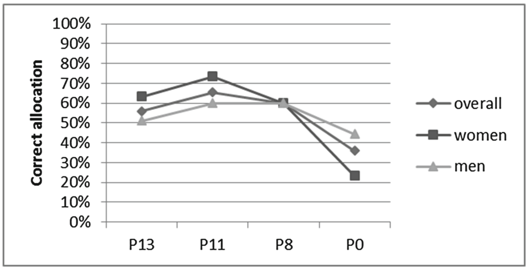

Fig. 7. Comparison of correct identification of given stimuli beneath the foot sole (male – female, different points of stimulation, cf. Fig. 6).

Results. There was no significant difference between men and women. But the results show, that the rate of identification at the heel was significantly worse than the rate of the other three points (see Fig. 7, P0 and Fig. 8). A probable explanation might be the thickness of the callus at the heel, which has influence on the stiffness of the skin and changes the modulus of elasticity. This influences the perception of the pressure to lower degrees and consequently the stimulation of the mechanoreceptors. In addition the stimulated FA II receptors have barely any receptive field on the heel (see Fig. 2), so the sensitivity for frequencies in the chosen range may be lower compared to those on the forefoot.

The results of differences between left and right side of foot are not comparable to other studies. This might be eliminated by further tests with a larger amount of probands, the current results not explainable at this time.

Experiment 2. As a second test only one actuator was focused on in each trial. Whether the one at Position 1, Position 2 or Position 4. Position 3 was negligible because of the rather similarity with Position 2. The aim in this experimental set was to

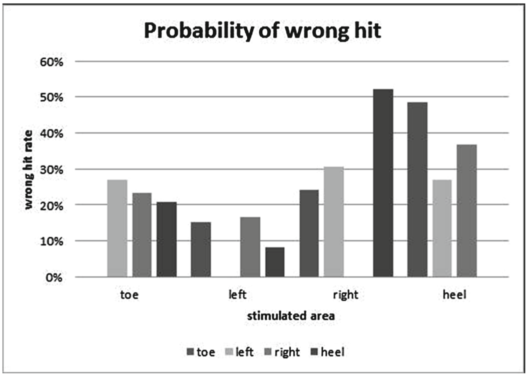

Fig. 8. Observed frequency of wrong recognition at different areas of foot sole

analyze if the subjective perception of different frequencies matches the law of Weber/Fechner and Stevens (and of course matches the readings in literature).

Two frequencies, one after the other, were applied to the actuators. The participant gave a verbal response which of the two compared frequencies is, subjectively, the more intensive vibration. The distance between the frequency steps were 25 Hz, 50 Hz and 75 Hz. The frequency range was between 100 Hz and 225 Hz. The order in which the different frequencies appeared was subject of the random principle.

Results. Step 25 Hz: At the frequencies of 150 Hz, 175 Hz and 225 Hz the sensitivity from the lower to the higher frequency was better than the difference up to down, but significant differences only occured at 150 Hz (see Fig. 9).

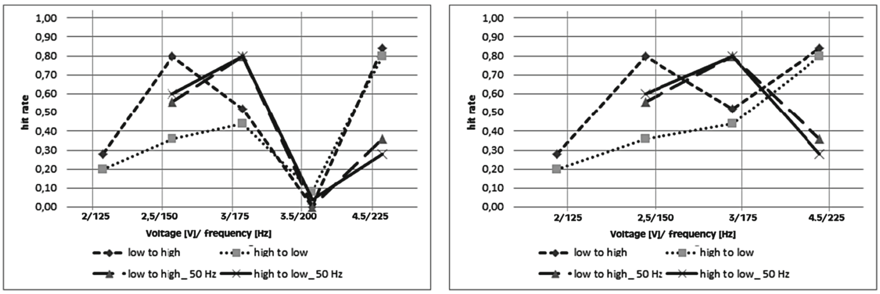

Fig. 9. Test results of experiment 2 (alteration of frequencies upwards and downwards)

Step 50 Hz: Within the test set the results were similar, but the hit rate at a frequency of 225 Hz was not as good as it was by the step size of 25 Hz. The first test set compared the sensitivity at 200 Hz with the sensitivity at 225 Hz. Because of the poor recognition of the lower frequency it was easier to feel the difference in the second test set. Within the second set the compared frequencies were 175 Hz and 225 Hz.

Both showed in the first set a similar recognition rate, so it is more difficult to distinguish between these two frequencies.

The results for a frequency of 200 Hz (3.5 V) were significantly “worse” than the other results (level of significance: $\alpha = 0.05$). This single effect does not match with the expected result, and also with results in other references, in which the maximum of sensitivity reported is at 200 Hz. Thus the right diagram in was drawn without data at 3.5 V ($\triangleq$200 Hz).

Probably this is a summation of several physiological effects. One of these might be the pressure on the foot the participant felt in this study (provoked by own weight), which surely changes the sensitivity, due to the pre-stress of the arches of the foot and the exciting effect on other receptors.

The participants also claimed that the surface of the device used was very (to) cold. With a change of the temperature, a change of the sensitivity threshold goes along. The sensitivity of mechanoreceptors is closely coupled with the ambient temperature. If the temperature decreases, also the sensitivity decreases but the threshold of sensitivity grows [5].

Step 75 Hz: In the last test set the effects were similar to those described in the first two step sizes. Most evident is again the loss of sensitivity at a frequency of 200 Hz.

Experiment 3. The last test was supposed to examine the relation between spatial resolution capacity and the changing of frequencies on the foot sole. Therefore the three most outstanding frequencies in the pretests were used (100 Hz, 150 Hz and 200 Hz). Two actuators were applied at the same time with the same frequency and had to be differed. Similarly to the other experiments the participants’ feedback was verbal.

Results. As shown in Fig. 2 the actuator at Position 13 (P13) in combination with the one at Position 11 (P11) had the best spatial resolution capacity, as well as the combination of P13 and P8 where the results were only a little worse. The combination of P11 or P8 with P0 resulted in poor values. A possible explanation can be the lack of FA II receptors at the heel or a combination of multiple effects which provoked a crosstalk of mechanoreceptors and as a result of this the sensitivity decreased. The combination of P13 and P0 showed comparatively bad results. As in test run 1, in the individual tests a transmission occurred from the heel to the toe, this also might explain the outcome. The thicker epidermis causes a stronger attenuation. This results in a superposition of various effects, which may be an explanation for the decline of the hit rate. As mentioned before, also the temperature and the irritation of the other receptors could be the reason for these effects. Another point mentioned by the participants was the unpleasant and uncomfortable kind of standing on the device for the duration of the experiments.

4 Conclusion and Outlook

The results provided give an overview of the basic research on the sensitivity of foot soles to a vibrational stimulation. A second experimental pass is currently processed with varied parameter sets. The load on the foot sole is minimized to that the foot sole only comes in contact with the test bench surface (and actuators), so the resolution capability might increase because of the reduced or totally missing pre-stress of the foot sole.

Furthermore, the duration of one test set is shortened to the minimum length possible, and the cold metal plate is covered by a thermal isolating felt mat to avoid an influence of the temperature on the receptors in the foot sole.

To gain the necessary information for elderly people a third test set starts with the participation of people in the age between 70 years and 80 years with none or slight memory disorder. With this group of respondents we will also perform tests to determine the amount of information which can be transferred by the vibrational interface.

Pretests had shown that actuators placed directly next to each other had a poor spatial resolution capacity, so consequently the placement of two actuators will be used to increase the intensity of the stimulus. The number of motors can be reduced to at least ten (five at each side) vibrational actuators. The frequency range chosen showed results and effects which need to be evaluated. The difference between hit rate of men and women was also investigated, but a significant disparity could not be proven and won't be considered in further experiments (level of significance: $\alpha = 0.05$).

Another result of these first tests is that it is not possible to give vibrational stimuli during stand phase (not exceeding then unspecific vibrations for warning), so an intermediate change of vibrational stimuli from left to right side and back has to be realized. The foot contact can be detected with pressure sensors in the shoe soles, and the available time for information delivery can be calculated as a function to gait velocity (time of rolling motion of one foot is given by different references via gait diagrams).

The foot sole provides a good alternative for a stimulation area for the transmission of information on the human body. Because of various limitations e.g. the small useable space on the foot sole (and inside of shoes), or the decrease of sensibility during aging process, the design of a useful device for elderly people is still a great challenge.

Acknowledgement. This study was supported by the German Government with grant of Federal Ministry of Education and Research. The grant was given from funding program IKT 2020 ("Technologies adapting to people – innovative interfaces between human beings and technological systems").

References

1. Ho, C., Tan, H.Z., Spence, C.: Using spatial vibrotactile cues to direct visual attention in driving scenes (2008). http://www.soft.uni-linz.ac.at/Teaching/_2008SS/SeminarPervasiveComputingVibrotactile/Begleitmaterial/Related%20Work/2005_Using%20spatial%20vibrotactile%20cues%20to%20direct%20visual%20attention%20in%20driving%20scenes_HoTan.pdf. Accessed June 2014
2. van Erp, Jan B.F., van Veen, Hendrik A.H.C., Jansen, C., Dobbins, T.: Waypoint navigation with a vibrotactile waist belt. ACM Trans. Appl. Percept. **2**(2), 106–117 (2005)

3. Velazquez, R., Bazan, O., Magana, M.: A shoe-integrated tactile display for directional navigation, S. 1235–1240
4. LECHAL, Ducere Technologies, Telangana, India. http://lechal.com/shoe-design.html. Accessed January 2015
5. Schlee, G.: Der Einfluss der Temperatur der Fußsohle, des Blutflusses im Fußbereich und des Schuhwerks auf die plantare Fußsensibilität (2010)
6. Kennedy, P.M., Inglis, J.T.: Distribution and behaviour of glabrous cutaneous receptors in the human foot sole. J. Physiol. (Lond.) **538**(Pt 3), 995–1002 (2002)
7. Johannson, R.S., Valbo, A.B.: Tactile sensory coding in the glaborous skin of the human hand. In: Elsevier Biomedical Press, January 1983
8. Gekle, M.: Taschenlehrbuch Physiologie. 70 Tabellen. Stuttgart: Thieme (2010)
9. Preciscion Microdrives Limited (London, UK). http://catalog.precisionmicrodrives.com/order-parts/product/310-103-10mm-vibration-motor-3mm-type. Accessed January 2015