Insights into the Capabilities of Tactile-Foot Perception

Regular Paper

Ramiro Velázquez¹*, Omar Bazán¹, Jorge Varona¹, Carlos Delgado-Mata¹ and Carlos A. Gutiérrez¹

1 Mecatrónica y Control de Sistemas (MCS), Universidad Panamericana, Aguascalientes, Mexico
* Corresponding author E-mail: rvelazquez@up.edu.mx

Received 04 May 2012; Accepted 23 Aug 2012

© 2012 Velázquez et al.; licensee InTech. This is an open access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/3.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Abstract This paper presents a novel wearable interface for the foot: a shoe-integrated tactile display that enables users to obtain information through the sense of touch via their feet. A 16-point array of actuators stimulates the sole of the foot by inducing different vibration frequencies. A series of experiments were conducted with 20 sighted and 5 blind voluntary subjects to evaluate the role of tactile perception by the human foot and the tactile sensitivity of the plantar surface. Tests evaluated the perception of simple shapes, patterns and directional instructions. The results showed that some information is discriminable and that tactile-foot stimulation could be used for a wide number of applications in human-machine interaction. Furthermore, the results also suggested that the blind perform better in some key tasks and support the feasibility of footwear providing tactile feedback for situational awareness, mobility and the navigation assistance of the blind.

Keywords Assistive device, foot stimulation, on-shoe device, tactile display, vibrotactile interface

1. Introduction

Over the last decade, tactile feedback has received growing attention in several domains, such as virtual reality, sensory augmentation, sensory substitution, robotics, games and entertainment, among many others. This is attributable to the fact that touch is the chosen modality to convey information when sight and hearing are restricted or overloaded.

Much of what is found in the literature about tactile feedback concerns tactile stimulation of the fingers and hands. However, as the area of tactile feedback is a “hot” research topic in assistive robotics and complex multitasking environments, other body areas have been explored as well: the wrist/forearm [1], abdomen [2], chest [3], tongue [4], ears [5], head [6], and even the backside [7] have been studied to transmit information to a user.

The devices are as diverse as the technology used and the location on the body. However, the human foot has not received much attention.

What we know about the human foot is that it combines mechanical complexity and structural strength. The ankle
serves as a foundation, a shock absorber and a propulsion engine. The foot can sustain enormous pressure and provides flexibility and resilience. Apart from being a functional structure, the cutaneous receptors of the foot’s sole continuously provide feedback information to assist in balance and walking. The skin receptors in the sole are sensitive to contact pressures [8] and changes in the distribution of pressure [9]. As the load on the foot is transferred from heel to toe, pressure signals are automatically fed back to the brain to provide important information about the body’s position with respect to the supporting surface.

While several researchers [10-12] illustrate the importance of cutaneous receptors in the control of posture and standing balance, only limited work has focused on evaluating the performance of the foot’s sole receptors for tactile communication.

This paper presents a versatile, wearable human-computer interface for the foot: we have developed a shoe-integrated vibrotactile display to study how people understand information through their feet and to evaluate whether or not this comprehension level is sufficient to be exploited for human-computer interaction.

Potential applications include virtual reality, robotics, rehabilitation, games and entertainment, among many others. One of the most challenging applications is perhaps the assistance of the blind/visually impaired. Over the last four decades, a large number of electronic travel aids (ETAs) have been proposed to improve the mobility, safe navigation and independence of the blind. However, none of these devices are widely used and user acceptance is quite low. Several shortcomings have been identified in existing ETAs as the main reasons for this degree of rejection (a comprehensive survey, evaluation and synthesis of ETAs can be found in [13]). One of these reasons is that most ETAs are still too burdensome and visually noticeable as portable devices. Undoubtedly, this heightens the handicapped image and affects the user’s self-esteem. Unlike other portable/wearable assistive devices, an on-shoe, inconspicuous and visually unnoticeable ETA for blind people might represent a step forward in solving this problem.

The rest of the paper is organized as follows: Section 2 presents background information on tactile communication with the feet. Section 3 presents a brief review of human tactile-foot physiology and the requirements for a tactile-foot stimulating device. Section 4 introduces the shoe-integrated tactile display design concept and provides an overview of the implementation of a first prototype. Section 5 evaluates its performance with information transmission through a set of tactile perception experiments performed on a group of 20 sighted and 5 blind voluntary subjects. Finally, Section 6 concludes with main remarks and perspectives on future work.

2. Background

Tactile paving or tactile ground indicators are, with no doubt, the most representative example of tactile communication with the feet. They were first introduced in Japan in 1967 and, while international standards remain to be established, some national ones are already in use [14-16].

Tactile ground indicators consist of regularly textured ground areas in the form of patterns of raised domes, bars, or bumps. Their purpose is to provide a tactile surface that can be felt underfoot and recognized by pedestrians as a warning. They are widely used in stairways, ramps, escalators, road crossings and subway/railway platforms, etc.

Information transmitted by tactile ground indicators to the blind has two main purposes:

- To alert as to hazards in the immediate location or in the direction in which the individual is heading (Fig. 1(a)).
- To indicate a safe direction of travel (Fig. 1(b)).

Tactile ground indicators are of great help for both distracted sighted and blind pedestrians. However, their main inconvenience is that they simply cannot be installed everywhere.

More examples of tactile-foot stimulation can be found nowadays in certain user control interfaces, especially for machine operation: car pedals, dental equipment, fitness gear, music instruments, etc. They provide very simple, vibrating cues as alerts about well-defined machine situations.

The literature addressing electronic interfaces for presenting tactile information to the feet and their formal evaluation is quite limited. It seems that interest only began in 2006 when Rover and van Hessen found that users were able to identify several families of haptic icons through vibrations presented to the foot’s sole [17].

In 2008, three works addressed tactile communication with the feet: Kobayashi et al. investigated the feasibility of using the vibrations of an elastic material to simulate tactile ground indicators [18]. Law et al. proposed the use of vibrotactile information underfoot for increased immersion during locomotion in virtual environments [19]. Our own work presented the design of an on-shoe vibrotactile display prototype for navigation assistance of the blind [20].
Type I cells have small well-defined receptive areas and are sensitive to low frequencies (5-40 Hz). Type II cells have large hard-to-bound receptive areas and are sensitive to high frequencies (100-300 Hz). Therefore, four types of mechanoreceptors can be found: slow adapting type I (SAI), slow adapting type II (SAII), fast adapting type I (FAI), and fast adapting type II (FAII).

Fig. 2 shows the position of these receptors and their receptive fields in the plantar surface of the foot while Table 1 summarizes their profile, particularly their number, field size and triggering force. Note that there might be receptive fields common to several kinds of receptors. For example, in the medium part of the foot’s sole, FAI and FAII cells share receptive fields. Thus, a receptive field may not be exclusive to a particular function or stimuli.

Note that FAI cells constitute the majority by far and, as already mentioned, they are sensitive to vibrations. It seems then that stimulation of FAI mechanoreceptors is more suitable for information transmission to the foot.

Guidelines for the choice of actuator also involve spatial discrimination and the delivered force.

Concerning spatial discrimination, it can be seen from Table 1 that the median receptive field size for FAI cells is 38 mm² (range 38.8-333.6 mm²). Assuming a perfect circular area, this corresponds to a 7 mm centre-to-centre spacing.

Concerning force, FAI units can be activated with forces between 0.7-282 mN, with a median of 11.8 mN.

Table 1. Profiles of mechanoreceptors in the foot’s sole, following [26].

| Type  | Number | % of total | Median threshold (mN) | Range (mN) | Receptive field size (mm²) | Median | Range |
|-------|--------|------------|-----------------------|------------|---------------------------|--------|-------|
| SAI   | 15     | 14.4       | 35.6                  | 4.7-744    | 7.0.9                      | 11.8-277 |
| SAII  | 16     | 15.4       | 115.3                 | 36-2800    | 127.4                      | 44-296.2 |
| FAI   | 59     | 56.7       | 11.8                  | 0.7-282    | 38                         | 5.8-333.6 |
| FAII  | 14     | 13.5       | 4.0                   | 0.5-2800   | 284.2                      | 41.7-1248 |
| Total | 104    | 100        | -                     | -          | -                          | -      | -     |

Figure 1. Examples of tactile ground indicators for the blind: (a) getting on the subway and (b) passing through ticket gates.

In 2009, the last two works reported more mature results in [21] and [22] respectively, while in 2010 a combined audio-tactile system providing the sensation of walking over granular ground was presented in [23].

In 2011, Okamoto et al. presented a footstep display that recreates the sensation of stepping on fragile structures, such as paper, aluminium and polypropylene [24].

3. Guidelines for Tactile-Foot Stimulation

It is well known that skin is the sense organ which contains the essential biological sensors of touch. It encompasses 3 main groups of sensors, organized by function: the thermoreceptors, responsible for thermal sensing; the nociceptors, responsible for pain sensing; and the mechanoreceptors, sensitive to mechanical stimulus and skin deformation.

Our interest focuses on the mechanoreceptors, as they are responsible for sensing and the transmission of physical deformations by external forces to the nervous system.

Mechanoreceptors are usually classified based on their rate of adaptation and receptive field [25]. The first refers to how quickly the cell adapts to a stimulus. Fast cells are useful for sensing texture and vibrations, while slow ones are useful for proprioception. The second refers to the area within which the stimulus can excite the cell. Two types of mechanoreceptors can be found: type I and II.

Figure 2. Distribution of mechanoreceptors in the foot’s sole, following [26].
From this first general study, we conclude that the design goals for a FAI foot stimulation device should integrate an actuator array with 7 mm interspacing, stimuli frequencies between 5-40 Hz and delivered forces of around 11.8 mN.

4. Shoe-Integrated Tactile Display: Design and Prototype

A) Design concept

According to the physiological specifications just mentioned, a conceptual representation of the shoe-integrated tactile display is shown in fig. 3.

An initial prototype consisting of an array of 16 vibrotactile actuators has been envisaged to stimulate the medium part of the foot’s sole where FAI mechanoreceptors are most concentrated. Each actuator is to be independently addressed with a specific vibrating frequency command.

Fig. 3 inset shows the target stimulation area.

![Figure 3. Conceptual representation of a FAI cell stimulation device for the foot’s sole [20]. Inset: target stimulation area.](image)

B) Actuator

The actuator chosen for stimulating the sole of the foot is a miniature vibrating DC electric motor (Fig. 4 inset). These motors are of type CI030L-50 from Jinlong Machinery [27], originally intended for cell phones. Each motor is 10 mm in diameter, 3 mm thick, and has a mass of 12 g. It is commercially available for 10 USD.

Experimental tests [20] confirmed that this motor is capable of vibrating within a range of 10-55 Hz following a fairly linear relation with its operating voltage input: 2.5-4 V at a maximum operating current of 100 mA. As such, a vibration input command of 55 Hz would require a maximum of 400 mW from the power source.

Fig. 4 shows the experimental variation of the static axial force versus the applied current. The maximum static axial force delivered by the actuator is 13 mN.

Note that the proposed actuator allows a 10 mm interspacing and is capable of producing vibrating frequencies between 10-55 Hz and axial forces around 13 mN- features that meet the criteria established above while also being small, lightweight, low-cost and having low-power consumption.

C) Prototype

Fig. 5 shows the first prototype that was developed. It consists of 16 vibrating actuators all integrated in a foam shoe-insole. The effective tactile area is 30.25 cm², which conveniently covers the medium part of the sole.

Foam was chosen because it is easy to machine and it is well known for absorbing vibrations, shock and impact forces. Its material absorbing properties have a twofold purpose: to cushion the motors against the user’s load and to prevent from having an expanding motor vibration effect throughout the insole. Dots of an epoxy paste (Plasticine) cover the actuators’ entire upper surface and are in contact with the sole. This technique has proven to be an excellent vibration transmitter.

The prototype’s laboratory cost is only 200 USD. Note that the compactness of the vibrators allows an easy integration to the shoe-insole and does not obstruct its further insertion into a shoe.

D) Electronic drive

Fig. 6 shows a schematic representation of the electronic system used to drive the shoe-integrated tactile display. The system consists of a user friendly software interface that generates tactile data (such as shapes, pictures, patterns, sequences, etc.) by choosing directly the tactile actuators to activate and setting their desired vibrating frequency. Using the RS232 protocol, the computer transmits this information to an electronic module, where a controller interprets the command strings and sets each actuator of the display accordingly.

![Figure 4. Experimental measurements of the static axial force versus current. Inset: miniature vibrating DC motor.](image)
Figure 5. Shoe-integrated tactile display: back and forth. This prototype was featured in IEEE Spectrum Online [28] and was acknowledged by US Patent Application 20110242316 [29].

As a power source, an AC to DC converter has been temporarily adapted to the electronic drive to receive the AC input voltage from a wall power source. The ultimate goal is to develop a wireless system with microelectronics, an on-board compact battery and a RF (radio frequency) transmitter all built into the shoe.

Figure 6. Drive components of the shoe-integrated tactile display.

5. Preliminary Evaluation on Tactile Rendering

Preliminary psychophysical experiments were carried out to evaluate the prototype’s ability to transmit tactile information to the user and the user’s comprehension level to this feedback. Four experiments were conducted to gain insights into the capabilities of tactile-foot perception: direction, shape, pattern recognition and navigation in space.

A) Study participants and experimental procedure

A total of 25 subjects participated voluntarily in the experiments. All gave their consent in agreement with the university’s ethics guidelines: 20 were sighted and 5 were blind.

The sighted subjects (10 men and 10 women) were engineering undergraduate students at Panamerican University. No special criteria were used to select them apart from their availability. Their ages ranged from 18 to 24 years old, with an average age of 20.5. None of them reported any previous experience with tactile displays. All were right-handed.

The blind subjects included 3 adolescents (2 male and 1 female) and 2 adults (all male). All of them were either blind from birth or else had lost their sight within the first 3 years of life. The adolescents’ ages ranged from 13 to 15 years old with an average age of 14 while the adults ages were 28 and 32. All were right-handed Braille readers.

During the experiments, the subjects wore the tactile display on the right foot. For hygiene, all of the subjects were requested to use socks. Before each session, they were completely ignorant about any aspect of the test and were given general instructions concerning the task. A short familiarization time was granted prior to the tests. During this time, the subjects tested different vibration frequencies and had the opportunity to choose a preferred one. Although the physiology of the foot indicates a maximum stimuli frequency of 40 Hz, all 25 subjects chose 55 Hz, the maximum vibration frequency of the actuators. This is certainly due to the use of socks, which act as a low-pass filter.

For the sighted subjects, experiments I to III were conducted consecutively on the same day, while experiment IV was conducted two weeks later. For the blind, all of the experiments were conducted on the same day.

B) Experiment I: Direction recognition

The purpose of this test was to determine whether the subjects could recognize the direction of the motion of dynamic information.

Method:

A dynamic straight line was presented to the 25 subjects. Four patterns were chosen: North N (a line moving from the last row to the first one), South S (the inverse), East E (a line moving from the last column to the first one) and West W (the inverse) (Fig. 7).

A set of 14 directions was presented to the subjects in one trial: S-N-E-W-S-E-N-W-E-S-W-N-S-E. This set takes into account all possible transitions between directions. Subjects were asked to report the direction perceived with no time restriction.

Results:

Fig. 7 shows the results obtained from this test. Note the overall good performance between men, women and adult blind. The minimum success rate among these 3 groups is 64% while the maximum is 100%. Moreover, note that the adult blind performed better and that there is no significant difference between the average performances of men and women. The young blind performed much worse. Their minimum and maximum recognition rates were 16.6% and 55.5%, respectively. This group expressed the view that the information displayed was confusing.
The standard deviation of the mean or standard error shows that there is a statistically significant difference in performance, especially among women and the young blind: while some subjects performed quite, well others performed very poorly.

C) Experiment II: Shape identification
The goal of the second test was to determine whether the subjects could use the on-shoe tactile device to identify several simple, geometric shapes.

Method:
Six basic geometric shapes were used for the second experiment: square, circle, vertical line, horizontal line, diagonal and inverted diagonal (Fig. 8). All 25 of the subjects were asked to match what they felt tactually with one of these shapes.

The six shapes were presented randomly, three times each, during each trial. The subjects had no time restriction to provide their answers and, upon request, they could have the shape refreshed on the display.

Results:
Fig. 8 shows the results obtained from this test. This task is evidently much more complicated than the first one and poorer scores were obtained.

The average success rates were 32.3%, 31.3%, 22.2% and 44.4% for women, men, the young blind and the adult blind respectively.

Again, the adult blind performed better, the young blind performed the worse, and men and women performed very similarly. All of the subjects reported that this test was very complicated and - unlike the previous one - that they were sure to have made errors.

Note that the diagonal lines were the most difficult shapes to identify. They were taken for the square or circle in all cases. It seems that a vibrating point is not easy to discriminate within a vicinity of vibrating points. The same effect has been observed in vibrotactile displays for the fingers and hands [30-32]. Although vibrations minimally expand mechanically within the foam shoe-sole, they do expand throughout the skin, thereby affecting perception.

D) Experiment III: Pattern recognition
In human-computer interaction, there has been much interest in coded language: non-verbal visual, audio or tactile structured short messages that can provide information to the user.

The third test aimed to determine whether the subjects could recognize and associate tactile patterns displayed on the foot with daily information, familiar signals and emotions.

Method:
Five tactile patterns were used for this test: caution, SMS, phone call, exaltation and relaxation. Vibrotactile signals were modulated in accordance with these patterns:
- Caution was generated in accordance with its visual equivalent: 2 intermittent vertical bars (highway signal).
- SMS was generated in accordance with mobile phones: 2 consecutive short vibrations, then a pause, and then 2 more consecutive short vibrations.
- Phone call was also generated as with mobile phones: a long vibration, then a pause, and then a long vibration.
- Exaltation is defined as the transition between calm and excited. Inspired by the increase in cardiac rhythm, this emotion was generated by consecutively activating all the actuators.
- Relaxation is the inverse emotion. It was generated by consecutively turning all the actuators off.

Figure 7. Performance of the 25 subjects in identifying directions. The standard error is shown as an error bar.

Figure 8. Performance of the 25 subjects in identifying shapes. The standard error is shown as an error bar.
Again, all 25 subjects were asked to match what they felt tactually with one of these patterns. The test consisted of a single trial. Each pattern was displayed once. The subjects had no time restriction to provide their answers. Upon request, they could have the pattern refreshed on the display and they were allowed to modify their answers if they felt one pattern better suited an answer already given.

**Results:**
The young blind and adult blind recognized all the patterns (a 100% recognition rate) while the results for women and men are given in table 2.

Note that men performed much better than women, with an average percentage of 66% against 50%. Contrary to the performance observed in the previous tests, the young blind found this task very easy. The adult blind also reported that the patterns were easy to recognize and remember. For sighted subjects, note that the SMS and phone call patterns were perfectly well identified, while exaltation and relaxation were not so clear, especially among women. This is certainly due to the familiarity of the first two and the novelty of the last two signals.

The results obtained from this test are encouraging: they strongly suggest that people can easily identify and relate vibrotactile-foot patterns to information and emotions.

E) Experiment IV: Navigation in space
The fourth test aimed to determine whether the subjects could actually navigate in a structured environment using tactile-foot feedback.

For this purpose, the experimental tracking platform in fig. 9(a) was set. It encompassed 3 main elements: a wide angle colour camera, a PC and dedicated software running on a PC.

The camera was located 4 m above the ground surface at 25° from the vertical. It was configured to capture images every 0.5 s. The acquired images were sent to the PC for processing. The image processing focused on tracking the subjects’ feet: a Matlab self-developed script performs feet detection and confines the region of interest to a square (Fig. 9(c)) [22].

**Method:**
The best 5 sighted subjects and the best adult blind -identified from the previous tests- were invited to participate in this last experiment. All 6 were male. During the test, the sighted subjects were blindfolded so that no cue from sight could be obtained (Fig. 9(b)) while the blind subject was allowed to keep his white cane. As in the previous tests, all 6 subjects were wearing the shoe-integrated tactile display on their right foot.

|          | women |     |   |   |   |
|----------|-------|-----|---|---|---|
|          | caution | SMS | call | relaxation | exaltation |
| caution  | 40  | 10  | 10 | 10 | 30 |
| SMS      | 0   | 70  | 0  | 10 | 20 |
| call     | 0   | 0   | 80 | 20 | 0  |
| relaxation | 30 | 0   | 10 | 30 | 30 |
| exaltation | 20 | 20  | 0  | 30 | 30 |

Table 2. Distribution of answers (%) in the pattern recognition experiment (sighted subjects).

The four direction patterns of experiment I and the SMS pattern from experiment III were presented to the subjects. The following intuitive protocol was used: North for moving forward, South for moving backward, East for turning left, West for turning right and the SMS signal for stop. The navigation directions were provided by a human-assistant located outside the navigation environment.

The subjects were asked to move according to the pattern felt. They had no time restriction to complete the test and, upon request, they could have the direction instruction refreshed on the tactile display. The navigation time was recorded for each participant. Fig. 11 shows the indoor navigation environment proposed to the sighted subjects while fig. 10 shows a more complex outdoor navigation environment proposed to the adult blind. Note that both environments present a number of static obstacles.

**Results:**
Fig. 11 shows the 5 navigation trajectories performed by the sighted subjects. Note an overall good performance: all the subjects were capable of completing the task in less than 4 min. Subjects 2, 3 and 4 made no errors in following the instructions. Subject 1 performed a false turn which was immediately corrected. Subject 5 made several errors: 2 false turns and bumps into the obstacles once. Note that without the visual reference, most sighted subjects fail to walk in a straight line (subjects 2, 3, and 5).
This paper also presented some insights into the role of tactile perception by the human foot through a set of tests involving direction, shape, pattern recognition and directional navigation. The tests were conducted with 20 sighted and 5 blind voluntary subjects.

Globally, the results show that people easily understand the direction of the motion of dynamic information. However, shape recognition is more difficult. It seems that the foot is not appropriate for the recognition of precise or detailed information, such as shapes. The pattern recognition rates were very satisfying, which suggests that people can identify and relate tactile foot patterns to information, familiar signals and emotions. Finally, one of the most promising results was directional navigation. The collected data shows that it is feasible to exploit tactile-foot feedback for navigation in space.

In particular, the results show that a similar performance should be expected between sighted adult men and women. Tactile-foot feedback seems easier to understand for the adult blind, a result that might have been anticipated if we consider that they have been living with their disability for a long time and that their spatial-temporal reasoning skills are fully developed. However, this was not so for the young blind: it is well known that the spatial and reasoning skills of children and adolescents -sighted or blind- are not mature, and so poorer performances might be expected.

Some interesting questions arose out of this first evaluation and constitute the topics of current research: Do long-term vibrating stimuli affect balance and walking? How does user performance change depending on cognitive load? Is there any difference between wearing the tactile display on the right or the left foot?
Figure 11. Results of the 5 sighted subjects in the navigation task. A broken line is drawn to better appreciate the trajectory followed.

Figure 12. (a)-(b) Two new designs and (c)-(d) prototypes of shoe-integrated tactile displays. (e) Fully wearable devices with wireless connection.

The current work also focuses on new optimized versions of shoe-integrated tactile displays. The results reported in this paper revealed that the foot is not capable of precise discrimination. Therefore, the information displayed to the feet must be simple and - preferably - encoded as vibrating patterns. From a technological point of view, there would be no value in integrating a large number of actuators if the foot is not capable of accurately distinguishing which one of them is actually vibrating. Short structured tactile patterns could be used to
represent simple actions and these can then be combined in different ways to represent more complex messages and concepts.

Figs. 12 (a)-(b) show the conceptual representations of two new designs. Note that these designs have reduced the number of vibrators from 16 to 4 while keeping the correspondence with the location of FAI mechanoreceptors (Fig. 2).

Figs. 12 (c)-(d) show the corresponding prototypes. Besides the reduction in the number of vibrators, another major improvement is that these new prototypes eliminate all wires by using an RF transmission module. Another positive consequence of the reduction of vibrators is that the electronic drive becomes simpler and more compact. Moreover, a portable on-board power supply can now be envisaged. Tests with a rechargeable standard 6 V, 1000 mAh battery reveal a 6 h operation, which is large enough to meet the requirements of any journey while walking. The whole electronic drive (battery, circuits and RF module) can now be comfortably attached to the ankle (Fig. 12 (e)) or built into the shoe.

The challenge for these new prototypes will be to create a whole new tactile-foot language encoded in only 4 vibrators that allows users to easily understand a wide variety of information, such as instructions, situations and alert signals, etc.

Our future work looks to integrate the concept of tactile-foot stimulation in ETAs for the blind.

7. References

[1] Ng G, Barralon P, Dumont G, Schwarz S, and Ansermino J (2007) Optimizing the tactile display of physiological information: vibro-tactile vs. electro-tactile stimulation, and forearm or wrist location. Proc. of Annual International Conference of the IEEE Engineering in Medicine and Biology Society, pp 4202-4205.

[2] Tsukada K and Yasumura M (2004) ActiveBelt: belt-type wearable tactile display for directional navigation. Proc. of UbiComp2004, Springer LNCS 3205, pp 384-399.

[3] Jones L, Lockyer B, and Platecki E (2006) Tactile display and vibrotactile pattern recognition on the torso. Advanced Robotics. 20: 1359-1374.

[4] Pito M, Moesgaard S, Gjedde A, and Kupers R (2005) Cross-modal plasticity revealed by electrotactile stimulation of the tongue in the congenitally blind. Brain. 128: 606-614.

[5] Gemperle F, Ota N, and Siewiorek D (2001) Design of a wearable tactile display.Proc. of International Symposium on Wearable Computers, pp 5-12.

[6] Kalb J, Amrein B, and Myles K (2008) Instrumentation and tactor considerations for a head-mounted tactile display, Technical Report ARL-MR-705.

[7] Hogema J, de Vries S, van Erp J, and Kiefer R (2009) A tactile seat for direction coding in car driving: field evaluation. IEEE Transactions on Haptics. 2(4): 181-188.

[8] Magnusson M, Enbom H, Johansson R, and Pyykko I (1990) Significance of pressure input from the human feet in anterior-posterior postural control. ActaOto-Laryngolica. 110: 182-188.

[9] Kavounoudias A, Roll R, and Roll J (1998) The plantar sole is a dynamic map for human balance control. NeuroReport. 9: 3247-3252.

[10] Maurer C, Merger T, Bolha B, and Hlavacka F (2001) Human balance control during stimulation of the plantar soles. Neuroscience Letters. 302: 45-48.

[11] Do M, Bussel B, and Breniere Y (1990) Influence of plantar cutaneous afferents on early compensatory reactions to forward fall. Experimental Brain Research. 79: 319-324.

[12] Asai H, Fujiwara K, Toyama H, Yamashina T, Tachino K, and Nara I (1992) The influence of foot soles cooling on standing postural control analyzed by tracking the center of foot pressure. Posture and Gait: Control Mechanisms. 2: 151-154.

[13] Velazquez R (2006) Contribution à la conception et à la réalisation d’interfaces tactiles portables pour les déficients visuels. PhD thesis, Paris 6 University (In English). Available: http://tel.archives-ouvertes.fr/tel-00085703. Accessed 2012 May 2.

[14] Japan JIS T 9251:2001 Dimensions and patterns of raised parts of tactile ground surface indicators for blind persons.

[15] United Kingdom BS 7997:2003 Products for tactile paving surface indicators. Specification.

[16] Australia/New Zealand AS/NZS 1428:4:2002 Design for access and mobility - Tactile indicators.

[17] Rovers A and van Essen H (2006) Guidelines for haptic interpersonal communication applications: an exploration of foot interaction styles. Virtual Reality. 9: 177-191.

[18] Kobayashi Y, Osaka R, Hara T, and Fujimoto H (2008) How accurately people can discriminate the differences of floor materials with various elasticities. IEEE Transactions on Neural Systems and Rehabilitation Engineering. 16(1): 99-105.

[19] Law A, Peck B, Visell Y, Kry P, and Cooperstock J (2008) A multi-modal floor-space for displaying material deformation underfoot in virtual reality. Proc. of IEEE International Workshop on Haptic Audio Visual Environments and Games, pp 126-131.

[20] Magaña M and Velazquez R (2008) On-shoe tactile display. Proc. of IEEE International Workshop on Haptic Audio Visual Environments and Games, pp 114-119.
[21] Visell Y, Law A, and Cooperstock J (2009) Touch is everywhere: floor surfaces as ambient haptic interfaces. IEEE Transactions on Haptics. 2(3): 148-159.

[22] Velazquez R, Bazan O, and Magaña M (2009) A shoe-integrated tactile display for directional navigation. Proc. of IEEE/RSJ International Conference on Intelligent Robots and Systems, pp 1235-1240.

[23] Papetti S, Fontana F, Civolani M, Berrezag A, and Hayward V (2010) Audio-tactile display of ground properties using interactive shoes. Proc. of International Conference on Haptic and Audio Interaction Design, Springer LNCS 6306, pp 117-128.

[24] Okamoto S, Ishikawa S, Nagano H, and Yamada Y (2011) Spectrum-based vibrotactile footstep-display for crinkle of fragile structures. Proc. of IEEE International Conference on Robotics and Biomimetics, pp 2459-2464.

[25] Johnson K and Hsiao S (1992) Neural mechanisms of tactual form and texture-perception. Review of Neuroscience. 15: 227-250.

[26] Kennedy P and Inglis T (2002) Distribution and behavior of glabrous cutaneous receptors in the human foot sole. Journal of Physiology. 538(3): 995-1002.

[27] Jinlong Machinery, JinLong Science Park, Zhejiang 325603, China. Available: www.vibratormotor.com. Accessed 2012 May 2.

[28] Corley A (2009) Navigation by the soles of your feet. IEEE Spectrum Online. Available: http://spectrum.ieee.org/robotics/home-robots/navigation-by-the-soles-of-your-feet-and-the-seat-of-your-pants. Accessed 2012 May 2.

[29] Velazquez R (2011) Shoe-Integrated Tactile Display for Directional Navigation, US patent application filed on Sept 23, 2010, US Patent Application 20110242316 published on Oct 6, 2011.

[30] Borst C and Baiyya V (2007) Enhancing VR-based visualization with a 2D vibrotactile array. Proc. of ACM Virtual Reality Software and Technology, pp 183-186.

[31] Benali-Khoundja M, Hafez M, and Kheddar A (2007) VITAL: An electromagnetic integrated tactile display. Displays. 28(3): 133-144.

[32] Yanagida Y, Kakita M, Lindeman R, Kume Y, and Tetsutani N (2004) Vibrotactile letter reading using a low-resolution tactile array. Proc. of 12th Symposium on Haptic Interfaces for Virtual Environments and Teleoperator Systems, pp 400-406.