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FACULTAD DE INGENIERIA

DISPOSITIVO ELECTRÓNICO PARA COMUNICACIÓN TÁCTIL CON EL PIE: DISEÑO, OPTIMIZACIÓN Y EVALUACIÓN

TESIS

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ÍNDICE

AGRADECIMIENTOS

Las personas que dejan huella en nuestra vida merecen saberlo.

Para mi mamá y mi esposa por todo su apoyo y motivación.

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Wearable Electronic Tactile Display for the Foot

***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 of their feet. A four-point array of actuators stimulates the mechanoreceptors in the foot sole with vibrations. A series of perceptual experiments involving directional information, pattern and emotion recognition, and language learning were conducted with 20 voluntary subjects. Results obtained show the potentials of podotactile stimulation and the proposed device.*

***Streszczenie.** W artykule przedstawiono rozwiązanie dla wyświetlacza dotykowego montowanego w bucie. W ten sposób tworzony jest interfejs, który obsługiwany jest stopą użytkownika. Zamontowane w czterech punktach siłowniki stymulują mechanoreceptory w podeszwie poprzez wibracje. Przeprowadzono badania eksperymentalne z pomocą 20 ochotników, które potwierdziły wysoki potencjał tego rodzaju interfejsu i proponowanego rozwiązania. (**Elektroniczny wyświetlacz dotykowy dla stopy**).*

Keywords: podotactile stimulation, vibrotactile display, tactile perception, wearable device.
Słowa kluczowe: stymulacja stopą, wyświetlacz dotykowy naciskowy, postrzeganie dotykowe, urządzenia zdatne do noszenia.

Introduction

Just as sight and hearing, touch represents a means of interaction and communication for human beings. Among other capabilities, touch provides a whole non-verbal language that can be developed and offer much more possibilities than it is traditionally believed.

Much of what is found in the literature about tactile communication concerns tactile stimulation of the fingers and hands. However, as the area of tactile feedback is a “hot” research topic especially in assistive robotics and complex multitasking environments, other body areas have been explored as well: wrist/forearm [1], abdomen [2], chest [3], tongue [4], ears [5], and head [6] have been studied to transmit information to a user (a comprehensive survey of wearable tactile devices can be found in [7]). Devices are as diverse as the technology used and the location on the body. Yet, the human foot has not received much attention.

Tactile paving or tactile ground indicators are with no doubt the most representative example of tactile communication with the feet. They consist of regularly textured ground areas in the form of patterns of raised domes or bars. Their purpose is to provide a tactile surface that can be felt underfoot and recognized by pedestrians either as hazards in the immediate location (dome pattern) or as a safe direction of travel (bar pattern). They are widely used in stairways, ramps, escalators, road crossings, subway/railway platforms, etc.

Tactile ground indicators are of great help for both distracted sighted and blind pedestrians. However, their main inconvenient is that they just cannot be installed everywhere. A wearable electronic tactile-foot (podotactile) stimulation device could be interesting for providing diverse real-time information such as directions, situation awareness, alert signals, etc.

During the last years, we have being exploring the feasibility of providing tactile feedback via the feet. We have previously proposed in [8], a wearable human-computer interface for the foot consisting of a shoe-integrated vibrotactile display. This device was a first attempt to evaluate the role of tactile perception by the human foot. Perceptual experiments conducted with both sighted and blind users [8], [9] suggest that the comprehension level achieved is sufficient to be exploited in human-computer interaction tasks such as virtual reality, robotics, sensory substitution, game and entertainment, among many others.

Following the lessons learned from the first device, we report our progresses in podotactile stimulation with a technologically improved second device. This paper presents first a technical overview of the second prototype developed and then evaluates the capabilities of podotactile stimulation through a set of perceptual experiments performed on a group of 20 voluntary subjects. Results provide interesting insights into the real potential of podotactile perception and confirm the applicability of this approach in human-computer interaction.

Design and prototype

The conceptual representation of the second version of shoe-integrated tactile display is shown in Fig. 1(a). This design consists of four vibrating motors that stimulate the medial and lateral plantar areas of the foot sole, which are the most sensitive to vibrotactile stimulation [10].

In this prototype, vibrators are arranged in a diamond-like shape with 35 mm side-length (Fig. 1(b)). All four actuators are integrated in a commercial inexpensive foam shoe-insole. They provide axial forces up to 13 mN and vibrating frequencies between 10-55 Hz. Each vibrator is independently controlled with a specific vibrating frequency command.

This device is completely wearable and is intended to be used on the left foot (Fig. 1(c)): it includes an RF (radiofrequency) transmission module which allows simple and reliable point-to-point communication with a computer within a range of 100 m. It also includes the electronic drive to power the vibrating motors and an on-board power supply that ensures 6 h of autonomy. Fig. 1(c) inset details the electronic module that the user carries comfortably attached to the ankle. The prototype’s laboratory cost is low (only 200 USD) and it is easy/fast to assemble and maintain.

A key aspect of this prototype is a simple but effective mechanical design for ensuring an optimal transmission of vibrations to the skin. Foam insoles were chosen because foam is easy to machine and it is well known for absorbing vibrations, shock, and impact forces. Its absorbing material properties have a twofold purpose: to cushion the motors against the user’s load and to prevent from having an expanding vibration effect throughout the insole. Dots of an epoxy paste cover the motors’ entire upper surface and are in contact with the foot sole.

However, embedding the actuators within foam implies that vibrations transmitted to the skin will be damped as well. A simple solution to overcome this undesired attenuation is to set the motors at 45°. Fig. 2 illustrates this concept. When motors are perfectly set on the foam, an entire side of their structure is evidently in contact with the foam. In consequence, vibrations find a large viscoelastic contact surface that damps significantly their amplitude.

When motors are set at 45°, an entire side of the motor is contact-free. This produces vibrations of greater amplitude that are only transmitted to the solid epoxy paste. This simple design has experimentally proved to be an excellent vibration transmitter.

Evaluation and Results

Perceptual experiments were carried out to evaluate the prototype's ability to transmit tactile information to the user and to gain insights into the capabilities of podotactile perception. Four experiments were conducted for this purpose: direction, pattern, emotion recognition, and language learning.

A total of 20 subjects (14 men and 6 women) participated voluntarily in the experiments. All gave their consent in agreement with the university ethics guidelines. Subjects were undergraduate students at Panamericana University with no known impairments in tactile sensory or cognitive functions. Their ages ranged from 19 to 23 years old with an average age of 20.4. None of them reported previous experience using tactile displays.

During the experiments, the subjects were wearing the tactile display on the left foot. For hygiene, all subjects were requested to use socks. Before each session, they were totally naive about all aspects 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. All 20 subjects chose 55 Hz, the maximum vibration frequency of the actuators. For all subjects, the ensemble of experiments was conducted consecutively on the same day.

For statistical analysis, subjects were divided into two groups of 10 according to their educational background: engineering and non-engineering students. The first group involved subjects enrolled in Electronics Engineering and Computer Science while the second, subjects enrolled in programs such as Business Administration and Liberal Arts. The χ^2 distribution was used to evaluate difference in proportions across samples of a same group while the z-test to give a confidence interval for the true difference in proportions between groups. The level of significance to reject the null hypothesis (α) was set to 0.05 in all cases.

A. Cardinal direction recognition

The purpose of this test was to determine whether the subjects could recognize directional information represented by the cardinal points.

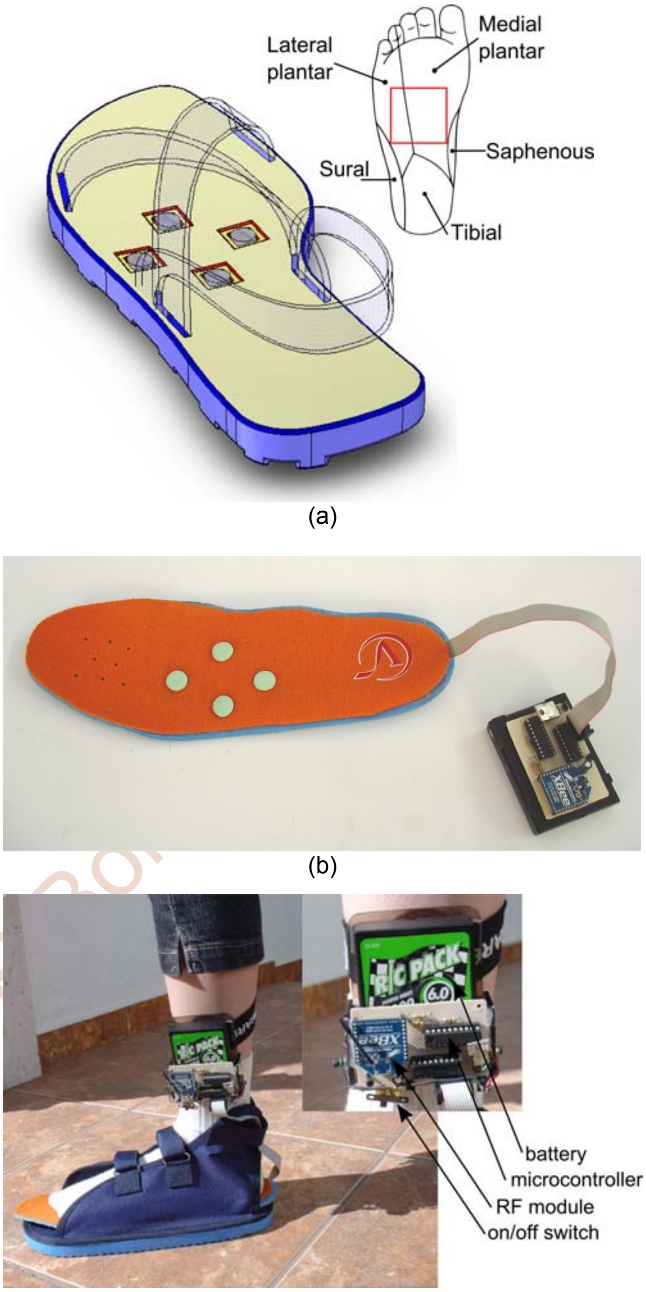
Method:

Each one of the four contact pins of the tactile display was set to represent a cardinal point. A cardinal direction is encoded in five sequences (t1-t5) as follows: three consecutive short vibrations in the corresponding contact pin, then a short vibration in the opposite contact pin, and again a short vibration in the correct contact pin.

Fig. 3 shows for example, the codification for North. Note that the contact pin **N** vibrates three times, then **S** once, and again **N**. A set of 14 directions was presented to the subjects in one trial. All 20 subjects were asked to report the direction perceived with no time restriction. Upon request, they could have the direction pattern refreshed on the display.

Results:

Results obtained are presented in confusion matrices (Table 1). For the engineering group, the average recognition rates were 83.3%, 90%, 87.5%, and 96.6% for **N**, **S**, **E**, and **W**, respectively. For the non-engineering group, these were 100%, 92.5%, 70%, and 86.6%, respectively. Note an overall good performance.



(a)

(b)

(c)

Fig.1. Tactile display for the left foot: (a) Design concept. Inset: target stimulation area enclosed in square. (b) Prototype. (c) Fully wearable device with wireless connection. Inset: electronic module. Design concept and prototype were acknowledged US Patent Application 20110242316 [11].

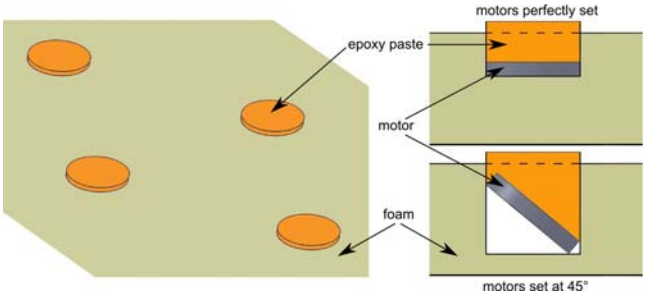


Fig.2. Arrangement of vibrating motors within the foam. When motors are set at 45°, vibrations of higher amplitude are transmitted to the foot sole.

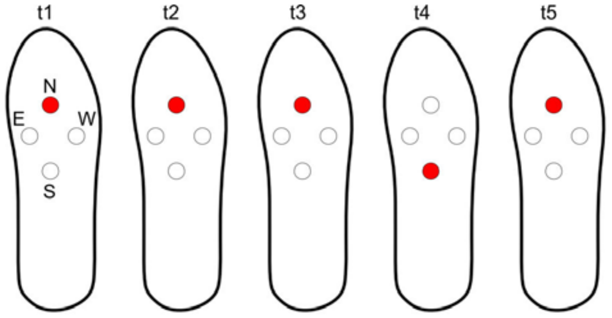


Fig.3: Schedule of activation of the motors for the cardinal direction recognition task (example for North).

Table 1. Cardinal direction recognition: average confusion matrices for the Engineering and Non-Engineering groups.

Eng.		answered (%)			
		North	South	East	West
presented	North	83.3	3.33	10	3.33
	South	2.5	90	2.5	5
	East	0	10	87.5	2.5
	West	0	3.33	0	96.6

Non-Eng.		answered (%)			
		North	South	East	West
presented	North	100	0	0	0
	South	7.5	92.5	0	0
	East	17.5	7.5	70	5
	West	0	10	3.33	86.6

Subjects in the engineering group exhibited a uniform performance across the test (χ^2=2.97, p=0.39). However subjects in the non-engineering group did not (χ^2=15.17, p=0.0016). For this group, East and West were significantly more difficult to identify than North and South. There was no statistically significant difference in the recognition rates between groups for South and West (p>0.05). Not so for North and East (p<0.05).

B. Pattern recognition

In human-computer interaction, there is much interest in coded language: non-verbal visual, audio, or tactile structured short messages that can provide information to the user. This test aimed to determine whether the subjects could recognize and associate tactile patterns displayed on the foot with familiar signals.

Method:

Five tactile patterns were used for this test: caution, SMS, phone call, tic-tac, and door knocking melody. Vibrotactile signals were modulated in accordance to these patterns:

- Caution was inspired by its visual equivalent: two intermittent vertical bars (highway signal). This pattern was generated by the alternative activation of pins **E-S** and **N-W** (refer to Fig. 3 for pin identification).
- SMS was generated in accordance to mobile phones: two consecutive short vibrations, then a pause, then two consecutive short vibrations. All four pins vibrated simultaneously when required.
- Phone call was also generated as in mobile phones: a long vibration, then a pause, then a long vibration. Again, all four pins were involved in this pattern.
- Tic-Tac intended to simulate the sound of a ticking clock. This pattern was generated by activating pin **E**, then a short pause, then pin **W**.
- Door knocking melody intended to reproduce the well-known melody used when knocking on a door or when honking: five consecutive short vibrations, then a pause, then two consecutive short vibrations. Pins **N** and **S** were involved during the first five vibrations while all pins for the last two.

All 20 subjects were asked to match what they felt tactually with one of these patterns. The test consisted of a single trial. No familiarization time with the patterns was granted prior to this test. Each pattern was displayed once. 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 suited better an answer already given.

Results:

Table 2 summarizes the results obtained for both test groups. For most of the patterns, engineering students (Eng.) obtained higher average success rates than non-engineering students (Non-Eng.). However, there was no statistically significant difference in the performances of the two groups (p>0.05). Subjects in both groups exhibited a uniform performance across the test (Eng. Group: χ^2=8.67, p=0.06, Non-Eng. group: χ^2=2.88, p=0.57).

Note that the SMS, phone call, and melody patterns were quite well identified by most of the subjects while tic-tac was sometimes confused with caution and SMS.

These results suggest that people can easily identify and relate tactile-foot patterns to familiar visual, audio, or tactile signals.

Table 2. Pattern recognition: average confusion matrices for the Engineering and Non-Engineering groups.

Eng.		answered (%)				
		Caution	SMS	Call	Tic-Tac	Melody
presented	Caution	80	10	0	10	0
	SMS	0	70	0	30	0
	Call	0	0	100	0	0
	Tic-Tac	20	20	0	60	0
	Melody	0	0	0	0	100

Non-Eng.		answered (%)				
		Caution	SMS	Call	Tic-Tac	Melody
presented	Caution	50	10	20	0	20
	SMS	10	50	0	40	0
	Call	10	20	70	0	0
	Tic-Tac	20	20	0	60	0
	Melody	20	0	0	0	80

C. Emotion recognition

Emotions are necessary for us humans to function properly. Research has shown that they play an important role in our decision making mechanism and imbue strong or important events in our memory [12]. For example, we might remember losing money by associating the event to a negative emotion, whereas the birth of our child to a positive emotion.

Because of the aforementioned, digital treatment of emotions has been an active area. In particular, research has been carried out to generate, display, and recognize emotions. While this work does not pretend to present an emotional architecture, like the ones discussed in [13]; it does notice that emotions can be displayed by conventional and nonconventional means. Examples of the first are facial and verbal expressions while a representative example of the second is the work reported in [14], where a virtual flock displays emotions through its movement.

It is recognized that music is a conventional mean of inducing strong emotions. Cinema musical scores are particularly effective at transmitting emotions to the audience. Moreover, the audience can actually perceive and remember emotions transmitted by music [15]. Perhaps the clearest example is the musical score of the movie Jaws, which effectively transmits the emotion of fear.

Method:

The emotions selected for the third test are a subset of the so-called primary emotions: happiness, sadness, anger, and fear. To transmit this emotional content, vibrations similar to those produced by sound were modulated in the shoe-integrated tactile display according to these patterns:

- Happiness was inspired by laughter. It is the most evident visual expression of happiness. This emotion was generated by a set of three strong short vibrations, then a pause, and again three strong short vibrations. This pattern intends to reproduce the iconic "Hahaha!".
- Sadness is characterized by feelings of disadvantage such as sorrow and lowering of mood. This emotion was generated by setting all four vibrators at maximum vibrating frequency and gradually decreasing their frequency until vibration is no longer perceived. This pattern intends to communicate a lowering of energy.
- Anger can be defined as an emotional response to a perceived provocation. This emotion was generated by setting all actuators at a low -yet perceivable- vibrating frequency and suddenly setting them all at maximum frequency. This pattern intends to communicate an explosion of feelings.
- Fear is a distressing emotion induced by a perceived threat. To generate this emotion, we coded the classical musical score of the movie Jaws.

Subjects were asked to match what they felt tactually with one of these emotions. The test consisted of a single trial. No familiarization time was granted prior to this test. Each emotion was displayed once. Subjects had no time restriction to provide their answers. Upon request, they could have the emotion refreshed on the display and they were allowed to modify their answers if they felt one emotion suited better an answer already given.

Results:

Table 3 summarizes the results obtained for the 20 subjects. Again, for all emotions, engineering students (Eng.) obtained higher average success rates than non-engineering students (Non-Eng.). However, this is not enough to state that there was a statistically significant difference in the performances of the two groups ($p>0.05$). Subjects in both groups exhibited a uniform performance across the test (Eng. group: $\chi^2=0.43$, $p=0.93$, Non-Eng. group: $\chi^2=1.66$, $p=0.64$).

Table 3. Emotion recognition: average confusion matrices for the Engineering and Non-Engineering groups.

Eng.		answered (%)			
		Happiness	Sadness	Anger	Fear
presented	Happiness	70	0	20	10
	Sadness	0	80	0	20
	Anger	20	0	80	0
	Fear	10	10	0	80

Non-Eng.		answered (%)			
		Happiness	Sadness	Anger	Fear
presented	Happiness	50	20	30	0
	Sadness	0	70	10	20
	Anger	50	0	50	0
	Fear	10	10	10	70

Note that the proposed tactile emotions were easy to recognize by most of the subjects. It is interesting to note that anger was sometimes confused with happiness. For some subjects, the explosion of feelings sensation can also be interpreted as happiness. Note that the Jaws musical score obtained high recognition rates. Subjects were asked at the end of the test if they had recognized the melody. None of them did and realized when told. This confirms how well the melody represents fear.

Results obtained from this test strongly suggest that people can easily relate vibrotactile-foot patterns to emotions.

D. Language learning

Language learning is the process by which humans acquire the capacity to perceive and use words to understand and communicate [16]. From a neuroscience point of view, the language learning process is very different whether it is the first or second language. While the first refers to an infant's acquisition of his native language, the second deals with the process of learning an additional language when a native one has been already learned.

In particular, learning a second language is a complex process extensively studied in neuroscience, applied linguistics, sociolinguistics, psychology, and education. With no intention of further reviewing this process, we shall limit the discussion to state that humans learn a second language by making relations with their own native language and by memorizing. Think of a Spanish speaking native learning Italian; as both are Latin-based languages, relations can be easily established. However, for a Spanish speaking native learning Chinese, memorizing words seems the only way.

In this context, we propose a fourth test dealing with memorizing and tactile language learning. Its purpose is to evaluate whether the subjects could quickly learn tactile words and retain them in memory.

Method:

Five tactile words were chosen for this test: day, night, water, hello, and goodbye. The vibrotactile patterns in Fig. 4 were arbitrarily chosen to represent these words. For example, "day" in tactile language is represented by a long vibration followed by a short one while "night" by a long vibration followed by a short one, and again a long vibration.

Subjects were asked to match what they felt tactually with one of these words. Before each session, all five tactile words were displayed to the subjects so that they could make a mental representation of them. Upon request, they could have the tactile word refreshed on the display. When ready, the tester made a 1 min small talk on purpose to distract their mind from the test. After that, the test started. It consisted of a single trial. Each word was randomly displayed twice. Subjects had no time restriction to provide their answers and they were allowed to modify them if they felt they had made a mistake.

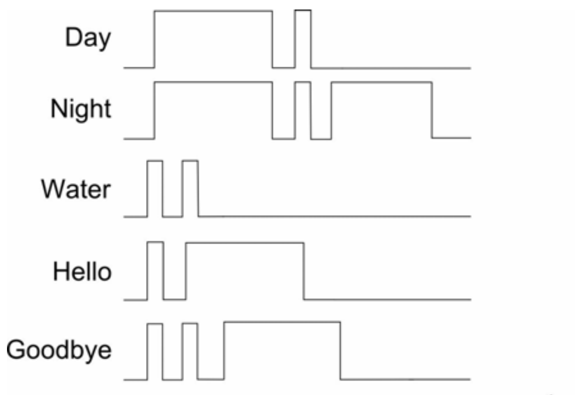


Fig.4: The five tactile words.

Results:

Table 4 shows the results obtained from this session. Note that the Eng. group obtained once again higher average success rates. For this test, the Eng. group was statistically significant better than the Non-Eng. group particularly at recognizing the “night” and “goodbye” patterns ($p<0.05$). Subjects in the Eng. group did not perform uniformly across the test ($\chi^2=18.21$, $p=0.001$). For this group, “day” and “hello” were significantly more difficult to identify than the other three tactile words. On the other hand, the Non-Eng. group performed uniformly across the entire test ($\chi^2=7.47$, $p=0.11$).

Table 4. Language learning: average confusion matrices for the Engineering and Non-Engineering groups.

Eng.		answered (%)				
presented		Day	Night	Water	Hello	Goodbye
	Day	75	15	0	10	0
	Night	0	100	0	0	0
	Water	0	0	95	5	0
	Hello	25	0	0	65	10
	Goodbye	0	0	0	0	100

Non-Eng.		answered (%)				
presented		Day	Night	Water	Hello	Goodbye
	Day	75	10	0	10	5
	Night	5	55	0	5	35
	Water	0	0	80	10	10
	Hello	20	15	0	55	10
	Goodbye	5	15	15	20	45

When asked about the effort invested, all subjects stated that this last test was the most difficult and that it required high concentration.

Results obtained from this test are undoubtedly encouraging: they strongly suggest that people can easily understand, learn, and remember abstract vibrotactile-foot patterns and relate them to verbal language.

Conclusion and future work

This paper has presented the design, technical overview, and preliminary evaluation of a shoe-integrated tactile display.

Using vibrating motors, a simple, fully wearable, low cost, and easy/fast to assemble device has been proposed to stimulate the mechanoreceptors in the foot sole.

Some insights into the role of tactile perception by the human foot were evaluated through a set of tests involving direction, pattern and emotion recognition, and language learning. Results obtained from these tests seem very promising for podotactile stimulation.

Success rates in cardinal direction recognition strongly suggest the possibility of guiding people through environments. This could be exploited in virtual reality or in mobility assistive devices for the blind. We found that vibrating patterns indicating cardinal directional information are easier to understand if the opposite direction is also displayed to indicate a direction. This provides a reliable reference to identify points of vibration when users are unable to locate them precisely throughout the foot sole.

Familiar patterns and emotions can be easily recognized by the foot if information displayed is simple and encoded as short structured messages. This could be useful for applications using alert signals and platforms communicating emotions (such as games and platforms seeking to complete visual feedback with haptics).

New patterns abstractly representing verbal language can also be understood, quickly learned, and retained in memory.

Tactile-foot feedback seems slightly easier to understand for those with engineering background. This is certainly due to the spatial-temporal reasoning skills developed during education that allow an easier visualization and conceptualization of abstract and spatial concepts.

Future work will focus on language learning: several tactile words will be displayed sequentially expecting that subjects are capable of constructing sentences. This intends to broaden the possibilities for describing complex ideas and situations.

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Insights into the Capabilities of Tactile-Foot Perception

Regular Paper

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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].

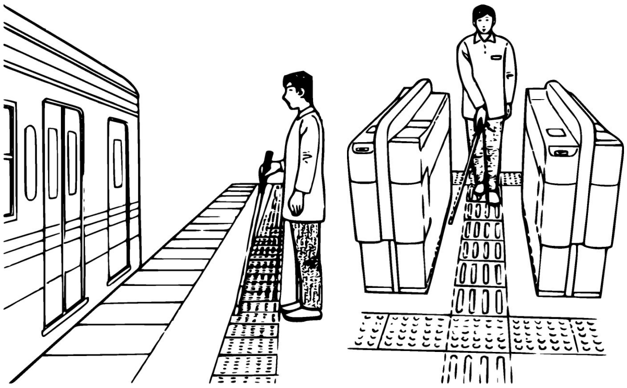


Figure 1. Examples of tactile ground indicators for the blind: (a) getting on the subway and (b) passing through ticket gates.

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. 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 mm^2 (range 5.8-333.6 mm^2). 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.

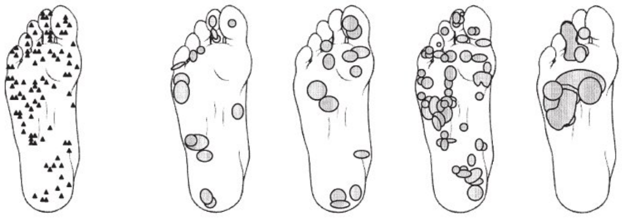


Figure 2. Distribution of mechanoreceptors in the foot's sole, following [26].

Type	Number	% of total	Median threshold (mN)	Range (mN)	Receptive field size (mm^2) Median	Receptive field size (mm^2) Range
SAI	15	14.4	35.6	4-744	70.9	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	-	-	-	-

Table 1. Profiles 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.

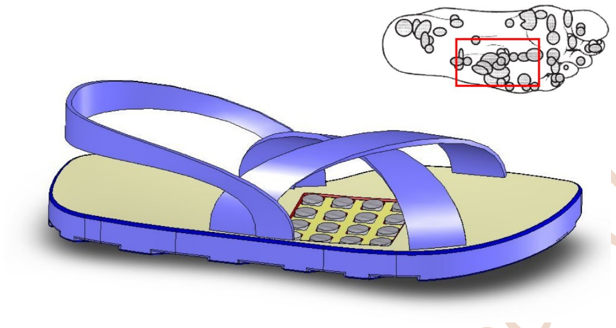


Figure 3. Conceptual representation of a FAI cell stimulation device for the foot's sole [20]. Inset: target stimulation area.

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 C1030L-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.

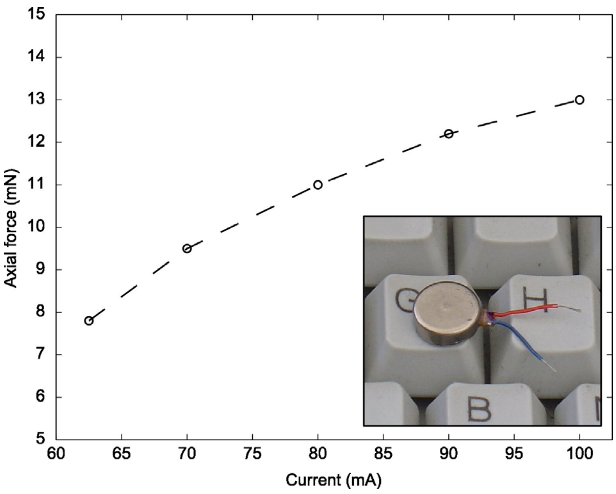


Figure 4. Experimental measurements of the static axial force versus current. Inset: miniature vibrating DC motor.

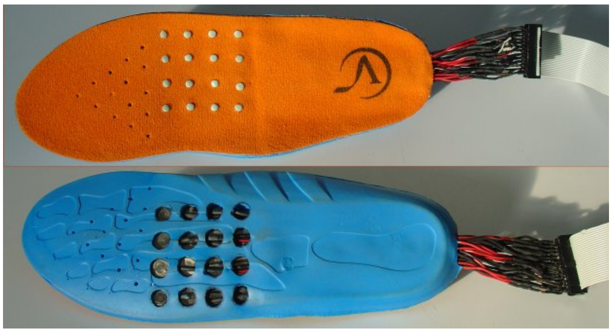


Figure 5. Shoe-integrated tactile display: back and forth. This prototype was featured in IEEE Spectrum Online [28] and was acknowledged by US Patent Application 20110242316 [29].

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.

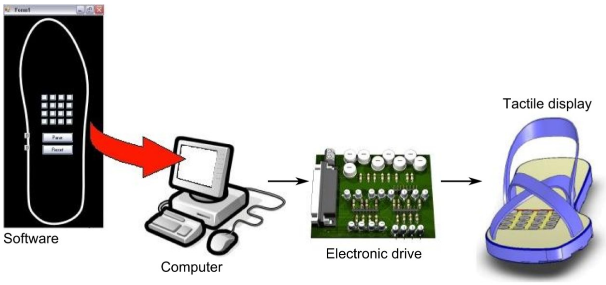


Figure 6. Drive components of the shoe-integrated tactile display.

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 Panamericana 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.

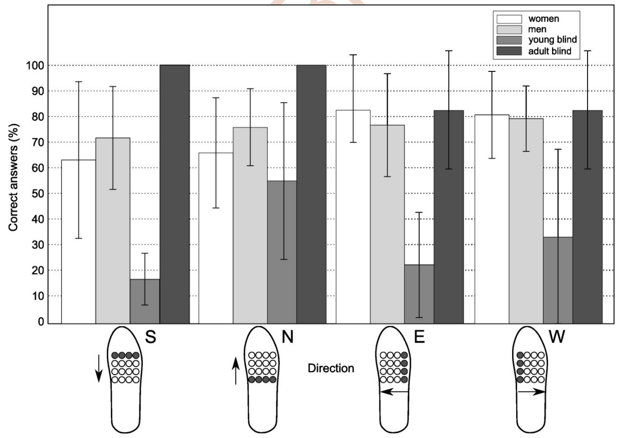


Figure 7. Performance of the 25 subjects in identifying directions. The standard error is shown as an error bar.

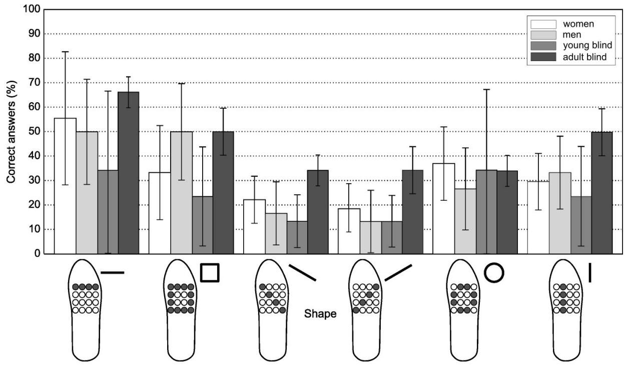


Figure 8. Performance of the 25 subjects in identifying shapes. The standard error is shown as an error bar.

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-insole, 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.

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.

		answered(%)				
	women	caution	SMS	call	relaxation	exaltation
presented	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**

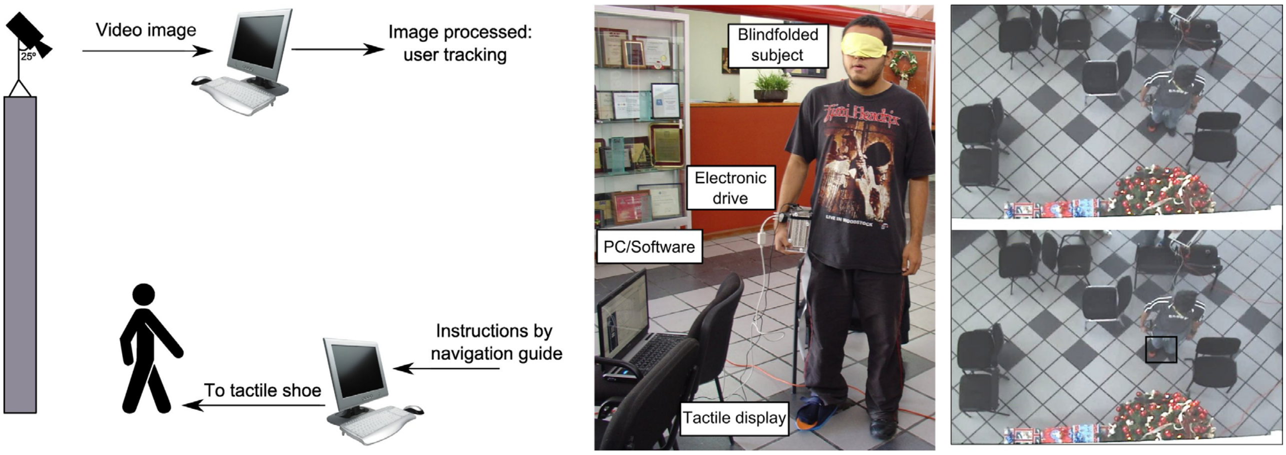
		answered(%)				
	men	caution	SMS	call	relaxation	exaltation
presented	caution	**50**	10	20	10	10
	SMS	10	**80**	0	10	0
	call	10	0	**80**	10	0
	relaxation	30	0	0	**50**	20
	exaltation	0	10	0	20	**70**

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).



(a) (b) (c)

Figure 9. (a) The experimental tracking platform. (b) Sighted subject in the navigation task. (c) One of the structured navigation environments: (top) original image as obtained from the camera and (bottom) subject feet detection by software.

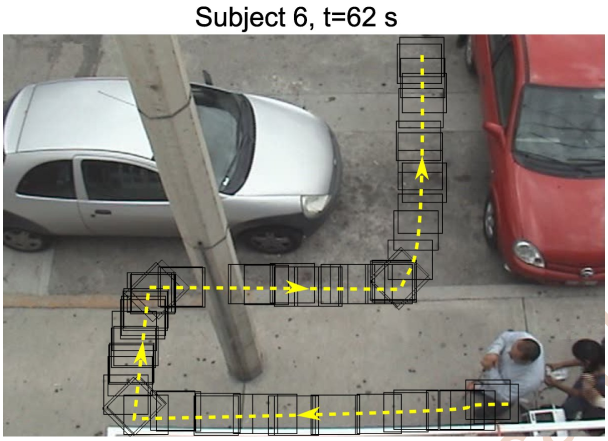


Figure 10. Results of the blind subject during the navigation task. A broken line is drawn to better appreciate the trajectory followed.

Fig. 10 shows the navigation trajectory performed by the blind subject. It is interesting to note that the blind subject performed in a more complex environment in much less time. Upon practice, it is expected that subjects become more efficient and used to the device.

The results are undoubtedly encouraging: they suggest that it is feasible to exploit tactile-foot stimulation for directional navigation in space.

6. Conclusion

This paper has presented the design, technical overview and preliminary evaluation of a novel human-computer interface for the foot: a shoe-integrated vibrotactile display.

Using an electromagnetic approach, a first prototype of 16 points has been developed. The prototype is compact, wearable and low-cost, as well as being simple and quick to assemble.

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?

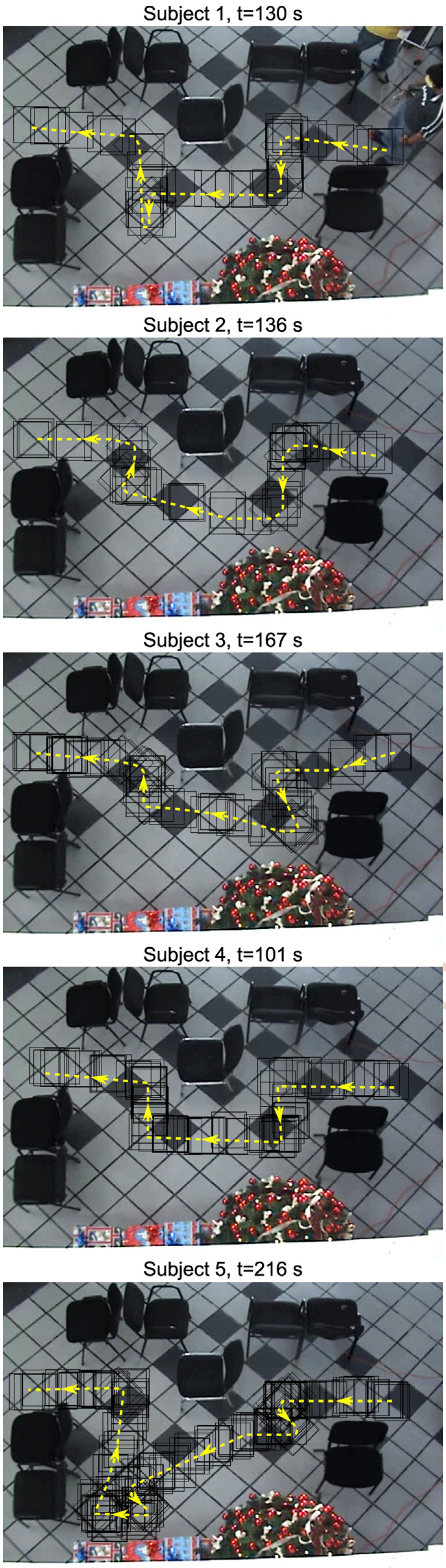


Figure 11. Results of the 5 sighted subjects in the navigation task. A broken line is drawn to better appreciate the trajectory followed.

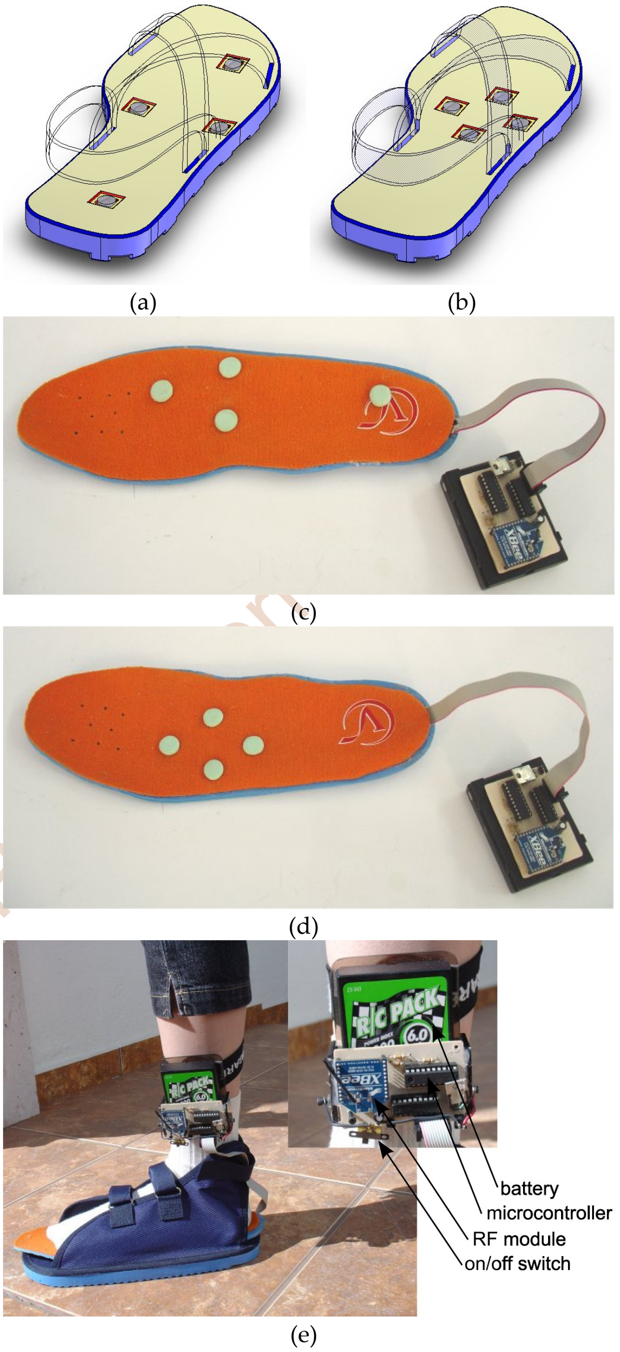


Figure 12. (a)-(b) Two new designs and (c)-(d) prototypes of shoe-integrated tactile displays. (e) Fully wearable devices with wireless connection.

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.

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ÍNDICE DE REVISTAS

TITLE	TITLE ABBREVIATION	COUNTRY	SCIENCE	SOCIAL SCIENCE
PROTEIN AND PEPTIDE LETTERS	PROTEIN PEPTIDE LETT	NETHERLANDS	Y	
PROTEIN ENGINEERING DESIGN & SELECTION	PROTEIN ENG DES SEL	ENGLAND	Y	
PROTEIN EXPRESSION AND PURIFICATION	PROTEIN EXPRES PURIF	UNITED STATES	Y	
PROTEIN JOURNAL	PROTEIN J	UNITED STATES	Y	
PROTEIN SCIENCE	PROTEIN SCI	UNITED STATES	Y	
PROTEINS-STRUCTURE FUNCTION AND BIOINFORMATICS	PROTEINS	UNITED STATES	Y	
PROTEOME SCIENCE	PROTEOME SCI	ENGLAND	Y	
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PROTEOMICS CLINICAL APPLICATIONS	PROTEOM CLIN APPL	GERMANY	Y	
PROTIST	PROTIST	GERMANY	Y	
PROTOPLASMA	PROTOPLASMA	AUSTRIA	Y	
★ PRZEGLAD ELEKTROTECHNICZNY	PRZ ELEKTROTECHNICZN	POLAND	Y	
PRZEGLAD GASTROENTEROLOGICZNY	PRZ GASTROENTEROL	POLAND	Y	
PRZEGLAD MENOPAUZALNY	PRZ MENOPAUZALNY	POLAND	Y	
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PSICOLOGICA	PSICOLOGICA	SPAIN		Y
PSICOTHEMA	PSICOTHEMA	SPAIN		Y
PSIHOLOGIJA	PSIHOLOGIJA	SERBIA		Y
PSIKHOLOGICHESKII ZHURNAL	PSIKHOL ZH	RUSSIA		Y
PSN-PSYCHIATRIE SCIENCES HUMAINES NEUROSCIENCES	PSN-PSYCHIAT SCI HUM	FRANCE	Y	
PS-POLITICAL SCIENCE & POLITICS	PS-POLIT SCI POLIT	UNITED STATES		Y
PSYCHE-ZEITSCHRIFT FUR PSYCHOANALYSE UND IHRE ANWENDUNGEN	PSYCHE-Z PSYCHOANAL	GERMANY		Y
PSYCHIATRIA DANUBINA	PSYCHIAT DANUB	CROATIA	Y	Y
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PSYCHIATRY INVESTIGATION	PSYCHIAT INVEST	SOUTH KOREA	Y	Y
PSYCHIATRY PSYCHOLOGY AND LAW	PSYCHIAT PSYCHOL LAW	AUSTRALIA		Y

TITLE	TITLE20	COUNTRY	SCIENCE	SOCIAL SCIENCE
INTERNATIONAL JOURNAL OF ACOUSTICS AND VIBRATION	INT J ACOUST VIB	UNITED STATES	Y	
INTERNATIONAL JOURNAL OF AD HOC AND UBIQUITOUS COMPUTING	INT J AD HOC UBIQ CO	SWITZERLAND	Y	
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