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A Shoe-Integrated Tactile Display for Directional Navigation

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Abstract— **This paper proposes a novel wearable interface for the foot: an on-shoe tactile display that enables users to obtain information through the sense of touch of their feet. A 16-point array of actuators stimulates the sole of the foot by inducing different vibration frequencies. Experiments to study how people understand information through their feet were conducted with 20 voluntary subjects. Results show that some shapes and patterns are discriminable and that tactile-foot stimulation could be used for a wide number of applications in human-machine interaction. In particular, results show that it is possible to exploit podotactile information for navigation in space.**

I. INTRODUCTION

Human interaction with space is based on cognitive representations built upon somatosensory data. The majority of the somatosensory information transmitted through the nerves into the brain is critical for key human functions such as motion, posture and sensing.

Somatosensory input from the lower limb, particularly from the foot sole, has long been recognized as an important source of sensory information in controlling movement and standing balance [1]. However the capabilities of the foot for information transmission have not been thoroughly explored.

What we know about the human foot is that it combines mechanical complexity and structural strength. The ankle serves as foundation, shock absorber and propulsion engine. The foot can sustain enormous pressure and provides flexibility and resiliency. Besides from being a functional structure, the cutaneous receptors of the foot sole continuously provide feedback information to assist in balance and walking. Skin receptors in the foot sole are sensitive to contact pressures [2] and to changes in the distribution of pressure [3]. 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 [4]-[5] illustrate the importance of cutaneous receptors in the control of posture and standing balance, no work to our knowledge has focused on evaluating the performance of the foot sole receptors for information transmission.

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, game 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) has been proposed to improve mobility and safety navigation independence of the blind. However, none of these devices is widely used and user acceptance is quite low. Several shortcomings have been identified in existing ETAs as main reasons for this rejection (a comprehensive review, evaluation and synthesis of ETAs can be found in [6]). One of these reasons is that most ETAs are still too burdensome and visually noticeable to be portable devices. Undoubtedly, this heightens the handicapped image and affects the user's self-esteem.

An on-shoe inconspicuous and visually unnoticeable ETA for blind people might represent a potential solution to this problem.

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

II. GUIDELINES FOR TACTILE-FOOT STIMULATION

It is well known that skin is the sense organ that 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 transmission of physical deformations by external forces to the nervous system.

Mechanoreceptors are usually classified based on their rate of adaptivity and receptive field [7]. The first refers to how quickly the cell adapts to a stimulus. Fast cells are useful for sensing texture and vibrations while the 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

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TABLE I

PROFILES OF CUTANEOUS MECHANORECEPTORS IN THE FOOT SOLE, AFTER [8].

Type	Number	% of total	Median threshold (mN)	Range (mN)	Receptive field size (mm^2)	
					Median	Range
SAI	15	14.4	35.6	4-744	70.9	11.8-277.5
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	0.5-2800	284.2	41.7-1248
Total	104	100	-	-	-	-

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. 1 shows the position of these receptors and their receptive fields in the plantar surface of the foot while table I 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 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 are by far majority and as aforementioned, 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 delivered force.

Concerning spatial discrimination, it can be seen from table I 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 center-to-center spacing.

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

From this first general study, we conclude that design goals for a FAI foot stimulation device should integrate an actuator array with 7 mm interspacing, stimuli frequencies of 5 to 40 Hz and delivered forces around 11.8 mN.

III. ON-SHOE TACTILE DISPLAY: DESIGN AND PROTOTYPE

A. Design concept

According to the physiological specifications just mentioned, a conceptual representation of the on-shoe tactile display is shown in fig. 2.

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

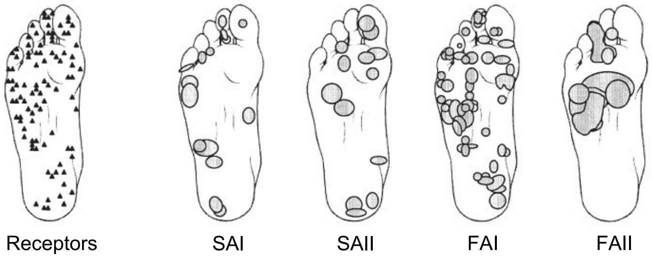


Fig. 1. Distribution of mechanoreceptors in the foot sole, after [8].

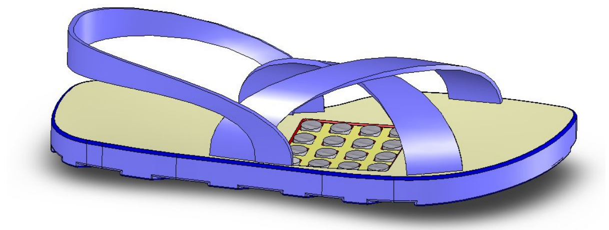


Fig. 2. Conceptual representation of a FAI cell stimulation device for the foot sole, [9].

B. Actuator

The actuator chosen for stimulating the sole of the foot is a miniature vibrating DC electric motor. The motors we use are of type C1030L-50 from Jinlong Machinery [10] originally intended for cell phones (Fig. 3 inset). Each motor is 10 mm diameter, 3 mm thick and 12 g weight. It is commercially available for 10 USD.

Experimental tests [9] 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. So, a vibration input command of 55 Hz would require a maximum of 400 mW from the power source.

Fig. 3 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 actuator allows a 10 mm interspacing, is capable of producing vibrating frequencies between 10-55Hz and axial forces around 13 mN, features that meet the criteria established above while being small, lightweight, low-cost and low-power consumption.

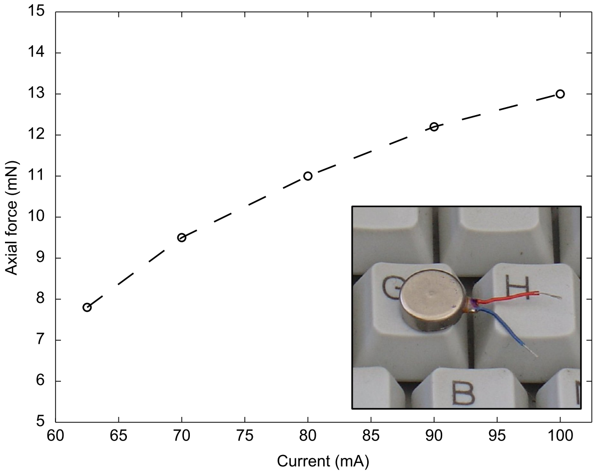


Fig. 3. Experimental measurements of the static axial force versus current. Inset: miniature vibrating motor.

C. Prototype

Fig. 4 shows the first prototype developed. It consists of 16 vibrating actuators all integrated in a foam shoe-insole.

Foam was chosen because it is easy to machine and it is well known for absorbing vibrations, shock and impact forces. Its absorbing material properties prevents from having an expanding vibration effect throughout the insole. Dots of an epoxy paste (plasticine) cover the actuators' entire upper surface and are in contact with the foot sole. This technique has proved to be an excellent vibration transmitter.

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

D. Electronic drive

Fig. 5 shows a schematic representation of the electronic system used to drive the on-shoe 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 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.

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

IV. PRELIMINARY EVALUATION ON TACTILE RENDERING

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

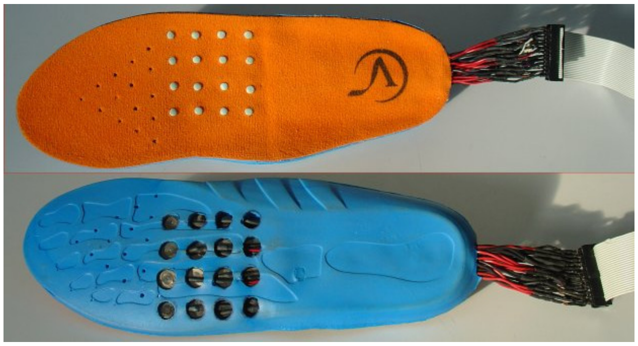


Fig. 4. Shoe-integrated tactile display: back and forth.

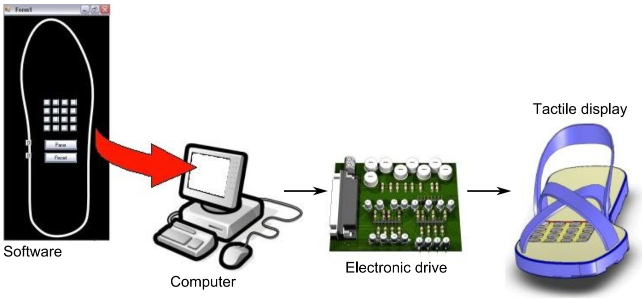


Fig. 5. Drive components of the shoe-integrated tactile display.

Twenty undergraduate students (10 men and 10 women) at Panamericana University participated voluntarily in the experiments. No special criteria were used to select them but availability. All participants were healthy sighted with no known impairments in tactile sensory or cognitive functions. Their ages ranged from 18 to 24 years old with an average age of 20.5. All were right-handed.

During the experiments, the subjects were seated wearing the tactile display on the right 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. Although the physiology of the foot indicates a maximum stimuli frequency of 40 Hz, all 20 subjects chose 55 Hz, the maximum vibration frequency of the actuators.

A. Experiment I: Direction recognition

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

Method

A dynamic straight line was presented to the 20 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. 6(a)).

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. 6(b) shows the results obtained from this session. Note an overall good performance: the minimum success rate is 64% while the maximum one is 83%. Also, note that there is no significant difference between the mean performances of men and women.

The standard deviation of the mean or standard error shows that there is a statistically significant difference in performance among women: 6 women performed almost perfect while 4 performed very poor.

B. *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 geometric and various simple shapes.

Method

Six basic geometric shapes were used for the second session: square, circle, vertical line, horizontal line, diagonal and inverted diagonal. All 20 subjects were asked to match what they felt tactually with one of these shapes.

A set of 18 shapes was presented to the subjects in one trial. During the trial, each shape was presented 3 times randomly. Subjects had no time restriction to provide their answers and, upon request, they could have the shape refreshed on the display.

Results

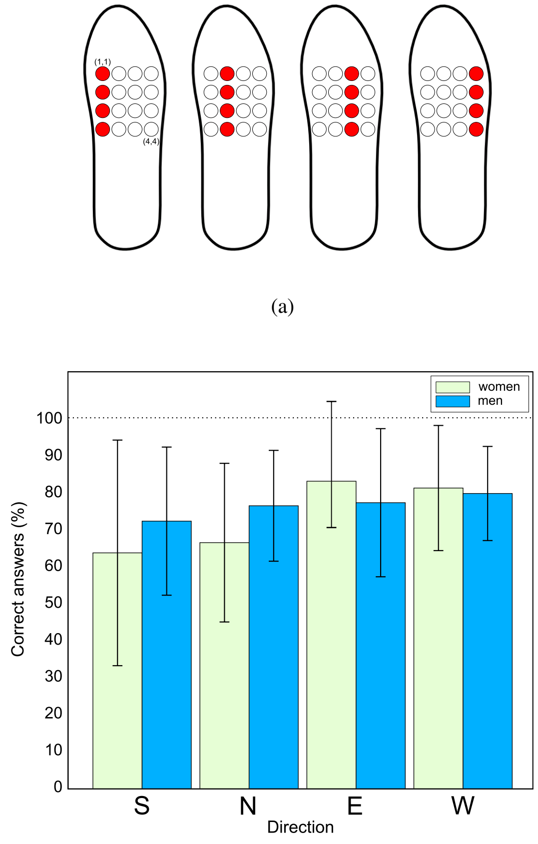
Fig. 7 shows the results obtained from this session. This task is evidently much more complicated than the first one and poorer scores were obtained.

The minimum and maximum recognition rates were 18.5% and 55.5% for women and 13.3% and 50% for men. The mean percents were 32.3% and 31.3% for women and men, respectively. Again, there is no significant difference between the mean performances of men and women.

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. Although vibrations minimally expand mechanically within the foam shoe-insole, they do expand throughout the skin affecting perception.

C. *Experiment III: Pattern recognition*

In human-computer interaction, there is the challenge to display information in a kind of short messages such as warning signals or emotions. The third session aimed to determine whether the subjects could recognize and associate tactile patterns displayed on the foot with daily information, familiar signals and emotions.



(a)

(b)

Fig. 6. Direction recognition task: (a) Schedule of activation of the vibrating actuators for the direction recognition task. Example for West. (b) Performance of the 20 subjects at identifying directions. The standard error is shown as an error bar.

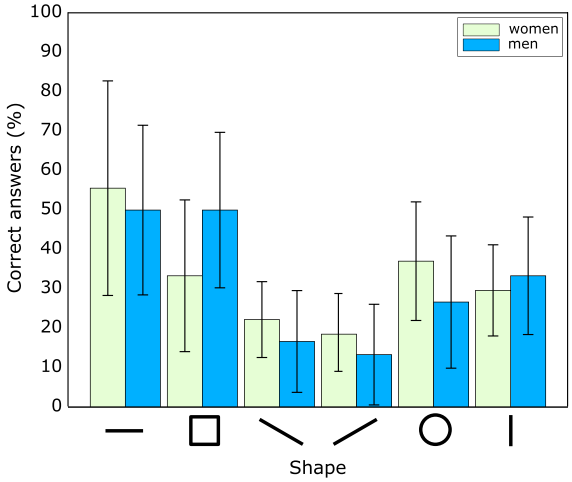
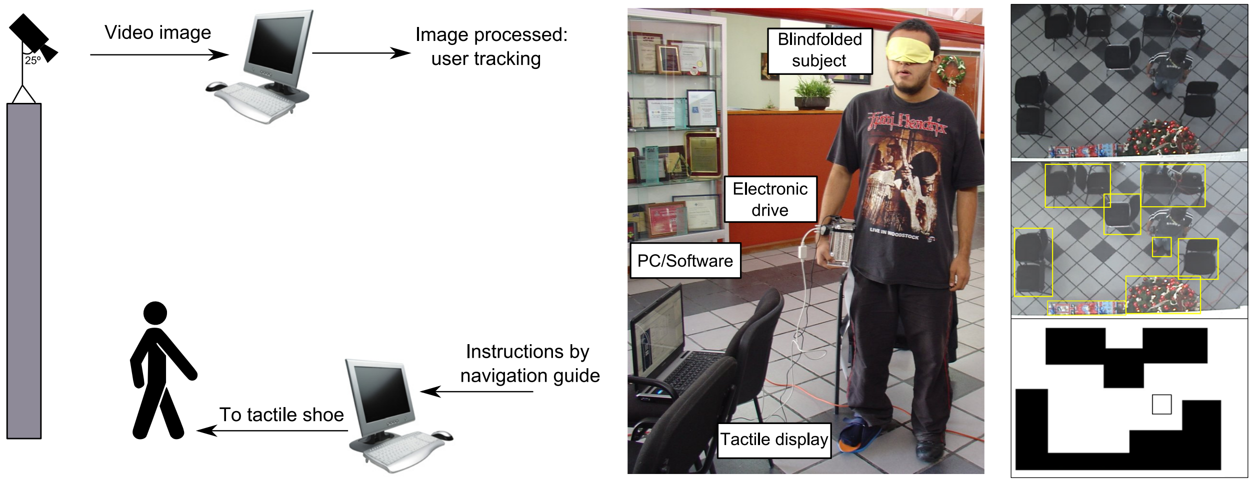


Fig. 7. Performance of the 20 subjects at identifying shapes. The standard error is shown as an error bar.

Method

Five tactile patterns were used for this session: caution, SMS, phone call, relaxation and exaltation. Vibrotactile signals were modulated in accordance to these patterns:



(a) (b) (c)

Fig. 8. (a) The experimental tracking platform. (b) Subject in the navigation task. (c) The structured navigation environment with static obstacles: (top) original image as obtained from the camera, (middle) obstacle and subject feet detection by software and (bottom) final processed image.

- <u>Caution</u> was generated in accordance to its visual equivalent: 2 intermittent vertical bars (highway signal).
- <u>SMS</u> was generated in accordance to mobile phones: 2 consecutive short vibrations, then a pause, then 2 consecutive short vibrations.
- <u>Phone call</u> was also generated as in mobile phones: a long vibration, then a pause, then a long vibration.
- <u>Exaltation</u> is defined as the transition between calm and exited. This emotion was generated by activating consecutively all actuators.
- <u>Relaxation</u> is the inverse emotion. It was generated by turning consecutively all actuators off.

Again, all 20 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. 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 once given.

Results

Table II summarizes the results obtained for both women and men. Men performed much better than women with a mean percent of 66% against 50%.

Note that the SMS and phone call patterns were perfectly well identified by most of the subjects while exaltation and relaxation were not so clear among women. These results suggest that people can easily identify and relate tactile-foot signals to information and emotions.

TABLE II

Distribution of answers (%) in the pattern recognition experiment.

		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

D. Experiment IV: Navigation in space

The fourth session aimed to determine whether the subjects could actually navigate in a 3D environment using podotactile information. For this purpose, the experimental tracking platform in fig. 8(a) was set. It encompasses 3 main elements: a wide angle color camera, a PC and a dedicated software running on the PC.

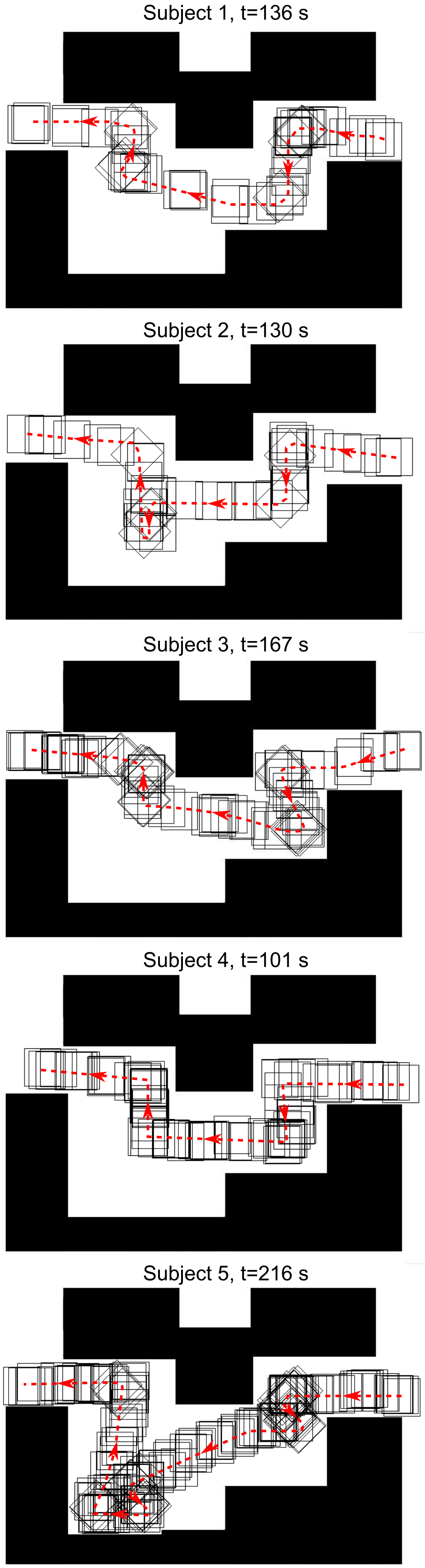
The camera is located 4 m above the ground surface at 25° from vertical. It was configured to capture images every 0.5 s. Acquired images are sent to the PC for processing. Image processing focuses on subject tracking: due to the angle of the camera, it was experimentally verified that the subject's position and orientation in the environment is best determined by the feet. A Matlab self-developed script performs feet detection and confines the surface of interest into a square. Fig. 8(c) shows the navigation environment proposed to the subjects and the equivalent processed image.

Method

The best five subjects -identified from the previous tests- were invited to participate in this last session. All 5 were male. During the test, the subjects were blindfolded so that no cue from sight could be obtained. They were wearing the on-shoe tactile display on the right foot while holding the electronic drive with the right hand (Fig. 8(b)).

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. Navigation directions were provided by a human-assistant located outside the navigation environment.

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.



Subject 1, t=136 s

Subject 2, t=130 s

Subject 3, t=167 s

Subject 4, t=101 s

Subject 5, t=216 s

Fig. 9. Results of the 5 subjects in the navigation task. A broken line is drawn to better appreciate the trajectory followed.

Results

Fig. 9 shows the 5 navigation trajectories. Note an overall good performance: all subjects were capable of completing the task in less than 4 min. Upon training, it is expected that subjects become more efficient and used to the device.

Subjects 1, 3 and 4 had no error following the instructions. Subject 2 performed a false turn which was immediately corrected. Subject 5 had several errors: 2 false turns and bumps into the obstacles once.

Results are undoubtedly encouraging: they suggest that it is feasible to exploit podotactile information for directional navigation in space.

V. CONCLUSION

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

The role of tactile perception by the human foot and the performance of the on-shoe tactile system were evaluated through a set of tactile perception tests involving direction, shape, pattern recognition and directional navigation.

Results show that people understand easily the direction of motion of dynamic information. However, shape recognition is more difficult. Vibrating information on the foot is not appropriate for precise recognition of a shape. Pattern recognition rates were satisfying which suggest 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. Collected data show that it is feasible to exploit podotactile information for navigation in space.

Current work evaluates (1) whether long-term vibrating stimuli affects balance and walking and (2) user performance depending on cognitive load. Future work expects to integrate the concept of podotactile stimulation in ETAs for the blind.

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