# Wearable cutaneous device for applying position/location haptic feedback in navigation applications

Lisheng Kuang, Marco Aggravi, Paolo Robuffo Giordano, Claudio Pacchierotti

***Abstract*— We present a wearable cutaneous device capable of applying lateral stretch and position/location haptic feedback to the user's skin. It is composed of a 2D Cartesian-like structure able to move a pin on the plane parallel to the skin. The pin houses a small metallic sphere of 8 mm of diameter. The sphere can be either left free to rotate when the pin moves, providing location feedback about its absolute position, or kept fixed, providing skin stretch about its relative displacement. The device weighs 30 g for a workspace of 12×12 mm. This paper presents the device's design and actuation together with a perceptual evaluation of the position/location feedback provided by the device when worn around the forehead, forearm, and hand. Finally, we test the device in a preliminary human navigation task. Results show an average navigation error of 0.26 m, which is comparable to state-of-the-art vibrotactile guidance techniques using two vibrating armbands.**

## I. Introduction

Wearable haptic devices have been used in various human-machine and human-robot interaction applications [1], including robotic teleoperation [2], rehabilitation [3], and guidance [4], [5], [6], [7], [8]. Indeed, using wearable haptics for navigation is promising. In this respect, vibrotactile feedback has been the most popular choice. For example, Kerdegari et al. [4] and Bertram et al. [9] proposed a head-mounted device conveying ultrasonic range information trough vibrations; blindfolded participants navigated a maze with and without the vibrotactile assistance on the helmet. Scheggi et al. [5] used two vibrotactile bracelets on the left and right forearms to make a user follow a mobile robot while avoiding static and dynamic obstacles. On the other hand, non-vibrotactile haptics is less common for navigation. Examples are the works of Aggravi et al. [6], whose haptic device provides skin stretch, pressure, and vibrations for robotic teleoperation and guidance applications; Chinello et al. [8], who designed a skin stretch device for generating guidance stimuli at the palmar, dorsal, ulnar, and radial sides of the arm; and Berning et al. [10], who used six pressure actuators around the forehead to convey spatial information for obstacle avoidance. Similarly, Bark et al. [11] and Stanley et al. [12] used skin stretch to provide directional cues, while Spiers et al. [13] presented a hand-held shape-changing device to represent heading and proximity to targets.

We present a 2-DoF wearable cutaneous device able to provide skin stretch and position/location haptic feedback in a 12×12 mm workspace. Two servomotors move a Cartesian-like structure, actuating a pin housing a small metallic sphere. The sphere can be either left free to rotate when the pin moves, providing location feedback about its absolute position, or kept fixed, providing skin stretch about its relative displacement. The device is worn using an elastic belt that can be easily adapted to many parts of the body. After presenting the mechanical design of the device, we evaluate the effectiveness of using location haptic feedback when the device is worn on the forehead, forearm, and back of the hand. Finally, we test the device in a human navigation task. Users are asked to move along a target trajectory following the cutaneous location/position feedback provided by the device. While the proposed device is also capable of providing skin stretch, we focus our evaluation on *position* feedback. Wearable devices providing position feedback are quite rare. For example, Rossi et al. [14] developed a 1-D position-feedback device for the forearm, able to convey proprioceptive information about the aperture of a prosthetic hand, while Provancher et al. [15] developed a 2-D position-feedback device for the fingertip to render the contact location in telemanipulation and virtual reality applications. We present one the first wearable device capable of providing skin stretch and position feedback for guidance.

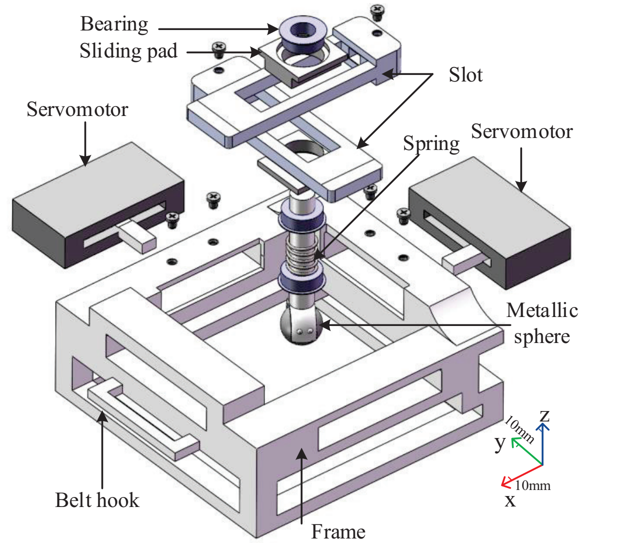


Fig. 1. Assembly of the 2-DoF wearable cutaneous device. A metallic sphere either provides position/location feedback or skin stretch in a 12×12 mm workspace. We tested the device at the forehead, forearm, and hand. A video is available as supplemental material and at https://youtu.be/38BHsYCQ6uM.

## II. Device design and actuation

The CAD assembly of the device is shown in Fig. 1, while a detail of its actuated parts is shown in Fig. 2a. A video of the device is available at https://youtu.be/38BHsYCQ6uM.

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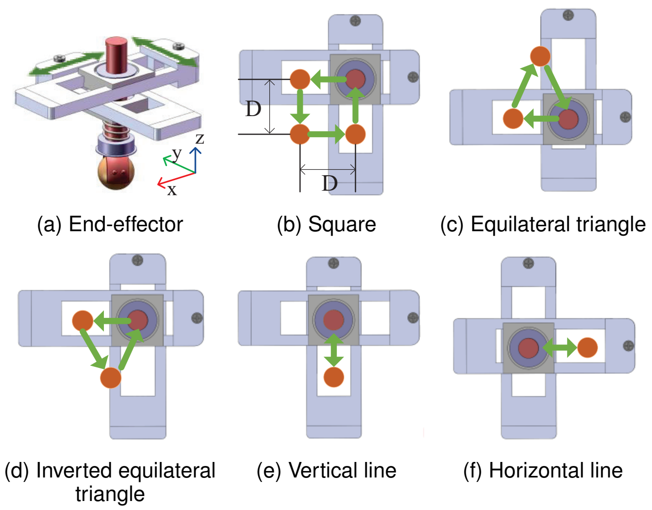



Fig. 2. Actuation principle. (a) The servomotors move two intersecting guides housing a cylindrical pin, that in turn houses a metallic sphere contacting the skin. The maximum displacement of each guide is D = 12 mm. (b)-(f) To evaluate the rendering capabilities of our device, we ask subjects to recognize five different shapes: (b) a square, (c) an equilateral triangle, (d) an inverted triangle, (e) a vertical line, and (f) a horizontal line.

### A. Mechanism and structure

The cutaneous device is composed of a squared 60×60×30 mm ABS frame housing two linear servomotors that drive two intersecting guides. For our prototype, we used two VS-19 Linear Pico Servomotors (max. stall torque of 60 gf.cm at 3.7 VDC, yielding a theoretuca). A Maestro board (Pololu, USA) is in charge of controlling the motors. At the intersection of the guides, we fixed a cylindrical pin indenting the skin. It has a diameter of 6 mm and a length of 30 mm. A metallic sphere is housed at the end of the pin, in contact with the skin. When the pin moves, the sphere can be either left free to rotate or not. If it rotates freely on the skin, it provides position/location feedback about its absolute position; if it is blocked, it provides skin stretch about its relative motion. The behavior of the sphere, and thus the feedback provided, can be chosen by adjusting how strong the sphere is fastened to the pin. We also explored the possibility of employing a small electromagnet between the pin and the sphere to dynamically change the sphere's behavior without any manual intervention; however, this technique is not used in this work. Finally, a spring on the pin ensures that the sphere is always in contact with the skin, applying a constant pressure throughout the interaction.

### B. Wearability

At two opposite sides of the ABS frame, we placed two hooks for fixing an elastic belt. In the following Sections, we evaluate the device around the forehead, forearm, and hand. However, the device can be easily worn in other parts of the body. A thin layer of foam between the frame and the skin ensures a comfortable and firm fastening, enabling the user to focus on the feedback provided by the sphere. Figure 3 shows the device worn by a user. For attaining increased wearability, we can also directly attach the cutaneous device on the skin using a layer of adhesive silicone, without needing the elastic belt. We already used this technique for fixing a much heavier wearable haptic device on the back of a user's hand [16]. This approach enables to attach the device wherever needed, with very little impact on the user's mobility.

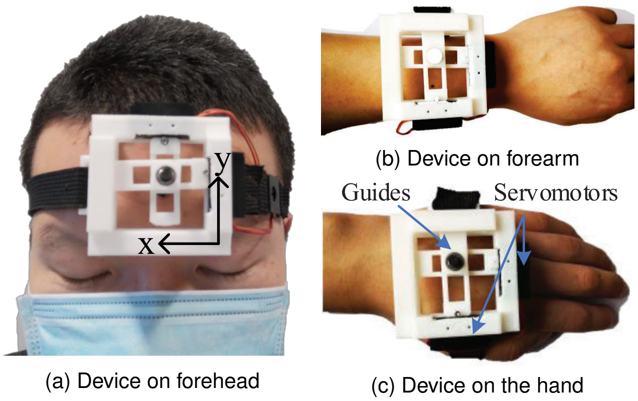



Fig. 3. The prototype of our wearable cutaneous device worn on the (a) forehead, (b) forearm, and (c) back of the hand.

## III. Perceptual Evaluations

While research on skin stretch devices is well documented [17], [18], we focus on evaluating the effectiveness of our wearable cutaneous device in providing position/location feedback. We carried out two perceptual experiments. The first one evaluates the differential threshold for the location feedback (see Sec. III-C), while the second one analyses the capability of recognizing different shapes/patterns (see Sec. III-D). In both experiments, we tested the device when worn on the forehead, forearm, and back of the hand. As already discussed in Sec. I, although the device is also capable of providing skin stretch, we focus our evaluation on position/location feedback.

### A. Participants

Five subjects participated in the experiments (4 males, 1 females, age 27–34, right-handed). Two of them had previous experience with haptic interfaces. None of the participants reported any deficiencies in their haptic perception abilities. Participants received an information sheet with the experiment details and signed a consent form. The study has been approved by Inria's ethics committee (Saisine 513).

### B. Setup

Users were asked to wear the wearable cutaneous device around the considered part of the body (forehead, forearm, or hand) in a comfortable yet firm way (see Sec. II-B for details). A picture of the device being worn is shown in Fig. 3. Then, the experimenter spent around two minutes ensuring that the device was worn correctly and that the end-effector contacted the skin. As the servomotors make some noise when actuated, users were also required to wear a pair of noise-cancelling headphones. Finally, the Maestro board commanding the servomotors was controlled by an external computer through ROS.

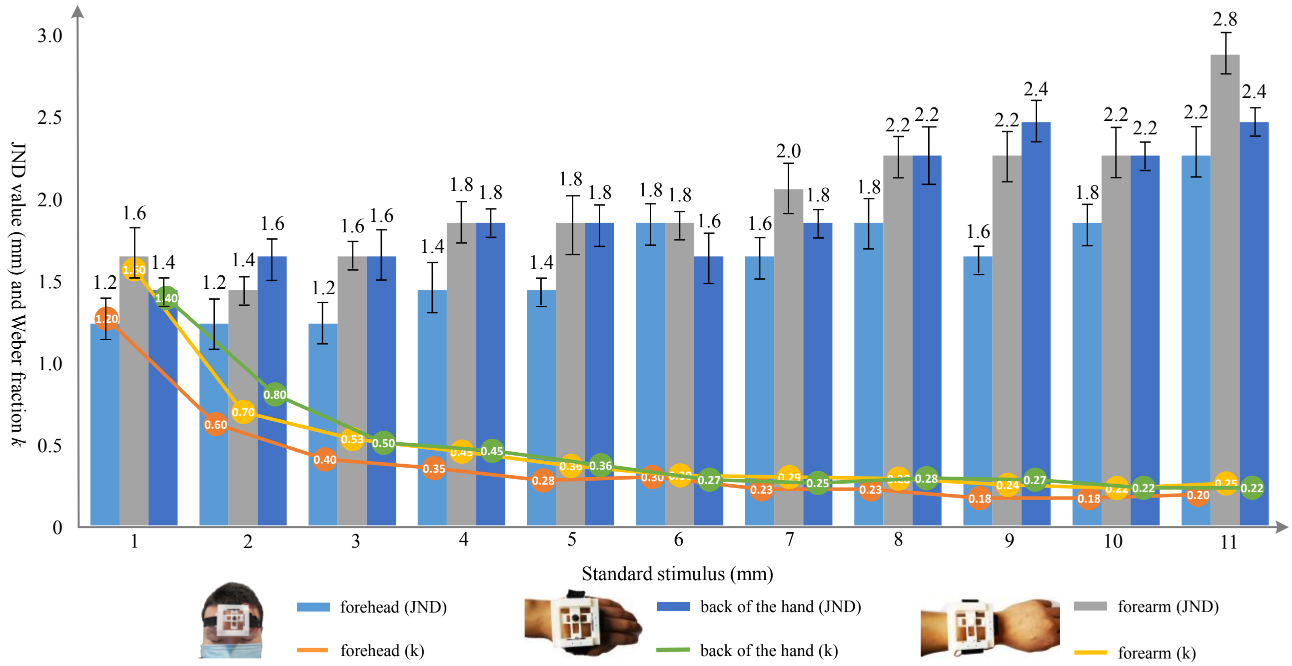



Fig. 4. Perceptual experiment: differential threshold. Results per each standard stimulus and considered location, considering the absolute JND value (mm) and the Weber fraction $k$.

### C. Differential threshold or Just-Noticeable Difference (JND)

The Just-Noticeable Difference (JND) provides information about how different two displacements conveyed with our device need to be so as to be *perceived* as different. This information is important for correctly controlling the device's output and known the renderable range of information. It also reflects the fact that humans are usually more sensitive to changes in weak stimuli than they are to similar changes in stronger stimuli. E. Weber proposed the proportional law $JND = kI$, suggesting that the differential threshold increases with increasing intensity $I$ of the stimulus. Constant $k$ is thus referred to as "Weber's fraction".

In our experiment, subjects were asked to wear the device as indicated in Sec. III-B and shown in Fig. 3. We evaluated the JND for two directions of motion, vertical (y axis in Fig. 3a) and horizontal (x axis in Fig. 3a), using the method of limits adapted for finding JND values [19]. Subjects were required to tell the experimenter when the two provided stimuli felt different. We tested the JND at eleven standard/reference stimuli, from 1 mm to 11 mm, with a step-size of 0.1 mm (the minimum displacement the servomotors can actuate).

Fig. 4 show the recorded JND and Weber's fraction for each standard stimuli and considered location. Although further analysis is needed, we can already see that the forehead shows the highest recognition rates, followed by the forearm and the back of the hand, which shows little difference between each other. As expected, Weber fractions $k$ are quite consistent across columns, except for the standard stimulus of 1 mm. We did not report separately the results of the two directions of motion as we did not find any relevant difference between them.

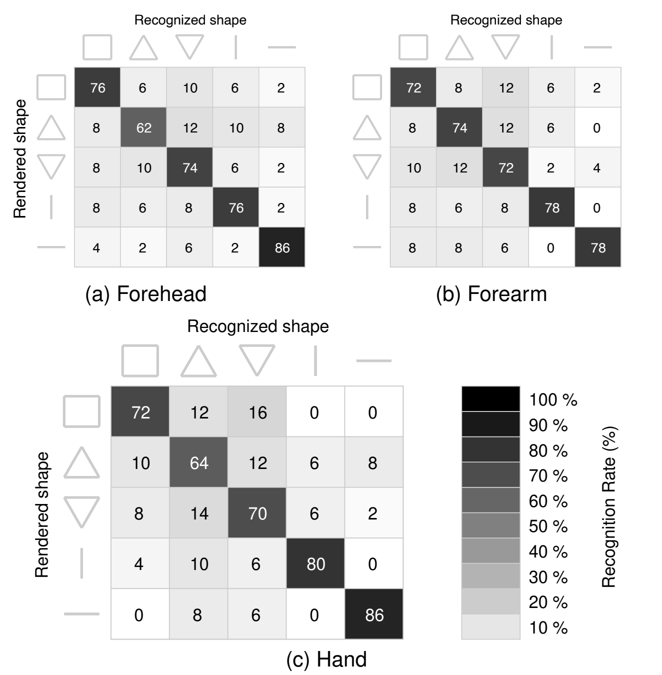



Fig. 5. Perceptual experiment: shape recognition. Confusion matrices showing the recognition rates of five shapes (square, equilateral triangle, inverted equilateral triangle, vertical line, horizontal line) in the three tested location ((a) forehead, (b) forearm, (c) hand).

### D. Shape recognition

Our second experiment aimed at evaluating the capability of our device in rendering different shapes on the user's skin, once again when worn on the forehead, arm, and hand. As shown in Fig. 2(b)-(f), we considered five shapes: square, equilateral triangle, inverted equilateral triangle, vertical line, and horizontal line. We chose these shapes as they have

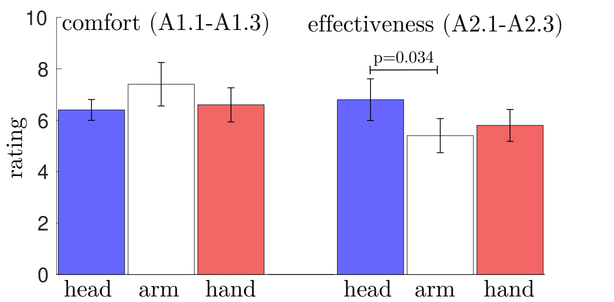
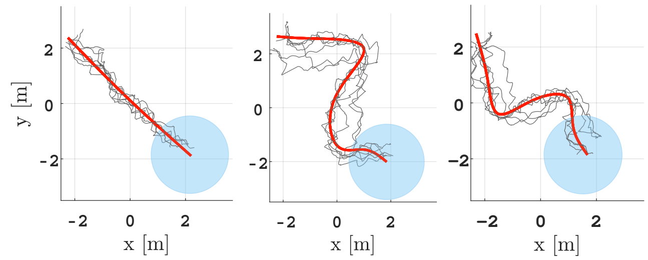



Fig. 6. Perceptual experiment: shape recognition. Mean and 95% confidence interval of the subjective ratings given by the subjects in the questionnaire, with noncontiguous Likert scale answer. They were asked to evaluate the comfort and effectiveness of wearing the device on the head, arm, and hand.




(a) path $p_1$ (b) path $p_2$ (c) path $p_3$

Fig. 7. Navigation use case. We considered three target paths (red), inspired from [7]. Six subjects carried out one navigation trial per path (grey).

edges, which are known to be salient features in haptic shape perception [20], and they could be used for navigation purposes, e.g., to indicate the user to stop, look up, look down, move up/down, move left/right, respectively. The pin moved at a speed of 12 mm/s.

Subjects were again asked to wear the device as indicated in Sec. III-B and shown in Fig. 3. They were then given the possibility of trying/feeling each shape once before the beginning of the experiment. After that, subjects were presented with ten sequences of rendering, each sequence contains 15 rendering of shapes in a random order, i.e., each shape was repeated three times. After each sequence, subjects were asked to tell which shape they felt.

Figure 5 shows the results of this experiment for each shape and considered location. Confusion matrices indicate that subjects were able to well recognize the five shapes in all the considered situations. The lowest recognition rate, 62%, was registered when the equilateral triangle was rendered on the forehead, while the highest one, 88%, was registered when the horizontal line was rendered on the back of the forehead. As expected, more complex shapes (square and triangles) were harder to recognize than easier ones (lines).

Immediately after the experiment, participants were asked to fill in a six-item questionnaire using bipolar Likert-type 9-point scales, rating the following assertions:

(A1.1) It was comfortable to wear the device on the forehead.
(A1.2) It was comfortable to wear the device on the forearm.
(A1.3) It was comfortable to wear the device on the hand.
(A2.1) It was easy to identify the shapes when the device was worn on the forehead.
(A2.2) It was easy to identify the shapes when the device was worn on the forearm.
(A2.3) It was easy to identify the shapes when the device was worn on the hand.

A score of 9 indicated that the subjects fully agreed with the assertion, while a score of 1 indicated that they completely disagreed with it.

Fig. 6 shows the average evaluation of each question. A Friedman test showed a statistically significant difference between the means of the three locations in terms of effectiveness ($\chi^2(2)$ = 7.444, $p$ = 0.024, a = 0.05) but not in terms of comfort ($\chi^2(2)$ = 1.529, $p > 0.05$, a = 0.05). The Friedman test is the non-parametric equivalent of the more popular repeated-measures ANOVA. The latter is not appropriate here since the dependent variable (i.e., the subjects' answer to the questionnaire) was measured at the ordinal level. Post hoc analysis with Bonferroni adjustments revealed a statistically significant difference in the perceived effectiveness when the device was worn on the forehead vs. forearm ($p = 0.034$).

In addition to this questionnaire, subjects were also asked which position of the device they preferred. Four out of six preferred when the device was placed on the forehead, one on the back of the hand, and one on the arm.

## IV. Navigation Use Case

After this perceptual evaluation, we tested the effectiveness of the proposed device in a human navigation task.

### A. Experimental setup

The navigation was carried out in an indoor 4×5 m room instrumented with twelve optical cameras (Vicon Motion Systems, UK) tracking the motion of the human users in real time. Such tracking system features little latency and it is suitable for the real-time tracking and guidance of human users, as already proven in [21], [22].

Participants wore the cutaneous device around the forehead in a comfortable yet firm way (see Sec. II-B for details). To avoid receiving any additional information about the environment, participants were also blindfolded and wearing headphones. We chose to wear the device on the forehead as it showed good performance and was the location most preferred by the subjects in Sec. III. As before, the experimenter spent around two minutes ensuring that the device was worn correctly and that the end-effector contacted the skin. Users were required to wear a pair of noise-cancelling headphones. A computer, carried on a backpack by the user, controlled the device's Maestro board through ROS.

A video of the navigation experiment is available as supplemental material and at https://youtu.be/38BHsYCQ6uM. In the trial shown in the video, the subject does not wear the headphones so as to better show the device.

### B. Subjects

Six subjects participated in this navigation experiment (4 males, 2 females, age 27–34, right-handed). Five of them had also participated in the shape recognition experiment. Two of them had previous experience with haptic interfaces. None of the participants reported any deficiencies in their haptic perception abilities.

### C. Task and methods

Inspired from our previous work [7], we considered three target paths, shown in red in Fig. 7. Participants were asked to wear the device on the forehead, keep their head pointed forward, and follow the provided guidance feedback as closely as possible. At the end of the indicated path, subjects were provided with three shape patterns in a randomized order, similarly to what we did in Sec. III-D. The rendering of shapes at the end of the path can convey the user with information about additional tasks to carry, e.g., push a button, open a door, turn a valve. We decided to render the three most complex shapes for this use case, i.e., square, equilateral triangle, or inverted equilateral triangle. The area where subjects were provided with the target shape instead of guidance feedback is shown in light blue in Sec. III-D (an area of 1.4 m radius centered at the end of each path). While subjects knew they were going to receive a shape to identify at some point during the task, they did not know when it would happen. Each participant repeated the combined navigation/recognition task once per path, yielding to 18 navigation trials in total. Recorded paths are depicted in grey in Fig. 7. This task was inspired from industrial training tasks, where operators need to carry out a target movement and then execute a specific action, e.g., pushing a button, pulling a level, turning a knob.

Guidance feedback was conveyed through location/position feedback provided by the cutaneous device, indicating the direction toward the reference target path. Given the similarity between the human locomotion and the simplified kinematics of a unicycle robot [23], and considering that the user is moving forward, it is possible to indicate a desired rotation that would lead him or her to the desired path. This control approach has been described in [24] and has been used in [5], [7] for human navigation using vibrotactile haptic feedback. In our case, this rotation feedback was delivered through our position/location cutaneous system and it was proportional to the distance of the user from the path: if the person had to turn left, the pin end-effector would move the sphere toward the left, i.e., $P_{(x,y)} = [\,6 - \alpha,\ 6\,]^T$ with $0 \leq \alpha \leq 6$ proportional to the user error in following the path; conversely, if the person had to turn right, the pin would move toward the right, i.e., $P_{(x,y)} = [\,6 + \alpha,\ 6\,]^T$.

### D. Results

As a measure of performance, we registered the error in following the target path, calculated as the average distance of the user from the path throughout the trial. We compare the performance of our device with a recent vibrotactile haptic guidance technique [7]. Aggravi et al. [7] evaluated the use of two vibrotactile armbands, one on each arm, to guide a human user along predefined paths very similar to the ones considered in this work. Each armband was composed of four vibrotactile motors positioned evenly around the arm.

Figure 8 shows the results of the navigation experiment for each path, 1, 2, 3, and for each guidance methods, our position/location feedback technique and the state-of-the-art vibrotactile method of [7]. Figure 9 shows the recognition rate for the shape provided at the end of the path. Results show that, for all paths, the average walking speed in the navigation is 0.207 m/s, the navigation error was rather small (0.26 m in average) and comparable with that registered by Aggravi et al. [7]. However, with respect to [7], here we only use one device. Moreover, it is known that providing sustained vibrations becomes quickly uncomfortable [25], so other types of feedback might be preferable. Finally, the proposed device can be more easily worn wherever needed, especially in the version using adhesive silicon (see Sec. II-B). All these considerations make the proposed navigation technique and device design rather promising.

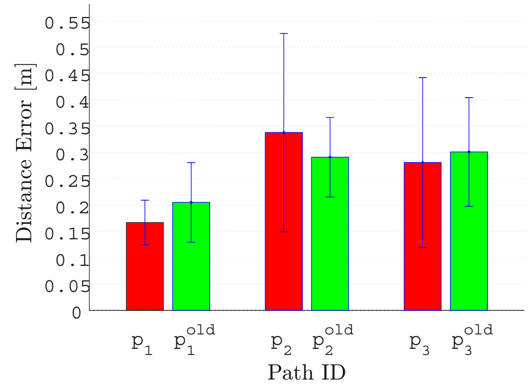



Fig. 8. Navigation use case. Mean and standard deviation of the error in following the target path for the three paths and two guidance methods: using position feedback provided by our device or vibrotactile feedback provided by two vibrotactile armbands from [7] (superscript "old").

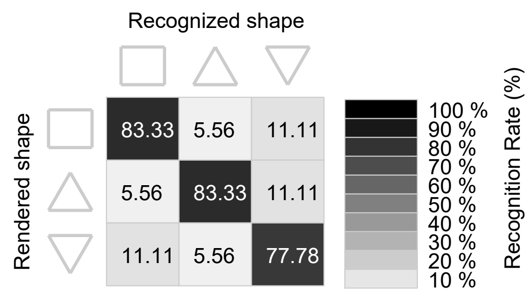



Fig. 9. Navigation use case. Recognition rate for the shape provided at the end of the path. Each shape was provided twice.

## V. Conclusions and Future Work

We presented a wearable cutaneous device able to apply 2D skin stretch and position/location haptic feedback on a workspace of 12×12 mm. Two linear servomotors actuate two intersecting guides housing a cylindrical pin at their intersection. By moving the guides, the motors can control the position of the pin within the workspace. At the end of the pin, in contact with the skin, we placed a metallic sphere, which can be either left free to rotate when the pin moves or not. In the first case, the sphere provides location feedback about its absolute position, while in the second case it provides skin stretch about its relative displacement. The device weighs 30 g for an overall encumbrance of 60×60×30 mm. It can be easily worn through an elastic band, similarly to an armband, or using a layer of adhesive silicone, similarly to a gel patch. The device can be embedded in garments or other devices, such as a bike helmet.

This paper presents the device design, its actuation principle, and a series of experiments evaluating the position/location feedback it provides. First, we evaluate the differential threshold of the provided feedback when the device is worn on the forehead, forearm, and hand. The device showed the lowest JND (best performance) when worn on the forehead, but also the two other locations performed rather well, with a Weber fraction around 0.20. Then, we carried out a shape recognition experiment, where subjects were asked to recognize five shapes rendered by the device on the forehead, forearm, and hand. Recognition rates varied between 62% and 86%, well above the chance level. No striking difference between the three locations was observed, although further statistical analysis is needed. As expected, more complex shapes (square and the two triangles) were harder to recognize than simpler shapes (the two lines). Finally, we evaluate the performance of our device in guiding blindfolded users along three predefined paths. Users were asked to wear the device on the forehead and follow its guiding feedback while walking in an instrumented room. Results show that users were able to follow the indicated paths rather well and that their performance is comparable with that registered in another work on human haptic guidance, where users were guided using two vibrotactile armbands. The results of our experimentation show that the proposed device and feedback is a viable approach for navigation, providing a more comfortable and flexible solution with respect to more popular vibrotactile solutions.

Future work will focus on improving the device design: reduce its encumbrance and weight, following the guidelines of [1]; improve the actuation system, increasing the device's resolution and workspace; dynamically change the feedback provided between skin stretch and location/position stimuli, adjusting the friction between the sphere and the pin using an electromagnet. Moreover, we want to carry a more extensive experimentation, involving more subjects in a wider range of navigation scenarios (e.g., outdoor) and testing also the skin stretch feedback. Another important variable to consider is the speed is the provided sensation, which might play a role in the perception and recognition of sensations and was not addressed in this work.

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