The hRing: a Wearable Haptic Device to Avoid Occlusions in Hand Tracking

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***Abstract*— The wearable electronics business has powered over $14 billion in 2014 and it is estimated to power over $70 billion by 2024. However, commercially-available wearable devices still provide very limited haptic feedback, mainly focusing on vibrotactile sensations. Towards a more realistic feeling of interacting with virtual and remote objects, we propose a novel wearable cutaneous device for the proximal finger phalanx, called "hRing". It consists of two servo motors that move a belt placed in contact with the user's finger skin. When the motors spin in opposite directions, the belt presses into the user's finger, while when the motors spin in the same direction, the belt applies a shear force to the skin. Its positioning on the proximal finger phalanx improves the capability of this device to be used together with unobtrusive hand tracking systems, such as the LeapMotion controller and the Kinect sensor. The viability of the proposed approach is demonstrated through a pick-and-place experiment involving seven human subjects. Providing cutaneous feedback through the proposed device improved the performance and perceived effectiveness of the considered task of 20% and 47% with respect to not providing any force feedback, respectively. All subjects found no difference in the quality of the tracking when carrying out the task wearing the device versus barehanded.**

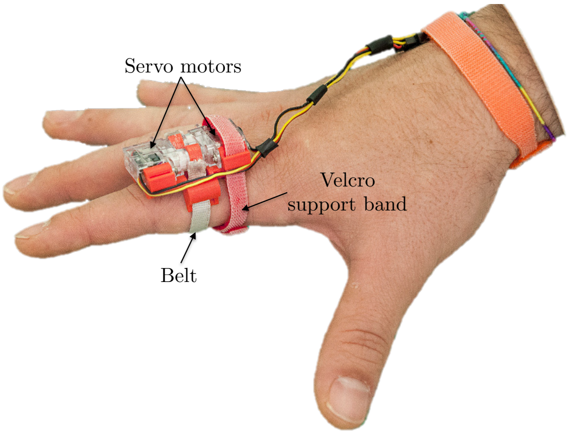

Fig. 1. The proposed 2-DoF cutaneous device. It consists of two servo motors that move a belt placed in contact with the user's finger skin. It is able to provide both normal and shear forces to the finger. Its positioning on the proximal finger phalanx improves the capability of this device to be used together with unobtrusive tracking systems such as the LeapMotion controller.

I. INTRODUCTION

The complexity of the world around us is creating a demand for novel interfaces that will simplify and enhance the way we interact with the environment. In this respect, there is a variety of new *wearable* devices, called "wearables", that have been developed specifically for this purpose. Notable examples are the Google Moto 360, the Asus ZenWatch, the Samsung Gear Live, and the Apple Watch. There are even dedicated operating systems, such as the Android Wear and the watchOS, that provide functions and applications customized for these devices. This market stems from the need for wearability, which is a key element for a natural interaction with nowadays technology [1], [2]. Wearability of robotic devices will enable novel forms of communication, cooperation, and integration between humans and robots. Specifically, wearable *haptics* will enable devices to communicate with the human wearer during his or her natural interaction with the environment they share. In this respect, Apple recently unveiled the Apple Watch, which embeds a linear actuator able to make the watch vibrate. It is used whenever the wearer receives an alert or notification, or to communicate with other Apple Watch owners. You can get someone's attention with a gentle vibration, or even send some personal information like your heartbeat. Similarly, Android-equipped smartwatches can vibrate using miniaturized vibrotactile actuators. Dedicated applications, such as "Feel The Wear", enable the user to even create custom vibration patterns by tapping the screen.

However, the haptic feedback provided by these devices is still limited to vibrations, reducing the possibility of simulating any rich contact interaction. Towards a more realistic feeling of interacting with virtual and remote objects, researchers focused on glove-type haptic displays such as the CyberGrasp, which provides force sensations to all the fingers of the hand simultaneously. However, although they provide a compelling force feedback, these displays are still complex and *very* expensive. Finding a trade-off between a realistic feeling of touch and cost/wearability of the system is therefore crucial. In this regard, we found *cutaneous technologies* very promising. Cutaneous stimuli are sensed by mechanoreceptors in the skin and they are useful to recognize the local properties of objects such as shape, edges, embossings, and recessed features [3], [4]. The richness of information cutaneous receptors are able to detect, together with their broad distribution throughout the body, makes the skin a perfect channel to communicate with the human user [5]. Moreover, cutaneous haptic feedback provides an effective and elegant way to simplify the design

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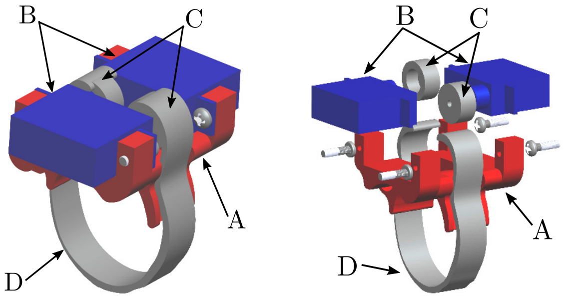
of this type of haptic interfaces: skin receptors' very low activation thresholds [5], [6] enable researchers to design small, lightweight, and inexpensive cutaneous haptic interfaces [2], [7], [8]. Finally, cutaneous feedback has been also proven to play a key role in enhancing the performance and effectiveness of teleoperation and immersive systems [8], [9], [10], [11].

An example of a cutaneous device exploiting these capabilities is the one presented by Minamizawa et al. [7], developed to display the weight of virtual objects. It consists of two motors that move a belt in contact with the user's fingertip. When the motors spin in opposite directions, the belt presses on the user's fingertip, while when the motors spin in the same direction, the belt applies a tangential force to the skin. This device was also used by Prattichizzo *et al.* [12] to display remote tactile experiences. Similarly, Solazzi et al. [13] developed a 3-DoF wearable cutaneous display to render virtual slanted surfaces. Four motors are placed on the forearm and two cables for each end-effector are necessary to transmit the motor torque. More recently, Prattichizzo et al. [2] presented a wearable cutaneous device able to provide contact deformations stimuli at the fingertip. The device weights only 35 g and it is composed of two platforms: one is located on the back of the finger, supporting three small DC motors, and the other one is in contact with the volar surface of the fingertip. The motors shorten and lengthen three cables to move the platform toward the user's fingertip and re-angle it to simulate contacts with arbitrarily oriented surfaces. The direction and amount of the force reflected to the user is changed by properly controlling the cable lengths. Three force-sensing resistors near the platform vertices measure the fingertip contact force for closed-loop control. A simplified version of this device was also used in [14] to interact with virtual objects. The authors presented a cutaneous system enabling a human user to interact with a virtual environment while being provided with compelling cutaneous stimuli about contacts with virtual objects. The system consisted of a Leap Motion controller and five wearable fingertip cutaneous devices. Although the system was quite effective, it still presented several occlusion-related issues caused by the relative large size of the cutaneous devices with respect to the fingertips. As a consequence, the Leap Motion controller was not able to track the device-equipped fingers as effectively as bare fingers. To tackle this problem, we decided to develop a novel cutaneous device to be worn on the proximal phalanx of the finger. This device is able to convey informative cutaneous stimuli while enabling a more effective tracking of the fingers. In fact, the proposed device preserves the concave features of a open hand, which are indeed important for robust fingertip tracking [15], [16].

In this paper, we present the design, development, and evaluation of a novel wearable cutaneous device for the proximal finger phalanx, that we call "haptic ring" (hRing). A prototype of this device is shown in Fig. 1. It consists of two servo motors that move a belt placed in contact with the user's finger skin. Similarly to [7], when the motors spin in opposite directions, the belt presses into the user's finger, while when the motors spin in the same direction, the belt applies a shear force to the skin. It weights only 15 g for 31×28×12 mm of dimensions, making it an extremely wearable and unobtrusive device.



(a) CAD design (b) Exploded view

Fig. 2. The proposed 2-DoF cutaneous device. It is designed to provide normal and shear stimuli to the proximal phalanx of the finger. The device is composed of a static platform (A), that houses two servomotors (B) and two pulleys (C), and a belt (D), that applies the requested stimuli to the skin.

To understand how to correctly modulate the cutaneous stimuli provided, we carried out two experiments evaluating the differential thresholds for normal and shear stimuli. After that, to evaluate the effectiveness of the proposed approach, we carried out a pick-and-place experiment in a virtual environment. A Leap Motion controller was in charge of tracking the position of the fingers, and the proposed cutaneous device provided stimuli about the interaction forces.

The rest of the paper is organized as it follows. Section II reports details on the device design and realization, Sec. III reports the results of the differential thresholds evaluation for normal and shear stimuli, and Sec. IV describes the pick-and-place experiment that we ran to evaluate the presented system. Finally, Sec. V provides concluding remarks and perspectives on the future of this line of research.

II. THE HRING HAPTIC INTERFACE

Wearability is the key concept in the design of the proposed hRing cutaneous device. Besides wearability, other essential features are comfort, effectiveness, and ease of use. For all the reasons mentioned in Sec. I, the hRing device has been designed to be worn on the proximal part of the index finger. A prototype is shown in Fig. 1, while Fig. 2 indicates its main parts. Referring to Fig. 2, the device is composed of a static platform (A), that houses two servo motors (B) and two pulleys (C), and a fabric belt (D), that applies the requested stimuli to the finger. A strap band is used to secure the device on the finger (see Fig. 1). The static platform and the pulleys are realized in Acrylonitrile Butadiene Styrene (ABS-Plus, Stratasys, USA) through the use of a commercial 3D printer. The servomotors are PWM-controlled HS-40 Microservo (HiTech, Republic of Korea). Each can provide a maximum torque of 0.05 Nm. The PWM signals are generated by an Atmega328 microcontroller installed on an Arduino Nano board. The device is powered by two batteries (4.8V 510 mAh , NI-MH) in parallel.

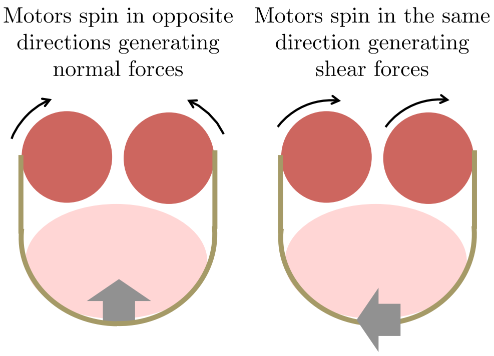


Fig. 3. Device actuation principle. When the motors spin in opposite directions, the belt presses into the user's finger (left), while when the motors spin in the same direction, the belt applies a shear force to the skin (right).

The working principle of the device is depicted in Fig. 3. Similarly to the principle proposed by Minamizawa et al. [7], when the two motors rotate in opposite directions, the belt is pulled up, providing a force normal to the finger (left side of Fig. 3). On the other hand, when motors spin in the same direction, the belt applies a shear force to the finger (right side of Fig. 3).

The servomotors are position controlled, which means that it is only possible to command a desired angle. The relationship between the commanded angle and belt displacement is

$$\Delta d = r\Delta\theta, \tag{1}$$

where $r = 5$ mm is the radius of the servo motor pulley, Δd the belt displacement, and $\Delta\theta$ the commanded angle expressed in radians. To relate the belt displacement to the force applied on the finger proximal phalanx $\boldsymbol{f} \in \mathbb{R}^3$, we assume

$$\boldsymbol{f} = Kd, \tag{2}$$

where $K \in \mathbb{R}^{3\times3}$ is the finger phalanx stiffness matrix and d is the displacement of the belt since it first made contact with the fingertip. In this work we considered an isotropic elastic behavior, so that the stiffness value is the same for all the elements of the matrix diagonal $K = kI$, with $k = 0.5$ N/m and $I \in \mathbb{R}^{3\times3}$ is the identity matrix [17].

Despite the simplicity of actuation, it has been demonstrated that the vertical and shearing forces generated by the deformation of the fingerpads can reproduce reliable weight sensations even when proprioceptive sensations on the wrist and the arm are absent [18]. Our objective is to understand if these type of stimuli are still effective when provided to the proximal phalanx of the finger instead of the fingertip.

III. DIFFERENTIAL THRESHOLDS

To understand how to correctly modulate the cutaneous stimuli provided, we carried out two preliminary experiments evaluating the differential thresholds for normal and shear stimuli. The differential threshold can be defined as "the smallest amount of stimulus change necessary to achieve some criterion level of performance in a discrimination task" [19]. It gives us information about how different two displacements provided with our device need to be in order to be perceived as different by a human user. This threshold is often referred to as just-noticeable difference or JND. The differential threshold of a perceptual stimulus reflects also the fact that people are usually more sensitive to changes in weak stimuli than they are to similar changes in stronger or more intense stimuli. The German physician Ernst Heinrich Weber proposed the simple proportional law $JND = kI$, suggesting that the differential threshold increases with increasing the stimulus intensity I. Constant k is thus referred to as "Weber's fraction". For example, Schorr et al. [9] measured the ability of users to discriminate environment stiffness using varying levels of skin stretch at the finger pad. Results showed a mean Weber fractions of 0.168. Similarly, Guinan et al. [20] found a mean Weber fraction of 0.2 for their skin stretch sliding plate tactile device.

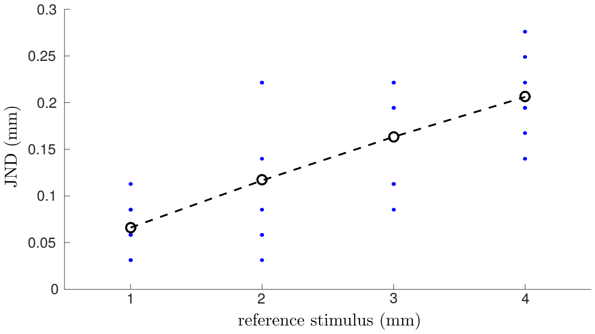
Seven participants took part in the experiments, including one woman and six men. Four of them had previous experience with haptic interfaces. None of the participants reported any deficiencies in their visual or haptic perception abilities, and all of them were right-hand dominant. Subjects were required to wear the device on their right index proximal phalanx, as shown in Fig. 1. To avoid providing any additional cue, subjects were blindfolded and wore noise-canceling headphones.

A. *Normal stimuli*

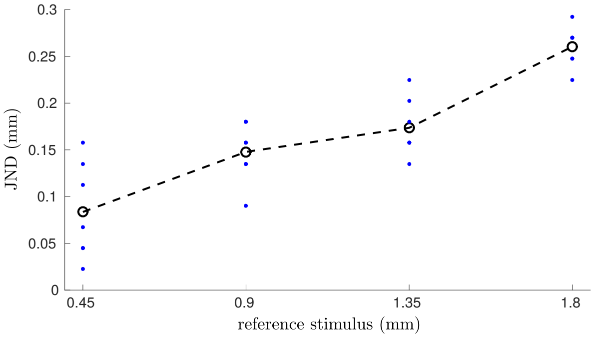
We evaluated the differential threshold for normal stimuli using the simple up-down method [21]. We used a step-size for the servo motors of $\alpha = 1°$, that corresponded to a normal displacement of the belt of 0.09 mm (see eq. (1)). We considered the task completed when six reversals occurred. Subjects were required to wear the cutaneous device and tell the experimenter when the two stimuli provided felt different. We tested the JND at three standard stimuli: 1 mm, 2 mm, 3 mm, and 4 mm of displacement into the finger pad. Each participant performed eight trials of the simple up-down procedure, with two repetitions for each standard stimulus considered. Fig. 4a shows the differential thresholds registered for each reference stimulus. For the reference stimuli of 1 mm, 2 mm, 3 mm, and 4 mm, the average JNDs are 0.07 mm, 0.12 mm, 0.16 mm, and 0.19 mm. respectively. Thus, the Weber fractions are 0.07, 0.06, 0.05, 0.05, respectively, following Weber's Law.

B. *Shear stimuli*

We evaluated the differential threshold for shear stimuli using the simple up-down method again [21]. We used a step-size for the servo motors of $\alpha = 1°$, that corresponds to a lateral movement of the belt on the finger pad of 0.09 mm (see eq. (1)). We considered the task completed when six reversals occurred. Subjects were required to wear the cutaneous device and tell the experimenter when the two stretches provided felt different. We tested the JND at three standard stimuli: 0.45 mm, 0.90 mm, 1.35 mm, and 1.80 mm of stretch on the finger pad. The normal displacement into the skin was fixed to 6 mm. Each participant performed eight trials of the simple up-down procedure, with two repetitions



(a) JND for normal stimuli



(b) JND for shear stimuli

Fig. 4. Differential threshold. Mean values are plotted as empty black circles, thresholds for each subject are plotted as blue dots.

for each standard stimulus considered. Fig. 4b shows the differential thresholds registered for each reference stimulus. For the reference stimuli of 0.45 mm, 0.90 mm, 1.35 mm, and 1.8, the average JNDs are 0.08 mm, 0.15 mm, 0.17 mm, and 0.26 mm, respectively. Thus, the Weber fractions are 0.18, 0.16, 0.13, 0.15, respectively, following Weber's Law. No slippage between the belt and the skin took place during the trials.

IV. EXPERIMENTAL EVALUATION

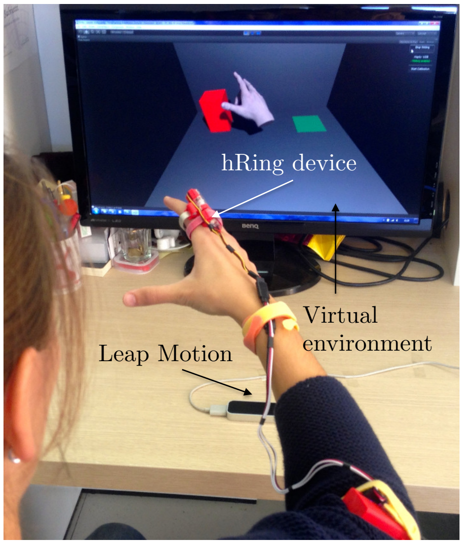
In order to evaluate the effectiveness of our wearable cutaneous device, we carried out a pick-and-place experiment in a virtual environment.

A. Setup

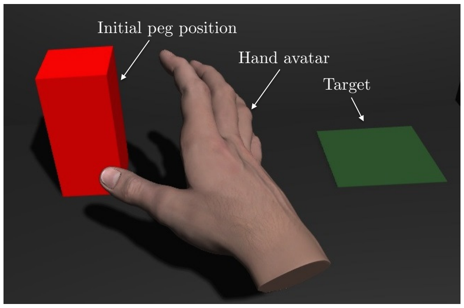
The experimental setup consists of a Leap Motion controller, the proposed wearable cutaneous device, and a virtual environment. The Leap Motion uses two monochromatic IR cameras and three infrared LEDs to track the position of the fingertips in 3-D space. It observes a hemispherical area up to a distance of 1 m with an accuracy up to 0.01 mm [22]. The virtual environment is composed of one peg and a target, as shown in Fig. 5b. The environment was designed using Unity, a proprietary cross-platform game engine.

B. Participants and methods

Seven participants took part in the experiment, including two women and five men. Two of them had previous experience with haptic interfaces. None of the participants reported any deficiencies in their visual or haptic perception abilities, and all of them were right-hand dominant. The experimenter explained the procedures and spent about two minutes adjusting the setup to be comfortable before the subject began the experiment.



(a) Experimental setup

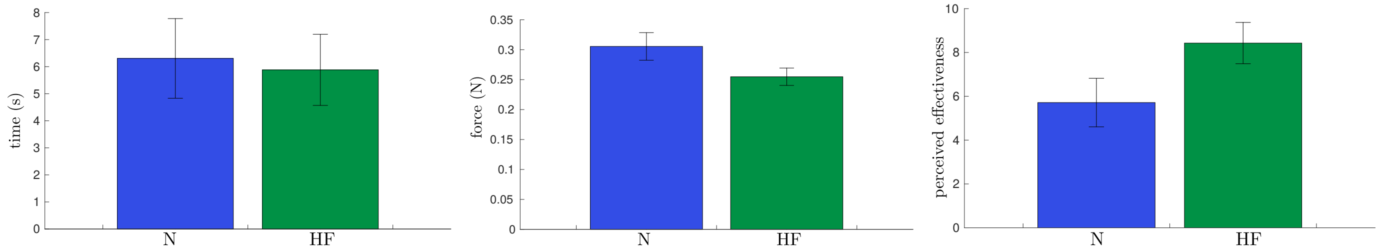


(b) Virtual environment

Fig. 5. Pick-and-place experiment. The experimental setup consisted of a Leap Motion controller, the proposed wearable cutaneous device, and a virtual environment. The task consisted of picking up the red peg and placing it on the corresponding green target. A video of the experiment can be downloaded from http://goo.gl/Yg1e6w.

Subjects were asked to wear the proposed cutaneous device on the right index finger, as shown in Fig. 5a. The task consisted of picking up the red peg and placing it on the target green square. A video of the task can be found at http://goo.gl/Yg1e6w. The position of the fingers was tracked using the Leap Motion controller. In order to increase the illusion of telepresence, a virtual human hand mimicked the user's hand pose in the virtual environment. Every time the hand came in contact with a virtual object, the wearable cutaneous device applied a suitable amount of force to the users' finger, providing them with the compelling sensation of *touching* the virtual environment.

Interaction forces in the virtual environment are computed using a virtual proxy approach [23]. For the sake of simplicity we consider solely precision grasps, computing only the interaction forces at the fingertips. Let $\boldsymbol{f}_{\boldsymbol{v}} \in \mathbb{R}^{15}$ include all the five forces measured at the fingertips of the hand avatar (5 fingers × 3 dimensional space). We consider a



(a) Completion Time (b) Exerted forces (c) Perceived Effectiveness

Fig. 6. Experimental results. We recorded (a) the time needed to complete the task, (b) the magnitude of the forces generated by the contact between the virtual fingertips, controlled by the subject, and the peg, and (c) the effectiveness perceived by the human subjects.

hard finger contact model, so only a linear force can be transmitted between the hand and the object [24].

In this work, we use only one haptic display placed on the index finger, which is able to reproduce forces on a plane perpendicular to the proximal phalanx (see Sec. II). Let $\boldsymbol{f_h} \in \mathbb{R}^2$ be the force displayed through the hRing. In case of high underactuation of the device, it may be more effective for users to receive force information along certain directions than along others [25]. For this reason, following the approach presented by Meli et al. [26], we emphasize forces that are more relevant for our task, aiming at a good perception even though the number of actuators is not sufficient to simulate the whole set of contact forces. In particular, we consider two distinct phases for the force feedback computation: (i) grasping approach, and (ii) object manipulation. During the grasping approach, only the interaction forces computed at the index of the hand avatar are displayed back to the user. In this case, a contact between the hand avatar and the virtual object is also visually displayed by changing the color of the peg from red to blue (please also refer to the supplemental material). When a stable grasp is achieved, the peg turns green, and the force feedback switches to the second phase. During object manipulation, we assume that the set of contacts defines a certain grasping configuration, whose geometry is described by the grasp matrix G [24]. Matrix G is used to asses the equilibrium of the grasp through equation $\boldsymbol{w} = G\boldsymbol{f_v}$, where $\boldsymbol{w}$ is the external wrench applied to the grasped object. From the equilibrium equation, it is possible to define the subspace of internal forces, i.e., the self balanced forces whose net wrench on the object is zero and that belong to the nullspace of the grasp matrix $\mathcal{N}(G)$. Such forces have been demonstrated to play a key role in grasp maintenance [27]. In order to emphasize internal forces, we compute $\boldsymbol{f_h}$ solving the system

$$\begin{cases} (N_G)^T \boldsymbol{f_v} = (N_G)^T M_a \boldsymbol{f_h}, \\ \boldsymbol{f_v} = M_a \boldsymbol{f_h}, \end{cases} \tag{3}$$

where N_G denotes a matrix whose columns form a basis for $\mathcal{N}(G)$, and M_a is referred to as the *actuation matrix*, whose structure and size depend on the number of contact points, the number of actuators, and the geometry of the system [26].

Subjects were asked to complete the pick-and-place task 10 times, either with cutaneous feedback (condition HF) or without it (condition N). In the condition where no cutaneous feedback was provided, subjects were required to remove the devices and interact with the virtual environment barehanded. Trials were randomized to eliminate learning effects. The experiment helped us in evaluating the role of cutaneous feedback in such a task and in understanding if wearing the proposed devices affects the quality of the tracking.

C. Results and Discussion

In order to evaluate the performance of the considered feedback conditions, we recorded (1) the time needed to complete the task and (2) the forces generated by the contact between the virtual fingertips, controlled by the subject, and the pegs. All the subjects were able to complete the task.

Figure 6a shows the average time elapsed between the instant the subject grasped the peg for the very first time and the instant he or she completed the pick-and-place task. The collected data passed the Shapiro-Wilk normality test. A paired-samples t-test determined that the time needed to complete the task did not differed statistically significantly between the conditions.

Figure 6b shows the average magnitude of the contact forces generated between the virtual fingertips, controlled by the subject, and the peg. The collected data passed the Shapiro-Wilk normality test. A paired-samples t-test determined that the force exerted on the environment differed statistically significantly between the conditions (t(6) = 4.786, p = 0.003, a = 0.05). Providing cutaneous haptic feedback enabled the subjects to complete the task exerting significantly less force on the environment with respect to not providing any force feedback.

In addition to the quantitative evaluation reported above, we also measured users' experience. Immediately after the experiment, participants were asked to rate from 1 to 10 the perceived effectiveness of the two conditions. Figure 6c shows the average rating given by the subjects. Since the data were registered at the ordinal level, we ran a Wilcoxon signed-rank test. Ratings were found statistically significantly different (z = 2.401, p = 0.016, a = 0.05). Providing cutaneous haptic feedback was found by the subjects significantly more effective than not providing any force feedback.

Participants were also asked to indicate their preferred feedback condition and if they felt a difference in the tracking accuracy between the two conditions. Six out of seven subjects preferred the condition employing the hRing device, and all the subjects found no difference in the tracking accuracy. Since in condition N subjects were interacting with the virtual environment barehanded, we can state that the proposed hRing device does not significantly affect the quality of this type of tracking.

V. CONCLUSIONS AND FUTURE WORK

This work presented a novel wearable 2-DoF cutaneous device for the finger, which we called "hRing". It is able to provide normal and shear cutaneous stimuli to the proximal phalanx of the index finger. We chose to place it on the proximal phalanx to improve the tracking of the fingertips using commercially-available tracking systems, such as the Leap Motion controller or the Kinect sensor. The viability of the proposed approach is demonstrated through a pick-and-place experiment involving seven human subjects. Providing cutaneous feedback improved the performance (completion time and exerted force) and perceived effectiveness of the task of 20% and 47% with respect to not providing any force feedback, respectively. Moreover, all subjects found no difference in the quality of the tracking when wearing the device vs. barehanded. The proposed hRing device is therefore proven to be able to convey informative cutaneous stimuli while enabling an effective tracking of the fingers. Finally, its compact form factor and light weight, make the hRing an extremely wearable and unobtrusive device.

In the future, we plan to run a more extensive evaluation, enrolling more human subjects, using more than one hRing device per hand, and comparing the proposed device with other similar systems, such as the ones presented by Prattichizzo et al. [2], Minamizawa et al. [7], Scheggi et al. [14], and Pacchierotti et al. [28]. Moreover, we plan to add a vibrotactile motor to the dorsal side of the device, in order to be able to render the feeling of interacting with different textures. Finally, we will also study different ways of arranging the actuators, with the objective of improving the wearability and the overall ergonomy of the device.

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