Wearable Haptics for Object Compliance Discrimination Through Passive Touch

N. D'Aurizio[1,2], T. Lisini Baldi[1], A. Villani[1], K. Minamizawa[3], Y. Tanaka[4], and Domenico Prattichizzo[1,2]

***Abstract*— An important aspect of tactile perception is the ability to estimate compliance. When the perception of compliance is mediated by haptic devices, the interaction with objects usually takes place through active exploration from the subject. In this paper, we present a wearable haptic device for transmitting information about object compliance through passive touch, meaning that stimuli are generated by an external agent rather than by user motion. More precisely, the dynamics describing the object indentation is reproduced on the user's forearm in the form of decoupled cues representing applied force and surface displacement. The development of such a device has a twofold purpose. Firstly, it allows the study of human capacity for processing decoupled information for deducing object compliance. Secondly, it makes possible to convey object compliance to someone who is not performing the object indentation. This is especially important in contexts like telemedicine and human-robot collaboration.**

Users' perception of stiffness, force, and displacement were estimated to assess device usability. Then, a two-phase experiment was carried out to compare the proposed approach with the state of the art. Results of the experimental campaign revealed the effectiveness of the proposed approach. Users were able to discriminate and order objects with different compliance with a success rate 9% greater than the one obtained exploiting state of the art strategies reproducing only forces.

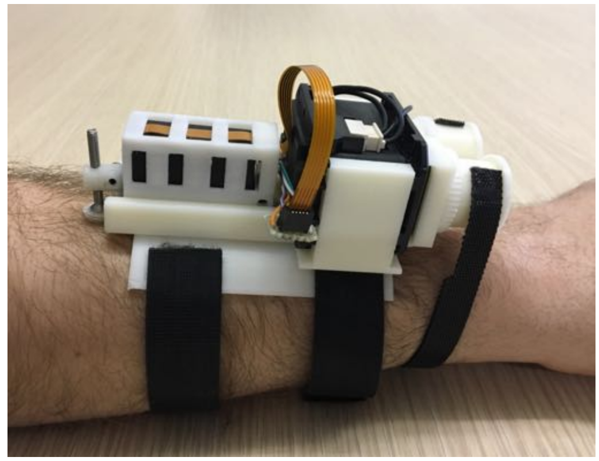


Fig. 1: The wearable haptic device developed to recreate the dynamics of the interaction with compliant objects. It is able to display two different cues: force (through squeezing effect) and displacement (through skin-stroking effect). The total weight of the device is 170 g.

I. INTRODUCTION

Object compliance can be defined as the amount of object deformation under a given applied force. When a tool or a finger indents a compliant object, the force applied and the displacement generated on the object are related to the extension of the contact area. This implies that compliance has not an absolute value, but depends on the way the object is touched [1]. Besides, humans perceive compliance through tactile interaction and in terms of *softness* and *hardness*, which are subjective rather than physical measures of compliance [2]. Such indeterminacy justifies the large number of published studies on human compliance perception, most of which concern the case of active touch, i.e. with voluntary movement on the part of the subject [3]. In [4], subjects were asked to squeeze a series of specimens between finger and thumb. Subjective hardness was found to follow the psycho-physical power law and to grow as the physical hardness raised to a power. In [5], an electro-mechanical system was used to measure the compliance Just Noticeable Difference (JND) and to investigate the roles of force and mechanical-work (i.e., force integrated over displacement) cues in compliance discrimination. The apparatus moved two plates which were grasped between thumb and index finger and squeezed together along a linear track by the user. Results suggested that people tend to use mechanical work cues for compliance discrimination whenever such cues are available. Compliance JNDs appeared to be considerably larger than force JNDs, and their values depended upon the particular experiment used for testing. In [6], subjects explored non-deformable, compliant objects with three different types of contact, namely discontinuous pressure, continuous pressure and continuous lateral motion. Discrimination performance was significantly better in the case of continuous pressure.

As regards the case of passive touch, i.e. when the stimuli are generated by an external agent rather than by the user motion, few studies have been done. Despite that, it is generally agreed that there is a difference in compliance perception between active and passive exploration. In [2], authors report that kinesthetic information alone is insufficient to judge the relative softness of objects with deformable surfaces in case of active touch. Differently, the lack of kinesthetic feedback in case of passive touch deteriorates only slightly the discriminability compared with active touch performance gained where both tactile and kinesthetic

[1] are with the Department of Information Engineering and Mathematics, University of Siena, Siena, Italy.
[2] are with the Department of Advanced Robotics, Istituto Italiano di Tecnologia, Genova, Italy.
[3] is with the Graduate School of Media Design, University of Keio, Keio, Japan.
[4] is with the Department of Electrical and Mechanical Engineering, Graduate School of Engineering, Nagoya Institute of Technology, Nagoya, Japan.

information are available. In [7], a neuronal spiking model emulating the firing activity of human mechanoreceptors was adopted to deliver haptic information about objects stiffness (i.e., the inverse of compliance) on thumb and index fingers of a remote subject. To indent each rubber sample, the experimental protocol provided for random force and duration, while the indentation velocity was constant. This approach enabled the remote discrimination of most of the proposed pairs of samples, with an overall average of $74 \pm 7\%$ of correct answers.

Within this context, this paper explores the use of a wearable device (see Fig. 1) worn on the forearm for conveying haptic feedback information about objects compliance through passive touch. More precisely, the device is meant to *i)* reproduce the dynamics describing the object indentation in the form of decoupled cues regarding applied force and surface displacement, *ii)* act as a sensory substitution system [8] in charge of presenting information to be processed by the intrinsic sensory body system for the compliance estimation, and *iii)* enable the real-time representation of tactile information coming from a remote operation context, without preventing the wearer from using the hand. The development of such a device has a twofold purpose. On the one hand, it allows us to investigate the human capacity for processing information provided in a very different way from how the person would actively acquire it. In particular, we are interested in understanding whether it is possible to deduce the compliance of an object starting from decoupled information on force and displacement, without establishing a constant speed of the indenter. This contributes to the body of knowledge in the human augmentation field [9] by providing a method to convey additional information without interfering with the main receptive channels of the human sensory system (in this case, the hand). On the other hand, our device is a haptic interface that can be adopted in teleoperation contexts where the person who has experience in the matter is not the operator. Explanatory examples are telemedicine activities [10], where the physical exam assessment through palpation still represents a limit. In fact, typically the patient is not able to evaluate tissues according to their compliance, which however is fundamental in order to localize tumours and lesions [11]. Another paradigmatic context is the industrial robotics field, where collaborative solutions in which human workers and robots share their skills are becoming the new frontier [12]. Supply human operators with intuitive tactile feedback can enhance their comprehension of the current system status and facilitate intervention in dynamic and unforeseen situations.

As a final remark, complying with wearability requirements is relevant to develop haptic systems capable of communicating in a natural and private way with the user [13]. Specifically, we designed a device to be worn on the forearm, leaving the hands free to interact with the surrounding. This requirement is crucial for exploiting the potential of passive touch, i.e. the possibility of perceiving information through haptic cues regardless of our actions.

II. System Overview

As introduced in the previous section, this work presents a novel approach to conveying object compliance through passive touch, based on the concept of sensory decoupling. To recreate the dynamics of the interaction with compliant objects, two haptic cues are needed: squeezing (displaying the force applied on the object) and skin-stroke (emulating the indentation of the object surface).

A. Device

A novel wearable haptic interface (depicted in Fig. 2) was designed to implement the envisaged sensory decoupling technique. The device is composed of two parts, one thought to convey *skin-stroking* cues (Fig. 2a), i.e. to stimulate the skin by means of a contact point that moves linearly, and the other intended to apply *squeezing* cues, i.e. to exert a force on the normal (radial) direction of the forearm (Fig. 2b).

The skin-stroking effect is realized through a Micro Linear Actuator PQ12-30-12-P (Actuonix, Canada), characterized by a maximum speed of $28\,\mathrm{mm\,s^{-1}}$, a stroke length of $20\,\mathrm{mm}$, a positional repeatability of $\pm 0.1\,\mathrm{mm}$, and a weight of $15\,\mathrm{g}$. This actuator was selected because it satisfied the requirements of being reliable, fast, and small enough to be embedded in a wearable device. The actuator is controlled with a linear actuator control (LAC) board (Actuonix Motion Devices Inc., USA), which receives a digital signal d_{LAC} from a PC. The linear actuator position d_{la} is computed according to the duty cycle of the input signal $d_{LAC} \in [0, 1]$ as $d_{la} = d_{LAC} M_{la}$, where $M_{la} = 2^{10} = 1023$ is the maximum actuator position. This results in a theoretical control resolution of $20\ \mathrm{mm}/1023 \approx 0.02\ \mathrm{mm}$, which is however subordinated to the resolution imposed by the mechanical characteristics of the actuator. A length-adjustable tip with an ABS end-effector is attached at the end of the stroke (as visible in Fig. 2a), with a contact surface of $2\,\mathrm{cm}^2$. This size was sufficient to stimulate the receptive field of a C-Tactile (CT) fibres unit, whose dimension ranges from 1 to 35 mm^2 [14]. CT afferents are known to respond to tactile stimuli with the specific characteristics of a gentle caress [15]. Although there is currently no accurate method to assess the innervation density of CT afferents in human body, there is scientific evidence that these fibres are present in the skin of the human forearm [16]. For this reason, we designed the device with the linear actuator stimulating the hairy skin of the user's forearm.

The squeezing effect is obtained by means of a $5\,\mathrm{mm}$ wide fabric belt, whose tension is controlled with a Dynamixel MX-28AT actuator (Robotis Inc., USA) with a stall torque of $2.5\,\mathrm{Nm}$ at $12\,\mathrm{V}$ and a weight of 72 g. An USB2Dynamixel controller (Robotis Inc., USA) mediates the communication between the PC and the actuator through serial communication and TTL protocol, respectively. The ends of the belt are attached to two pulleys, which in turn are housed on two mechanically coupled gears. Both pairs of pulleys and gears have the same radius, which corresponds to $1.0\,\mathrm{cm}$ and $1.2\,\mathrm{cm}$, respectively. When the motor drives the master gear, the torque applied on the latter is transmitted on the slave

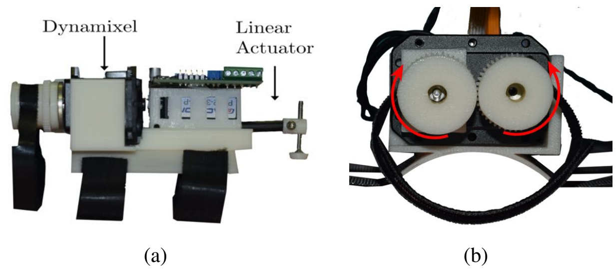


Fig. 2: Lateral and front views of the haptic device are in (a) and (b), respectively.

gear, which assumes an opposite spinning direction. As a consequence, the belt moves along the vertical axis (as depicted in Fig. 2b) applying a normal force on the user's forearm. We decided to display the force in the lower part of the forearm because of the wide distribution of Merkel nerve endings (mechanoreceptors that provide information on mechanical pressure) in the basal layer of glabrous skin [17].

To cope with the uncertainties due to the non-ideality of the mechanical system, an ATI Gamma sensor (SI-130-10, maximum torque $10\,\mathrm{Nm}$, resolution $1/800\,\mathrm{Nm}$) was used in a preparatory experiment to find the relationship mapping the digital motor torque input $d_{dyn} \in [0, 1023]$ into generated torque values τ. This relationship can be described by a linear model as:

$$\tau = -0.04012 + 0.00158 \cdot d_{dyn} \quad (1)$$

with a negligible error in the range $[0, 0.1]\mathrm{Nm}$ (mean RMSE $= 0.0013$ Nm). It follows that digital values $d_{dyn} \leq 25$ are not sufficient to actuate the motor and move the mechanism. In addition, preparatory experiments revealed that to apply a force greater than $7\,\mathrm{N}$ is perceived as uncomfortable by the users, therefore we decided to limit the maximum force exerted by the Dynamixel actuator to $F_{max} = 7\,\mathrm{N}$. Thus, the torque range exploited by the device is $[0, \tau_{max}]$, with $\tau_{max} = r_p \cdot F_{max} = 0.07\,\mathrm{N\,m}$, being $r_p = 10\,\mathrm{mm}$ the radius of the servo motor pulley. Following the relationship identified in (1), $[25, 69]$ is the range of d_{dyn} that generates $[0, 0.07]$ Nm, which implies a resolution of 0.07 Nm$/44 = 0.0016$ Nm. Equivalently, the smallest force variation exerted by the device is 0.16 N, a quantity which is lower than the average force JND (see Sect. II-B).

To reproduce the required forces, the squeezing mechanism needs an initial calibration procedure that brings the belt into contact with the user's arm. This is done by winding up the belt with a torque of $0.001\,\mathrm{N\,m}$ (i.e., $d_{dyn} = 26$) until the contact between the arm and the belt is detected by the motor. When this occurs, the motor is stopped and the current motor position is saved as starting position.

Controller boards and related electronic circuitry are enclosed in a external 3D printed box.

B. Device Usability

In order to evaluate the usability range of the device, we performed a preliminary campaign investigating about users' perception of stiffness, force and displacement in terms of JNDs. In psychophysics, a stimulus JND is the amount of change on a primary stimulus which is just sufficient to produce a change of one sensation JND upward at that point [18]. In particular, we assessed the JND for *i)* stiffness perceived during active exploration of virtual objects, *ii)* squeezing force applied on the lower part of the forearm, and *iii)* skin-stroking displayed on the higher part of the forearm. In the first case, the goal was to evaluate the users' ability in discriminating object stiffness in the most natural condition, that is with active exploration. This result was considered as the best achievable result for the purpose of evaluating users' performance in perceiving device-mediated stiffness. The second and the third cases were instead needed to characterize the range of stiffness representable with the device, which can be expressed as

$$[k_{min}, k_{max}] = \left[\frac{F_{min}}{x_{max}}, \frac{F_{max}}{x_{min}}\right]$$

where F_{min} and x_{min} are the force and displacement JND, respectively, while F_{max} and x_{max} are limits imposed by the device mechanical structure.

Ten subjects (6 males and 4 females, age 22-40) took part to the preliminary campaign, and all of them were involved in the three experiments. The experimental evaluation protocols followed the declaration of Helsinki, and participants were blindfolded and asked to wear a headset providing white noise to avoid visual-audio bias in the stimuli evaluation.

Stiffness JND: An Omega.3 (Force Dimension, CH) was used to render pairs of virtual objects with different stiffness. The reference object was displayed in the left part of the workspace with a constant stiffness k_{ref} which was maintained throughout the experiment, whereas the compared object was displayed in the right part of the workspace and its stiffness k_{com} was changed at each step.

Participants were asked whether there was a difference in stiffness between the two proposed objects. In order to perceive the stiffness, they were allowed to freely touch the virtual objects using their index fingertip as long as they needed and with the force they preferred. An ad-hoc thimble was mounted as end-effector on the haptic interface to facilitate the exploration. At each step, depending on the user's answer, the stiffness variation Δ computed with respect to k_{ref} was changed according to the one-up one-down single descending staircase procedure [19]. More precisely,

$$k_{com}(n) = k_{ref} + \Delta(n)$$

with

$$\Delta(n)|_{n=0} = 0.75k_{ref}$$
$$\Delta(n)|_{n\neq 0} = \Delta(n-1) \pm \delta k_{ref}$$

where $n = 1, 2, ..., 30$ was the current step, and $\delta = 0.05$ until the first reversal point of the participant's perception, after which the value was halved ($\delta = 0.025$). The same procedure was repeated four times, and for each trial a different value of $k_{ref} \in \{50, 150, 250, 350\}\ \mathrm{N\,m^{-1}}$ was selected. These values were chosen in accordance with the range of stiffness of the human skin within the limits considered in [20]. For each participant, the stiffness JND was evaluated as the average of the Δ values at the reversal points. The experiment revealed a linear dependence between stimulus and perception with an average stiffness JND of $(0.10 \pm 0.04)k_{ref}$.

The same comparative analysis was further repeated to evaluate the minimum stiffness that could be perceived with the proposed setup, in order to provide a lower bound for the validity range of the previous result. On average, the minimum perceptible stiffness was equal to $k_{min} = 14.8 \pm 2.3\ \mathrm{N\,m^{-1}}$.

Force and Displacement JNDs: The minimum force and displacement perceived with the device were evaluated with a procedure similar to the one used in the previous experiment. Depending on the JND of interest, the device was controlled to actuate only the squeezing effect or the skin-stroking one. Participants were asked to wear the device on the forearm of the dominant hand (one left-handed and nine right-handed) and to evaluate if there was a difference between the pair of proposed stimuli, i.e. F_{ref} and F_{com} in the first case, and x_{ref} and x_{com} in the second one. The reference value was always the first stimulus proposed and each test lasted $n = 30$ steps. At each step, depending on the user's answer, the stimulus variation Δ computed with respect to the reference value was changed according to the one-up one-down single descending staircase procedure [19]. We defined $F_{ref} = 0$ N, $\Delta(n)|_{n=0} = 5$ N and $\delta = 0.3$ N for the force case, and $x_{ref} = 0$ mm, $\Delta(n)|_{n=0} = 20$ mm and $\delta = 1$ mm for the displacement case, respectively. The value of δ was halved after the first reversal point and the stimulus JNDs were computed as the average Δ values provided at the reversal points. Results reported mean force JND of 0.87 ± 0.41 N and an average displacement JND of 1.51 ± 0.45 mm.

Device Characterization: Considering the boundaries identified in the previous experiments and the mechanical characteristics of the actuators, we can determine the usability range of the device. The theoretical range of stiffness representable with the device is $[45, 7000]\ \mathrm{N\,m^{-1}}$.

III. Experimental Validation

The aim of the experimental validation was to test the effectiveness of decoupling cues representing applied force and surface displacement to convey information about the objects compliance.

A two-phase experiment was carried out, with each phase lasting 24 trials. A software developed in LabVIEW (National Instruments, Texas) was used in both phases to simulate the indentation of virtual objects, modelled as ideal springs. In each trial, participants perceived the indentation of three virtual objects through the wearable haptic interface presented in Sect. II, and were asked to rearrange them according to ascending order of stiffness. At each indentation, the maximum force to apply on the virtual spring was pseudo-randomly selected from the set $\{2.5, 4, 5.5, 7\}$ N in order to have six repetitions per value across 24 trials. These values were selected to span the entire device force range and to comply with the average force JND (see Sect. II-B). As regards the stiffness values, we considered $k_1 = 350\ \mathrm{N\,m^{-1}}$, $k_2 = 420\ \mathrm{N\,m^{-1}}$, $k_3 = 525\ \mathrm{N\,m^{-1}}$, and $k_4 = 683\ \mathrm{N\,m^{-1}}$, being

$$k_1 = \frac{F_{max}}{x_{max}},$$
$$k_{i+1} = k_i + round((0.2 + 0.05(i-1))k_i), i = 1, 2, 3. \quad (2)$$

Notice that k_1 was chosen to make feasible all possible pairs of force and stiffness in terms of displacement, while the other values were chosen with increasing percentage increments. Despite the preliminary campaign revealed that the average stiffness JND is $(0.10 \pm 0.04)k_{ref}$ (see Sect. II-B), we decided to set greater percentage increments to account for the fact that passive touch is in general more challenging than active touch [2], [7].

For each trial, the three indentations were presented one after the other with a 2 s pause in between, and participants could ask to repeat the entire set a second time. To ensure that each stiffness value was presented an equal number of times and reduce order-effects, each participant tested all the combination resulting from simple dispositions of 3 elements out of 4, for a total of 24 trials per subject per phase. A 5 minutes break was given between the twelfth and thirteenth trial to enhance concentration and avoid distress. The order of the experiment phases was randomized for each participant.

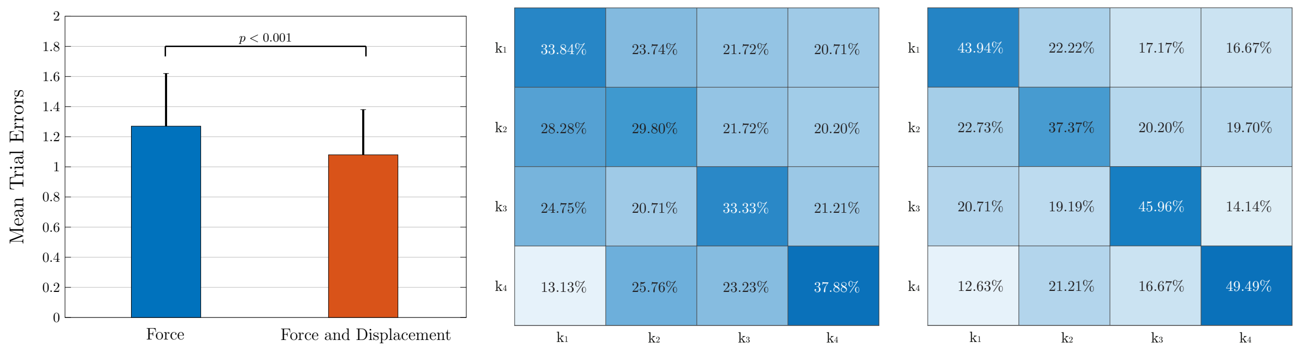
The perceived order of stiffness was communicated verbally to the experimenter by indicating with *A*, *B* and *C*, the first, second and third displayed stimulus, respectively. The error committed in arranging the stimuli was considered as a metric. This was computed for each trial as half of the sum of the distances between the virtual object position assigned by the subject and the correct one. For example, if the correct sequence was *'BCA'* and the subject declared *'ABC'*, the error associated to the trial was 2.

Eleven subjects (7 males and 4 females, age 22-50) took part to the experiment. Each participant was asked to wear the haptic interface on the forearm of the dominant hand (two left-handed and nine right-handed). To avoid visual-audio evaluation of the stimuli, participants were asked to place the arm in a box with the palm facing down and to wear a headset providing white noise to mask the sound from the activation of the motors. The experimental evaluation protocol followed the declaration of Helsinki, and there was no risk of harmful effects on subjects' health. Each participant gave written informed consent and was able to discontinue participation at any time during experiments.

The first experimental condition was in line with the state of the art and served as benchmark test, while the second one was focused on the approach proposed within this work.

A. Phase 1: Force (F)

In this phase, a single haptic cue was displayed to the user, i.e. the force applied on the virtual object, therefore subjects were not informed about the surface displacement. The indention velocity was fixed at $v = 1.25\ \mathrm{cm\,s^{-1}}$. This experimental condition was shaped to be representative of



(a) (b) (c)

Fig. 3: Experimental validation results. The average numbers of not correctly sorted objects stiffness are in (a). The p-value is reported on top of the bars. In (b) and (c) is reported the confusion matrix for the first and second phase of the experimental validation, respectively.

the state of the art and was instrumental for the second phase. Indeed, most devices developed for conveying stiffness make use of constant indentation speed, inducing users to evaluate stiffness on the basis of the integral of the force over time, i.e. the impulse [7], [21], [22]. In other words, the greater the perceived impulse, the greater the stiffness of the indented object. While functional, this approach imposes limits on how the object has to be indented, in this case with constant speed.

Before the starting of the experiment, every participant was presented with a training session consisting of three trials that were not counted for the purposes of the analysis. In these trials, the stiffness values were pseduo-randomly selected from those exploited for the stiffness JND evalutation, while the force applied was pseudo-randomly generated in the range $[1, 7]$ N.

B. Phase 2: Force and Displacement (FD)

In the second phase, both the force applied on the virtual objects and the surface displacements were displayed through the wearable haptic interface. For guaranteeing a very challenging task, the indention velocity was pseudo-randomly selected from the set $\{1, 1.25, 1.5\}$ $\mathrm{cm\,s^{-1}}$ in order to have eight repetitions per value across 24 trials.

Similarly to the first phase, each participant was presented with a training session consisting of three trials that were not counted for the purposes of the analysis. In these trials, the stiffness values were pseduo-randomly selected from those exploited for the stiffness JND evalutation, while the force applied and the indentation velocity were pseudo-randomly generated in the ranges $[1, 7]$ N and $[0.5, 1.5]$ $\mathrm{cm\,s^{-1}}$, respectively.

C. Results Analysis and Discussion

A statistical analysis was conducted to assess users performance in perceiving stiffness with the proposed sensor decoupling technique. The set of virtual objects combinations was the same across the two phases, thus a comparison of users capacity for discriminating stiffness using different approaches was obtained exploiting a paired sample t-test. The average of errors committed in sorting each triplet was compared considering the two feedback methodologies. No outliers were detected. The assumption of normality was not violated, as assessed by Shapiro-Wilk's test ($p > 0.05$). The t-test revealed that users better distinguished object compliance when both applied force and surface displacement were displayed (mean error per trial = 1.087 ± 0.300) as opposed to the single stimulus case (mean error per trial = 1.276 ± 0.355). A statistically significant mean decrease of 0.189 errors per triplet was observed, $t(23) = 4.509$, $p < 0.001$. Results are visually depicted in Fig. 3a.

For the sake of clarity and completeness, users' answers versus correct stiffness order for the two phases are reported in confusion matrix structures in Fig. 3b and Fig. 3c. A confusion matrix, also known as an error matrix, is a specific table layout that allows for performance visualization. Rows of the matrix represent the right objects positions with respect to a scale ordered by descending stiffness, while columns represent the ones guessed by the users. Each element of the matrix contains the occurrences of each assignment. For instance, the value in the first row and third column reports the amount of times that users identified k_3 as k_1. As a consequence, the diagonal outlines the number of correct compliance recognitions, whereas upper and lower triangular portions of the matrices indicate the errors. For an easier comprehension, we reported the results expressed as the percentage among all the users. As noticeable and supported by the statistical analysis, the percentage of correct matches is higher in the FD case than in the F one, i.e. users performed better when they could perceive the compliance with both squeezing and skin-stroking cues (case FD, Fig. 3c). These results are in line with the expectations and confirm the effectiveness of the proposed approach. In both cases, users found easier to discriminate higher stiffness rather than smaller ones, as it can be seen from the values reported in the main diagonals. It should also be emphasized that, moving away from the main diagonal, the extent of the errors depends on the stiffness that have been confused. As an example, to arrange k_4 in the place of k_1 is more serious than confusing k_2 and k_3 considering that $k_4 = k_1 + 0.95k_1$ while $k_3 = k_2 + 0.25k_2$ (see Eq. (2)). Both matrices report a percentage error that is higher in case of pairs made of similar stiffness than in case of pairs in which the stiffness difference was more relevant. This outcome confirms that perception through passive touch is in general more challenging than perception by means of active exploration. Besides, providing an enriched information on the object indentation dynamics contributes to reduce the error even in the most challenging cases.

IV. Conclusions

This work presents a novel wearable haptic device for object compliance discrimination through passive touch. To date, most of the haptic devices for transmitting stiffness exploit constant speed for object indentation, inducing users to evaluate stiffness on the basis of the integral of the force over time. Even if functional, this strategy imposes limits on how the object has to be indented to let the system work. Conversely, the proposed device implements a sensory decoupling approach with the aim of recreating the dynamics of the interaction with compliant objects. The combination of squeezing and skin-stroking cues provides the user with information about applied force and surface displacement, enabling the perception of objects stiffness.

We described the mechanical structure, the working principle, the sensory decoupling approach, and the control of the proposed device. In order to evaluate the performance, we conducted an experimental campaign where users wore the device to discriminate different objects stiffness. The results show that the envisaged sensory decoupling technique is effective to identify and sort different stiffness. In the future, we plan to run a more extensive evaluation by enrolling more subjects and assessing the perceived cognitive load. Moreover, we aim to improve the wearabiltiy and ergonomics of the device by reducing the size of actuators, or selecting more compact form-factor ones. It is worth to underline that this version of the device has been designed with powerful actuators to overcome any mechanical uncertainty and guarantee precise haptic cues. In general, the study presented in this work represents the first attempt to recreate the interaction with compliant objects displaying at the same time both the force applied and the indentation. The device here presented paves the way for further design choices and improvements in this direction. Finally, further psychophysical studies will be crucial to generating more informative tactile signals in order to improve the perception of object compliance.

V. Acknowledgments

We thank Alberto Fantozzi for the feasibility studies and the preliminary design of the device.

References

[1] W. M. B. Tiest and A. M. Kappers, "Cues for haptic perception of compliance," *IEEE transactions on haptics*, vol. 2, no. 4, pp. 189–199, 2009.

[2] M. A. Srinivasan and R. H. LaMotte, "Tactual discrimination of softness," *Journal of neurophysiology*, vol. 73, no. 1, pp. 88–101, 1995.

[3] J. J. Gibson, "Observations on active touch," *Psychological review*, vol. 69, no. 6, pp. 477–491, 1962.

[4] R. Harper and S. Stevens, "Subjective hardness of compliant materials," *Quarterly Journal of Experimental Psychology*, vol. 16, no. 3, pp. 204–215, 1964.

[5] H. Z. Tan, N. I. Durlach, G. L. Beauregard, and M. A. Srinivasan, "Manual discrimination of compliance using active pinch grasp: The roles of force and work cues," *Perception & psychophysics*, vol. 57, no. 4, pp. 495–510, 1995.

[6] U. Koçak, K. L. Palmerius, C. Forsell, A. Ynnerman, and M. Cooper, "Analysis of the jnd of stiffness in three modes of comparison," in *International Workshop on Haptic and Audio Interaction Design*. Springer, 2011, pp. 22–31.

[7] F. Sorgini, L. Massari, J. D'Abbraccio, E. Palermo, A. Menciassi, P. B. Petrovic, A. Mazzoni, M. C. Carrozza, F. N. Newell, and C. M. Oddo, "Neuromorphic vibrotactile stimulation of fingertips for encoding object stiffness in telepresence sensory substitution and augmentation applications," *Sensors*, vol. 18, no. 1, p. 261, 2018.

[8] Y. Visell, "Tactile sensory substitution: Models for enaction in hci," *Interacting with Computers*, vol. 21, no. 1-2, pp. 38–53, 2009.

[9] R. Raisamo, I. Rakkolainen, P. Majaranta, K. Salminen, J. Rantala, and A. Farooq, "Human augmentation: Past, present and future," *International Journal of Human-Computer Studies*, vol. 131, pp. 131–143, 2019.

[10] J. Craig and V. Petterson, "Introduction to the practice of telemedicine," *Journal of telemedicine and telecare*, vol. 11, no. 1, pp. 3–9, 2005.

[11] S. J. Sirintrapun and A. M. Lopez, "Telemedicine in cancer care," *American Society of Clinical Oncology Educational Book*, vol. 38, pp. 540–545, 2018.

[12] V. Villani, F. Pini, F. Leali, and C. Secchi, "Survey on human–robot collaboration in industrial settings: Safety, intuitive interfaces and applications," *Mechatronics*, vol. 55, pp. 248–266, 2018.

[13] C. Pacchierotti, S. Sinclair, M. Solazzi, A. Frisoli, V. Hayward, and D. Prattichizzo, "Wearable haptic systems for the fingertip and the hand: taxonomy, review, and perspectives," *IEEE Trans. Haptics*, vol. 10, no. 4, pp. 580–600, 2017.

[14] J. Wessberg, H. Olausson, K. W. Fernstroom, and A. B. Vallbo, "Receptive field properties of unmyelinated tactile afferents in the human skin," *Journal of neurophysiology*, vol. 89, no. 3, pp. 1567–1575, 2003.

[15] R. Ackerley, H. B. Wasling, J. Liljencrantz, H. Olausson, R. D. Johnson, and J. Wessberg, "Human c-tactile afferents are tuned to the temperature of a skin-stroking caress," *Journal of Neuroscience*, vol. 34, no. 8, pp. 2879–2883, 2014.

[16] Å. Vallbo, H. Olausson, and J. Wessberg, "Unmyelinated afferents constitute a second system coding tactile stimuli of the human hairy skin," *Journal of neurophysiology*, vol. 81, no. 6, pp. 2753–2763, 1999.

[17] K. S. Severson, D. Xu, M. Van de Loo, L. Bai, D. D. Ginty, and D. H. O'Connor, "Active touch and self-motion encoding by merkel cell-associated afferents," *Neuron*, vol. 94, no. 3, pp. 666–676, 2017.

[18] R. D. Luce and W. Edwards, "The derivation of subjective scales from just noticeable differences." *Psychological review*, vol. 65, no. 4, p. 222, 1958.

[19] M. Morioka and M. J. Griffin, "Dependence of vibrotactile thresholds on the psychophysical measurement method," *International Archives of Occupational and Environmental Health*, vol. 75, no. 1, pp. 78–84, 2002.

[20] H. Alexander and T. Cook, *Variations With Age In The Mechanical Properties of Human Skin in Vivo*. London: Macmillan Education UK, 1976, pp. 109–117. [Online]. Available: https://doi.org/10.1007/978-1-349-02492-6_15

[21] Q. H. Van and M. Harders, "Augmenting contact stiffness in passive haptics—preliminary results with twisted string actuation," in *2017 IEEE World Haptics Conference (WHC)*. IEEE, 2017, pp. 148–153.

[22] E. P. Scilingo, M. Bianchi, G. Grioli, and A. Bicchi, "Rendering softness: Integration of kinesthetic and cutaneous information in a haptic device," *IEEE Transactions on Haptics*, vol. 3, no. 2, pp. 109–118, 2010.