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Modulating the Perceived Softness of Real Objects through Wearable *Feel-Through* Haptics

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***Abstract*—In vision, Augmented Reality (AR) allows the superposition of digital content on real-world visual information, relying on the well-established See-through paradigm. In the haptic domain, a putative Feel-through wearable device should allow to modify the tactile sensation without masking the actual cutaneous perception of the physical objects. To the best of our knowledge, a similar technology is still far to be effectively implemented. In this work, we present an approach that allows, for the first time, to modulate the perceived softness of real objects using a Feel-through wearable that uses a thin fabric as interaction surface. During the interaction with real objects, the device can modulate the growth of the contact area over the fingerpad without affecting the force experienced by the user, thus modulating the perceived softness. To this aim, the lifting mechanism of our system warps the fabric around the fingerpad in a way proportional to the force exerted on the specimen under exploration. At the same time, the stretching state of the fabric is controlled to keep a loose contact with the fingerpad. We demonstrated that different softness perceptions for the same specimens can be elicited, by suitably controlling the lifting mechanism of the system.**

***Index Terms*—Tactile Augmented reality, Feel-through haptics, wearables, softness perception.**

I. Introduction

Augmented Reality (AR) technologies allow superimposing digital-virtual elements on the information retrieved from objects or places in the real world Nowadays, the majority of AR solutions relies on the interplay between digital visual content and real-world visual information, displaying virtual images while maintaining *See-Through* capability. Looking at haptic AR, where the user can feel real objects augmented with synthetic haptic stimuli [1]–[3], there is only limited evidence of cutaneous interfaces for tactile Augmented Reality (tAR). Indeed, while systems for delivering kinaesthetic haptic feedback have been proposed for AR applications, e.g. through passive actuation with tendon-based transmission mechanisms [4], the under-exploration of the sense of touch for tAR with respect to vision (or hearing) is mainly due to the challenges in designing *Feel-through* interfaces, i.e. wearables that are so soft to not block the cutaneous perception of the physical objects under exploration, yet able to change the tactile feeling of those objects [5], [6].

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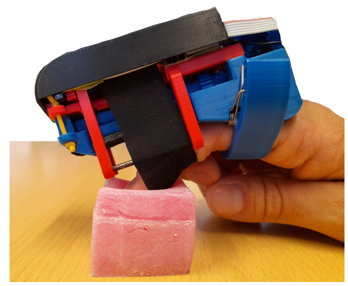

Fig. 1. The W-FYD *Feel-through* device worn by a user during the tactile exploration of a silicone specimen.

Electro-tactile stimulation that relies on the usage of driving currents through the skin to elicit in the user the feeling of a vibration has been proposed for the design of *Feel-through* devices [7], [8]. However, the fidelity of the evoked tactile sensation is limited compared to the direct mechanical stimulation of the skin [5].

Most of wearable haptic systems provide a direct mechanical stimulation to the skin by using a rigid contact surface to deliver tactile cues [9]. This implies that these systems work effectively in virtual reality applications but are not suited for tAR, since their rigid interaction surface limits the natural tactile perception of the real objects under exploration. To circumvent this problem and enable applications in AR, tactile stimuli can be applied not exactly where the contact with tangible objects occurs (e.g. at the fingertip) but at a different location (e.g. at the middle or proximal phalanx) [10]–[12]. These solutions enable users' free-hand interactions with real environments in AR, but cannot be considered *Feel-through* according to the definition provided above [5].

Recent advancements in material technologies have opened interesting perspectives for the design of *Feel-through* tactile interfaces [8], e.g. relying on the usage of soft dielectric elastomer actuators (DEAs) [5]. However, most of current solutions employing soft and mechanically-transparent materials focus on the delivery of vibrotactile feedback, and their usage to alter the perception of physical properties of the touched objects has not been explored yet. Looking at the perception of softness, which represents one of the most accessible sources of information after the initial phases of contact, and its possible alteration via tAR, it is worth reporting the wearable presented in [10]. This device can increase the perceived compliance of a tangible object by varying the pressure applied through the device at the middle phalanx. However, as discussed above, this solution cannot be considered *Feel-through*. Furthermore, the perception of softness was only altered in a binary way. In [13] the authors presented a system based on a rigid ring pressed on the finger-pad, which can reduce finger-pad deformation while leaving

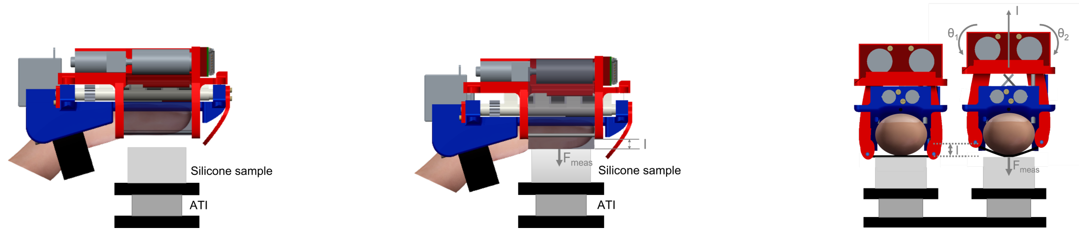

Fig. 2. W-FYD activation system. In the left part of the figure (from left to right), it is possible to observe the W-FYD at the first contact with the specimen (left) and when the lifting mechanism warps the fabric around the fingerpad to modulate the growth of the contact area based on the force read by the ATI sensor, placed under the physical specimen (right). In the right part of the figure (from left to right) it is possible to observe the frontal view of the system: on the left the initial contact; on the right during the specimen exploration, with the lifting mechanism on and the activation of the two DC motors for fabric band release. I and F_{meas} are the displacement commanded by the lifting mechanism as from Eq. 1 and the measured force used to compute F in Eq. 1. θ is the DC rotation angle based on Eq. 2.

the center of the fingerpad free. However, this system only works for objects that are smaller than the fingerpad areas and allows for a simple switch on the perceived softness state of an object.

To the best of authors' knowledge, there are no wearable systems for tAR that implement the *Feel through* paradigm for modulating the perceived softness of the touched objects, i.e. not simply altering in a binary fashion softness perception. Seeking for a *Feel-through* approach in haptics is not only motivated by the need for matching the analogous visual counterpart, which seems to work well in AR, but also by the observations on the intuitiveness of artificial tactile stimulation, as reported in [14]. Such an intuitiveness is related to the satisfaction of two conditions, namely *modality matching* and *somatotopic matching*, the latter implies that the artificial cues should be delivered in the same place where they would naturally be felt. In [15], we proposed a fabric-based wearable device (W-FYD) that can be worn on the users' index and enables both active and passive softness rendering, by varying the stretching state of a fabric through two DC motors (for more technical details please refer directly to [15]). The two DC motors independently move two rollers attached to the elastic fabric. Passive softness rendering (passive mode) is enabled by a lifting mechanism actuated by a servomotor. In this manner, the fabric is put in contact with the user's fingerpad, which is still. The user can hence experience different stiffness profiles that are determined by the regulation of the fabric stretching state performed by the two DC motors, independently from the force exerted on the user's fingerpad.

The deformability of the fabric also allows the implementation of tAR *Feel-Through*, i.e. the delivery of tactile cues that can be superimposed to the the sensation derived from the contact with external items. A customised version of W-FYD was used to superimpose artery pulse effects to artificial organs, without blocking or hampering the natural sensation derived from artery palpation [15].

However, the usage of W-FYD for modulating the perception of a tactile property of real objects, i.e. softness, in *Feel-through* tAR has not been demonstrated yet. In this work, we aim at bridging this gap, proposing the first *Feel-through* wearable for softness perception modulation in tAR through the alteration of contact area spread rate. In this paper, the W-FYD is controlled in the passive mode but with a different goal. The fabric is kept in loose contact with the fingerpad in a "resting stretching condition" (i.e. it does not produce any perceivable pressure on the users'). When the user's index finger probes for softness the external specimen (keeping the finger still), the lifting mechanism warps the fabric around the fingerpad. In parallel, the two motors rotate accordingly, to maintain the fabric in the resting stretching condition, to not alter the contact force experienced by the finger during the haptic interaction with the environment. In this manner, by varying the displacement commanded by the lifting mechanism that is proportional to the force exerted by the user on the real object, we can vary the contact area growth on the fingerpad. I.e. the larger is the displacement, the larger is the area growth, for the same indenting forces (see Figs 2 and 3).

The motivation underpinning this control mode moves from the Contact Area Spread Rate (CASR) paradigm [16], which states that a large part of cutaneous information necessary to discriminate softness of objects by touch is contained in the rate by which the contact area spreads over the finger surface, as the finger is increasingly pressed on the object. The larger is the spread of the contact area, the softer is the probed object. We used this paradigm to design the grounded version of W-FYD, i.e. a contact-area based softness display for VR [17], and other similar approaches can be found in literature, although not suitable for for wearable translations [18].

Our hypothesis is that, without blocking user's cutaneous perception of the softness of the probed object, we can manipulate the contact area growth on the user's fingerpad and increase the experienced softness.

We verified this hypothesis by performing psychophysical studies, where we asked participants to evaluate the experienced softness of silicone specimens according to a two Alternative Forced Choice (2AFC), while wearing the device. We considered three experimental conditions: ground truth (GT) (the W-FYD is kept deactivated); Low Alteration (LA) and High Alteration (HA) (corresponding to two different proportional coefficients that relate the displacement commanded by the lifting mechanism to the force produced on the real silicone specimens, resulting in lower and higher displacements for the same levels of force, respectively). We fitted the psychometric functions for the participants, observing a statistically significant shift of the Point of Subjective Equality (PSE). This indicates a systematic bias in the perceived levels of object softness, which can be sorted in descending order according to HA, LA, GT condition, respectively.

II. Softness Manipulation in tAR

The W-FYD is controlled to modulate the contact area growth over the fingerpad in relation to the force exerted on the physical specimen. To this aim, we use the device in the passive mode and control the lifting mechanism. The lifting mechanism is actuated by a servomotor (HS-5055MG Servo by Hitec), and it is based on two camshafts connected by gears to allow the vertical displacement of the frame part (which hosts the two DC motors by Pololu 298:1 Micro Metal Gearmotor that are independently, position-controlled with readings of two absolute 16 bit magnetic encoder AS5045 by Austria Microsystems). Two pins are connected to the frame through supports, to guarantee that, when the W-FYD is used for softness rendering, a planar surface is offered for the fingertip to interact with when the fabric. The frame part rests over the camshaft. The relationship between the angle of the servomotor and the height variation commanded by the lifting mechanism I was derived in [15]. When the lifting mechanism is actuated and a commanded vertical displacement I provided, the fabric is warped around the fingerpad (see Fig. 2).

The commanded displacement I is derived as

$$I = I_r \frac{F \cdot I_{Max}}{F_{Max}} \tag{1}$$

where I is the commanded displacement, I_r is the scaling value, used to control the amplitude of the warping effect, $F = F_{meas} - F_t$ where F_{meas} is the measured force through a F/T sensor placed under the physical specimen and F_t is a force threshold, I_{Max} is the maximum vertical displacement that the device is capable of generating (10.0 mm) and F_{Max} is the maximum force used for the calibration of the system. The force threshold (F_t) was heuristically set to 0.5 N to avoid oscillations in the force measurements due to noise that could overexcite the lifting mechanism. The maximum force was set to 5 N in a cautionary manner, to prevent possible damages to the W-FYD device during the physical exploration of the specimen and it is coherent with the range reported in [15]. To larger commanded displacements, for the same contact force values, a larger warping of the fabric would result in a larger contact area on the fingertip. In other terms, since I is proportional to F through the parameter I_r, a change in I_r would result in a change of the contact area growth under increasing values of F. This effect is schematically exemplified in Fig. 3b where increasing values of I_r (i.e. 0, 0.25,1) corresponds to steeper slopes in the force-area plot. $I_r = 0$ corresponds to the condition in which the lifting mechanism is deactivated.

When $I = 0$, the fabric (isotropic elastic fabric by Superbiflex HN by Mectex S.P.A with thickness $< 1mm$) is wrapped around the DC motors to be in loose contact with the fingerpad but still extended between the two pins (resting stretching state). This condition provides our reference (0 °) for the angular position of the two motors θ. Note that $\theta_1 = -\theta_2$ see Fig. 2. When the two motors are controlled to increase the stretching state of the fabric, motor 1 should rotate clockwise and motor 2 counterclockwise. Conversely, to maintain the condition of loose contact when the lifting mechanism is activated. the two DC motors are actuated to release the fabric (i.e. to rotate counterclockwise and clockwise, respectively), to not alter the contact force that the finger experiences during the physical item exploration (see Fig. 2c). The computation of the required rotation angle is performed considering the shape of the fabric below the finger and approximating it considering a triangle with height I. It is possible then to obtain the equation

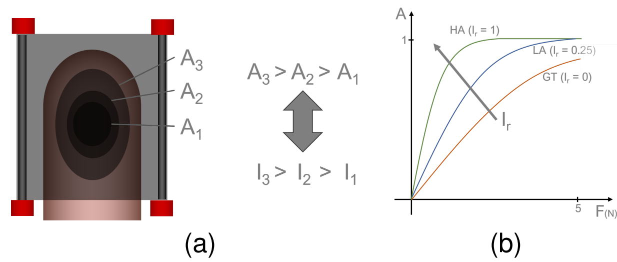

Fig. 3. Contact area evolution. In (a) it is reported a graphical representation of the growth of the contact area A when I increases, at the same value of force; changing the value of I_r in Eq.1 allows managing the rate at which the contact area grows with the increase of F - paradigmatic curves of the generated effect can be observed in (b).

$$\theta_1 = -\theta_2 = C_F \frac{\sqrt{\frac{b}{2}^2 + I^2}}{r} \tag{2}$$

where θ_1 and θ_2 are the angles to be applied to the two DC motors (0 ° at resting position), b is the distance between the two fabric guiding pins (acting as the base of the triangle - 25 mm), and r is the diameter of the rollers moved by the DC motors (6 mm). C_F is a corrective factor used to balance the fact that the two sides of the triangle are actually curved, set empirically to 1.15. Figure 3 shows a pictorial representation of the increase of contact area due to increasing values of I_r in the considered range of force considered. Fig. 3b shows the effect on the contact area growth for different values of I_r in paradigmatic area-force curves. Note that the velocity by which we can change the contact area is limited by the performance of the servomotor acting the lifting mechanism. In [15] we characterized it and showed that our system exhibits an expected low pass behavior with a cut frequency at 3dB and 6dB in 3.04 Hz and 4.36 Hz, respectively, which are coherent with typical indentation frequencies used by humans for active softness probing [15].

III. Experimental Validation

A. Participants

Seventeen naïve volunteers (7 female, age mean ± SD: 28.18 ± 2.81, right-handed) took part in the experimental tests. All participants gave informed consent to perform the experiments. No subjects reported physical nor psychological limitations that would affect their ability to perform the task. The experimental procedures were approved by the Committee on Bioethics of the University of Pisa - Review No. 30/2020.

B. Experimental Setup

For the experiment execution, the participant was sitting in front of the experimental setup, at a height allowing the user to rest the right elbow on the table in a comfortable position. The participant was wearing the W-FYD wearable haptic system on the index finger of the right hand.

In front of the participant, a cardboard panel was placed in order to hide the setup to participant's view, where a hole was cut out to allow the insertion of the right arm, to reach the sample to explore. A 27" 16:9 screen was placed in a position visible to the participant, to provide visual cues, i.e.: the full red screen was used to ask the participant to not perform exploration, keeping the finger raised from the sample; the full green screen was the indication to perform the exploration; a black screen with the question ”Which was the softer one?” written in white to require participant's' answer. A programmable mouse was placed in correspondence with participant's left hand and used to collect the answers. Only during the training phase (see Sec. III-C for more details) the screen was lit in whole orange to indicate that the exploration force on the sample was exceeding 5 N; this indication was used only to allow the participant to tune the exerted force.

The rest of the setup was composed of a force/torque sensor mini45 (ATI Industrial Automation, USA) to measure the interaction force of the participant with the silicone sample placed on it, see Fig. 2.

Five silicone samples were used for the experiment. All samples were built with the same cylindrical shape (30mm height, 30mm diameter) with Sylgard 184 silicone[1] (The Dow Chemical Company, USA) in different compositions (in terms of the ratio of base to curing agent by mass, i.e. 30:1, 35:1, 40:1, 45:1, 50:1), to obtain five different levels of compliance. We performed a characterization of the stiffness (in terms of force-indentation) of the specimens by using the indenting system reported in [19]. We considered a constant indenting speed equal to 5 mm/s and fitted the force-indentation values linearly - R^2 larger than 0.9, achieving the following stiffness values: 8.10 N/mm (30:1), 4.83 N/mm (35:1), 3.41 N/mm (40:1), 2.23 N/mm (45:1), 1.42 N/mm (50:1). To prevent any auditory cue, participants were asked to wear headphones delivering pink noise.

A computer with the Unix-based Ubuntu OS was used to manage the whole experiment. The computer was used to read force values from the F/T sensor, to compute the action of the W-FYD and control it, to control the visual instructions on the screen, and to set the timing of the explorations and the pauses. Moreover, the PC was used to record the participant answers and all the data-log of the experiment. The control loop of the system run at 500 Hz.

C. Experimental Protocol

The protocol used for the experiment was the same for all participants. A total of 305 couples of stimuli divided in four blocks were presented to the participant. Each couple was composed of a reference stimulus, always the 1:40 sample with the WFYD worn on the finger but deactivated, and a comparison stimulus randomly selected between the five possible samples (reported in Sec. III-B). Depending on the experimental block, the exploration of the silicone in the comparison stimulus was coupled or not with an additional tactile stimulus provided by the haptic device (see below). The order of the two stimuli was randomized across trials. The blocks were the following:

- TR TRaining: the first five couples were used as training session. In this session the pink noise was off and the participant was instructed on how to perform the exploration.
- GT Ground Truth (baseline): A series of 100 couples were used as ground truth. In this condition, the haptic device was kept deactivated also for the comparison stimulus.
- LA Low Alteration: A series of 100 couples for which the alteration of the contact area during the exploration was associate to I_r equal to 0.25.
- HA High Alteration: A series of 100 couples for which the alteration of the contact area during the exploration was the maximum possible. I_r was set to 1.

A mandatory five minutes pause was performed after 100 and 200 couples were tested.

The exploration of each sample was set to 4 s maximum.The participant was asked to perform the exploration trying to use always the same movement: a repeated dynamic vertical movement of the finger, normal to the top surface of the sample without rotational movement of the finger on the sample surface. Prior to the experiment, in the training phase, participants were required to wear the device, place the finger on one randomly selected specimen and to probe it for softness. With the other bare finger they were required to do the same with the same specimen. In the meantime, we heuristically set the position of the two DC motors to calibrate the resting stretching state of the fabric (corresponding to motor angular position 0). This position was identified as the position in which the stretching state of fabric was evaluated by the participant to not produce any perceivable force against the fingerpad, neither alter the actual softness probing, compared to the bare finger condition. In this condition, the fabric is still extended between the two pins and in contact with the fingerpad (loose contact).

Six out of the seventeen participants (3 female, age mean 27 std 2.37) performed the experiment with an additional experimental condition, *control experiment*, where they were asked to perform the exploration task with their bare index, without wearing the device, to evaluate the possible impairment that the fabric could induce in natural softness perception.

IV. Experimental results

By means of a Generalized Linear Mixed Model (GLMM) [20], we tested whether the three tactile stimuli delivered by the device (experimental blocks GT, LA, HA) affected the perceived stiffness. Based on Akaike Information Criterion-AIC, we selected a model of the form: $\Phi^{-1}[P(Y=1)] = \beta_0 + u_0 + \beta_1 X + u_1 X + \beta_2 D_{LA} + \beta_3 D_{HA} + \beta_4 D_{LA} X + \beta_5 D_{HA} X$, where Φ^{-1} is the probit link function, $P(Y=1)$ is the probability of perceiving the comparison stimulus as harder than the reference stimulus, X is the stiffness of the comparison silicone, β_* and u_* are the fixed- and random-effect parameters, respectively. We used a dummy predictors D_* and the interaction $D_* X$ to account for the difference in intercept and slope between the two experimental conditions LA and HA and the baseline in the model, GT.

The estimated coefficients of the model ($\pm$ standard errors) are $\beta_0 = -4.0(\pm 0.003)$, $\beta_1 = 1.17(\pm 0.003)$, $\beta_2 = 0.88(\pm 0.003)$, $\beta_3 = 0.92(\pm 0.003)$, $\beta_4 = -0.35(\pm 0.002)$, and $\beta_5 = -0.42(\pm 0.002)$. The p-values for all the parameters of the model were < 0.001. The scatter-plot in Fig. 4 illustrated the individual responses and the predictions from the Generalized Linear Mixed Model, for all participants (labelled as 1–17) and in all the experimental conditions.

Using the bootstrap method described in [20] we estimated the Point of Subjective Equality (PSE) and the Just Noticeable Differences (JND) in the three experimental conditions. To evaluate whether the two conditions were statistically different

[1] https://www.dow.com/en-us/pdp.sylgard-184-silicone-elastomer-kit.01064291z.html#overview

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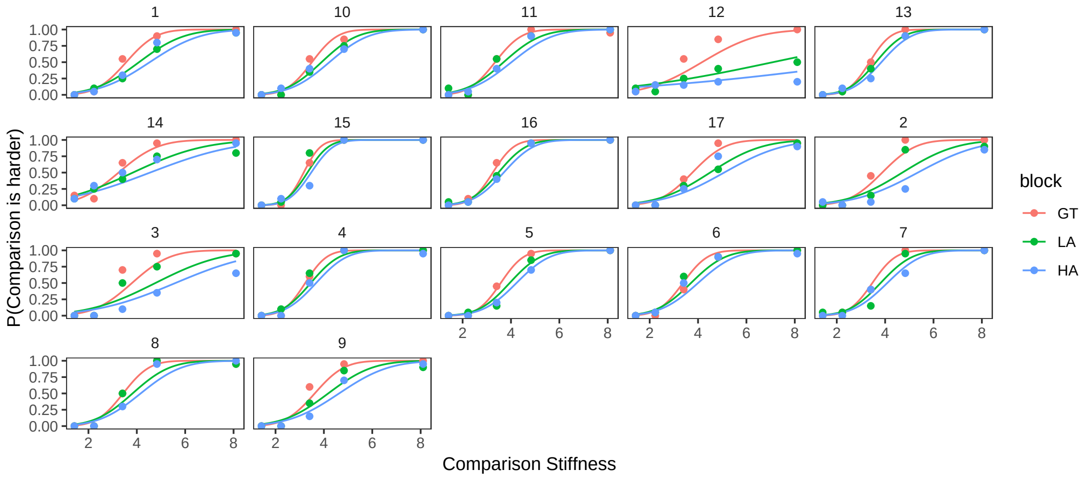

Fig. 4. Individual Responses from the Generalized Linear Mixed Model in all experimental conditions

TABLE I
DIFFERENCES BETWEEN EXPERIMENTAL CONDITIONS. THE 95% CIS OF THE DIFFERENCES WERE ESTIMATED WITH THE BOOTSTRAP METHOD.

Parameter	Contrast	Difference	l-95% CI	u-95% CI
PSE	$GT - LA$	-0.40	-0.59	-0.24
PSE	$GT - HA$	-0.74	-1.02	-0.53
PSE	$LA - HA$	-0.34	-0.53	-0.17
JND	$GT - LA$	-0.25	-0.36	-0.15
JND	$GT - HA$	-0.33	-0.47	-0.21
JND	$LA - HA$	-0.08	-0.18	0.01

from the baseline, the difference in the PSE and JND between the baseline GT and two experimental conditions LA and HA was calculated. Table I reports the 95% confidence intervals (CI) of the difference in PSE and JND values. The first three bootstrap intervals in the table show that: the PSE in the LA condition is significantly higher compared with the baseline GT; the PSE in the HA condition is significantly higher compared with the baseline GT; the PSE in the test condition HA is significantly higher compared with the test condition LA. This means that, on average, the stimulus was perceived as stiffer in GT compared with the other two conditions, and that the two test conditions LA and HA produced a significantly different perceived stiffness. The last three bootstrap intervals in the table show that the JND in the LA condition is significantly higher compared with the baseline GT, and that the JND in the HA condition is significantly higher compared with the baseline GT, respectively.The JND in the test conditions HA was not significantly higher than in the condition LA.

Next, we tested the linear relationship between the continuous predictor I_r characterising each block and the perceptual response estimated by the PSE of the model. The variable I_r ranges from 0 to 1 and represents the scaling value used to control the amplitude of the effect in each block (i.e. GT=0, LA=0.25, HA=1). We fit these data with a linear regression model. Fig. 5 reports the value of PSE for each participant calculated for different values of I_r dependent on the experimental conditions. Despite some individual references, the slope of the linear regression (m) was significantly different from zero confirming the association between the two variables (m=1.5, p = 0.027). That is, the higher the value of I_r the higher the perceptual bias, in agreement with the GLMM model.

In the *control experiment* we verified that the presence of the

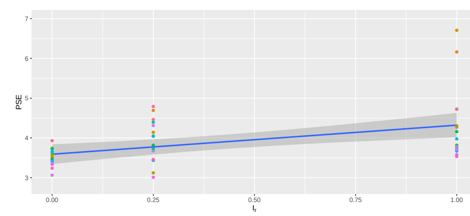

Fig. 5. Linear regression model fitted on individual PSE computed on the different values of I_r correspondent to all the experimental conditions.

fabric of device *per se* did not alter natural softness perception. The psychometric functions obtained without the device and in GT condition were largely overlapping, and the PSE and the JND of the model were not significantly different between the two conditions. Specifically, the difference in PSE was -0.1 (95% CI from -0.34 to 0.07) and the difference in JND was -0.05 (95% CI from -0.19 to 0.04).

V. DISCUSSION

The experimental results confirmed the capability of our device to induce an increase in the perceived softness of physical objects. In fact, as shown by the GLMM parameters' estimation, the two experimental conditions involving the active control of the W-FYD device (i.e. LA, HA) produced a significant shift in the PSE toward higher stiffness values with respect to the baseline condition GT, and this shift is different between LA and HA. Therefore, the physical object being touched when the lifting mechanism of the W-FYD device is activated was perceived to be significantly softer compared to the case with the W-FYD deactivated. Furthermore, it is possible to modulate the increase of softness perception, in terms of PSE shift, based on the scaling value I_r. The linear regression fitted on individual participants' data confirms these findings: in fact, the increase in the scaling value I_r of the three experimental conditions (i.e. 0, 0,25, 1) was associated with an increase of the perceived PSE. The JND was also affected by the activation of the W-FYD device such that in the HA and LA condition JND was larger compared to the GT condition. We also proved that the presence of the fabric does not alter natural softness perception when the device is worn but not activated (*control experiment*).

VI. Conclusions and Future Directions

This work presents the first implementation of the haptic *Feel-through* paradigm with a wearable device to be used in tAR, for modulating the perception of softness of real objects. The usage of a thin fabric allows to not block users' natural softness perception of the external items, when the system is not activated: at the same time, a suitable mechanism for controlling the growth of the contact area over the fingerpad based on the lifting mechanism of the device and the measured force exerted on the probed specimen enables a change of the perception of softness. We demonstrated that by varying the proportional factor that relates the vertical displacement of the lifting mechanism and the measured force, and releasing the fabric accordingly to not affect the contact force exerted on the physical item under exploration, it is possible to produce different perceived softness levels of real objects.

Although the results are encouraging, we are aware that the current setup has some limitations. First, with this control mode we can only make softer physical deformable objects. An extension to non deformable items is in principle feasible and it is currently under evaluation. Second, with this control mode, we cannot make stiffer real objects. The implementation of the latter modality will be addressed as future work. Furthermore, an effective usage for tAR would require that the external object should not embed any force-torque sensor. To circumvent this limitation, we are considering to integrate in the device a system to measure the contact force with the physical item, e.g. by exploiting the analysis of the fingernail coloration described in [21]. Finally, in this work we demonstrated the feasibility to change softness perception over a discrete set of control parameters (LA, HA in addition to GT) of the device. While this is already an advancement with respect to the SoA, where only one altered condition was considered with respect to GT for softness perception, in the future we will perform an exhaustive characterization of the system to identify the minimum variation of the commanded displacement that can elicit a change in softness perception to evaluate the increase of the number of the altered conditions. These tests will be performed with a re-engineered version of the W-FYD, taking into account the enhancement of the system form factor and overall wearability, and characterising the workspace in terms of controlled variables (CASR, force). It will be also interesting to investigate possible conflicts between kinesthetic cues and altered CASR behavior, by running active compliance discrimination experiments with specimens that can either have the same CASR characteristics but different kinesthetic (force-indentation) ones, or the other way around as in [22]. Possible applications involving the effects on shear cue perception will be also considered. Furthermore, we will perform a more-in-depth characterisation of the possible alteration that our approach can produce e.g. at microscale level. Indeed, while our *Feel-through* device seems to work properly in terms of CASR alteration (macro-geometrical changes of contact area shape do not play a fundamental role in CASR-enabled softness perception [16]), other aspects such as the microscale pressure distribution and the impairment of capacitive touch due to the fabric deserve future investigations, which will also include an in-depth evaluation of user's experience. To this aim, human studies for comparing the performance of our approach with non-*Feel-through* tAR [10]–[12] are also envisioned.

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