A Wearable Fabric-based Display for Haptic Multi-Cue Delivery

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***Abstract*— Softness represents one of the most informative haptic properties, which plays a fundamental role in both everyday tasks and more complex procedures. Thus, it is not surprising that a lot of effort has been devoted to designing haptic systems able to suitably reproduce this information. At the same time, wearability has gained an increasing importance as a novel paradigm to enable a more effective and naturalistic human robot interaction. Capitalizing upon our previous studies on grounded softness devices, in this paper we present the Wearable Fabric Yielding Display (W-FYD), a fabric-based tactile display for multi-cue delivery that can be worn by user's finger. W-FYD enables to implement both passive and active tactile exploration. Different levels of stiffness can be reproduced by modulating the stretching state of a fabric through two DC motors. An additional vertical degree of freedom is implemented through a lifting mechanism, which enables to convey softness stimuli to the user finger pad. Furthermore, a sliding effect on the finger can be also induced. Experiments with humans show the effectiveness of W-FYD for haptic multi-cue delivery.**

I. Introduction

In recent years, wearability has become popular as the novel paradigm for human robot interaction, paving the path towards new opportunities to convey haptic stimuli to users in a more naturalistic and effective manner. Wearable haptic systems (hereinafter referred to as WHS) can indeed be comfortably worn by humans, carried around and integrated into their everyday life, with ideal applications related (but not limited) to assistive technologies [1], virtual reality [2], affective touch [3] and tele-manipulation of remote robotic systems [4]. Furthermore, the possibility to integrate WHS with human body with minimal or no constraints to its motion [5] can be exploited to study human behavior in a more ecological way.

Looking at the different strategies used to design wearable/portable haptic devices, it is possible to find systems generating vibrations [1], pin-arrays [6], force applications at one or more contact points [7]. These devices can be applied to different parts of human body, such as arm [5], [8], foot [9] and finger [2], [10] – for a review on these topics, the reader is invited to refer to [10].

Focusing on the finger, different wearable technological solutions can be found in literature for tactile stimulation.

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Fig. 1: W-FYD worn by a user.

Array-based devices [6], [11], [12] although effective, flexible and compact are however limited in terms of portability due to the large number of actuators and/or the need of external drive units for the actuation system. In [2], authors presented a 3 Degrees Of Freedom (DOF(wearable system for modulating skin stretch. A tactor-based display to render planar displacement was presented in [13]. In [14], [15], authors presented a WHS that consists of two motors to convey both normal and tangential forces, thus simulating weight sensation. A novel wearable device as a parallel mechanism with three actuated DOFs, which is able to render contact forces with general direction was described in [10].

However, no one of the aforementioned solutions, although promising, was thought to provide controllable softness information to the user and to enable both active and passive haptic exploration. In this paper, we present a wearable device, hereinafter referred to as W-FYD (Fig. 1), which represents the wearable version of a grounded softness display we described in [16], [17], [18]. It relies on the control of the stretching state of a fabric to reproduce different stiffness levels and, for the first time, it can convey softness information, tangential cues and enable both passive and active haptic exploration in users. The mechanical structure, inspired by the grounded version of the device [18], is also similar to the one reported in [14], where two DC motors can vary the stiffness of the fabric and, if independently controlled, provide tangential force. In W-FYD an additional degree of freedom, implemented trough a servomotor, can enable a passive softness exploration of the fabric, putting it in contact with the user's finger pad.

A similar solution was used in [19], although not suitable for wearable implementation. However, compared to the previously cited solutions, W-FYD is the only device that can convey stiffness information independently from the force experienced by the user, thanks to its design and lifting mechanism, as it will be described with more details in the next Section.

In this work, we will first describe the mechatronic structure and control of the W-FYD and show its capabilities in softness rendering, through passive and active exploration. Then, we will describe experiments with humans and real silicone specimens that show the effectiveness of the system in enabling a correct softness discrimination in users. Furthermore, we will also investigate the effectiveness of the tangential cues W-FYD can convey to the user and the reliability of the slipping sensation such cues can elicit. Results are positive and encourage us to further investigate applications of W-FYD, possibly in multi-digit implementation, for neuroscientific studies, e.g. to investigate the role of softness information for slip control or softness perception of non-uniform materials [20].

II. System Architecture

The design of W-FYD (Fig. 2) was inspired by its grounded counterpart, the FYD-2 [18]. As for the FYD-2, we used a layer of isotropic elastic fabric (Superbiflex HN by Mectex S.P.A), which is offered to the user as interaction surface.

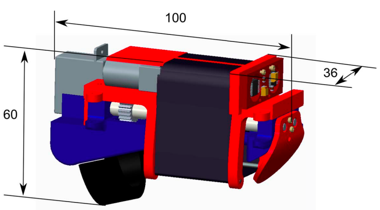


Fig. 2: W-FYD CAD design. Dimensions are in mm and the total mass is 100 g.

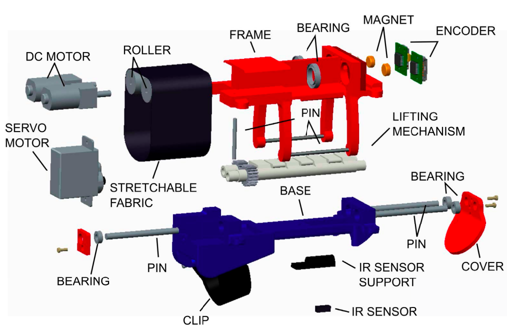


Fig. 3: W-FYD exploded view.

The device is placed over the user's finger, and fixed to it with an elastic clip that prevents rotation and ensures stability. Fig. 3 shows an exploded view of the W-FYD, which consists of two main parts: the base, which is fixed and hosts a lifting mechanism; and the frame, where we placed two DC motors that can independently move two rollers attached to the elastic fabric, thus varying its stiffness. The fabric is wrapped around two pins connected to the frame through suitable supports. As the user's finger is placed in the device, the finger pad can interact with the fabric passively (*passive mode*), thanks to the lifting mechanism pressing the fabric against the finger pad, or actively (*active mode*), with the finger actively probing the interaction surface for softness. Note that in the *passive mode*, the finger is fixed and the lifting mechanism enables to convey only tactile cues to the skin [24]. In the *active mode*, the device is attached to the back of the finger, hence the only movement the user can perform is the flexion of the distal phalanx, which provokes the indentation of the fabric, as reported in fig. 4a.

The main feature of the architecture of FYD-W is that, thanks to the fact that the fabric stretching is actuated separately from the indentation mechanism, it is possible to change the stiffness of the fabric independently and decouple it from the force exerted on the user. This is an important difference respect to previously proposed designs, e.g. [14]: indeed, in the latter case the force increases as the sheet is wrapped around the finger, thus not allowing to independently control force and stiffness.

The lifting mechanism on the base is actuated by a servomotor (HS-5055MG Servo by Hitec), and consists of two camshafts connected by gears. Over the camshaft there is the frame part, which is also connected to the base through pins. As the lifting mechanism is moved by the servo motor, the frame moves upward, together with all the parts attached to it (Fig. 4a). This causes the surface of the fabric, whose stretching state is independently regulated through the control of the DC motors, to be pressed against the finger pad. In particular, with reference to Fig. 4a and 4b, the relationship between the angle of the servomotor α and height variation of the frame h_p is given by the equation

$$h_p = h_0 + L \sin \alpha, \tag{1}$$

which makes it possible to determine h_p from the movement of the servomotor. We set as maximum value for h_p 10 mm, which was heuristically chosen to enable a compelling softness rendering in passive mode while guaranteeing user's comfort.

Two DC motors (Pololu 298:1 Micro Metal Gearmotor) were attached to the frame and, independently, position-controlled with readings of two absolute magnetic encoders (12 bit magnetic encoder AS5045 by Austria Microsystems). Different levels of stiffness can be obtained through a change of the stretching state of the fabric, which can be achieved by suitably controlling the two DC motors to change the relative angle.

In the active control mode, the user can explore different stiffness levels, by moving the inter-phalengeal (IP) and distal-interphalangeal (DIP) joints (Fig. 4c). This is made possible thanks to the clip mechanism, which ensures the stability of the worn system while preserving user's capability to actively interact with the fabric. In this case, the indentation h_a produced by the finger is measured by one contact-less infrared (IR) sensor (Avago HSDL-9100 analog distance sensor with detection range from 0 to 60 mm and 0.5 mm resolution). The IR sensor is attached to the base (Fig. 4d).

Finally, thanks to the presence of the two independently controlled DC motors, W-FYD is endowed with an additional *translational* degree of freedom, which can induce a sensation of sliding/slipping on the user's fingertip. In this case, the user wears the system and the DC motors are synchronously moved, so that the fabric slides against the user's finger (which is still), right and left.

A custom made electronic board (PSoC-based electronic board with RS485 communication protocol) controls motor positions based on the readings from the encoders, the servo motor and enables to acquire the measurements from the IR sensor. The entire cicle works at a frequency of 200 Hz. More details on the system control methods are provided in the following Sections. All the structural parts of W-FYD are in ABSplus - Stratasys, rapid prototyping material, except for the rollers, which are in aluminium, and were fabricated using a computer numeric control machine.

III. System Characterization and Softness Rendering

In this Section we describe the characterization of the system and the control modes of the W-FYD for active and passive delivery of softness stimuli.

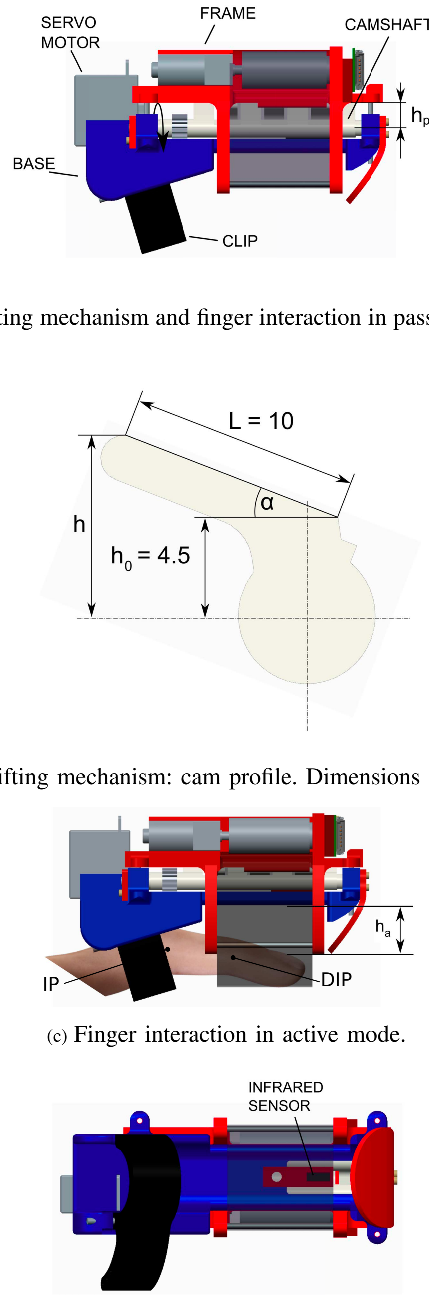
A. Characterization

In order to correctly use the W-FYD, the first mandatory step is a characterization of its stiffness workspace, in terms of force (F, in N) and indentation (δ, in mm), similar to what we did in [18]. For the characterization we used the indentation system described in [18] to apply a vertical force on the fabric, at different stretching states corresponding to different angular positions of the DC motors, hereinafter referred to as θ_1 and θ_2, respectively. With reference to Fig. 5, in this phase we assigned $\theta_2 = -\theta_1 = \theta$, and considered 10 values of θ ranging from 0 to 90 degrees, with step 10 degrees.

The characterization system can control the indentation through a linear actuator, and can measure the contact force. The W-FYD was mounted on a suitable mechanical support and placed over the base of the characterization device. The indenter consists of a cylinder (with radius r equal to 8 mm and length L equal to 21 mm) and a semi-sphere of the same radius fabricated in ABSplus - Stratasys (rapid prototyping material), to recall the shape of the last phalanx of a human finger. It was moved using fixed indentation steps of 1 mm each, for an overall displacement of 15 mm with an indenting velocity of 1 mm/s, and contact forces up to 8.5 N. As discussed in [18], ideally the differences between the indenter (which is a non-compliant object) and human fingertip (which is a compliant object) should be considered during the characterization procedure; however, since the deformation of the fingertip that interacts with the fabric is small, the approximation introduced by using a non-deformable object as indenter is still acceptable.

As we did in [18], we chose a linear interpolation for the force/indentation over different motor positions (goodness of fit $R^2 > 0.97$). In this manner we achieved the force-indentation characteristics for different motor positions as reported in Fig. 6. Thus, we can write the force/indentation characteristic as function of θ as $F = \sigma(\theta)\delta$, and we can interpolate $\sigma(\theta)$ over the motor positions ($R^2 = 0.98$) in order to build a complete stiffness map

$$\sigma(\theta) = m\theta + q = 0.0033\theta + 0.264. \quad (2)$$



(a) Lifting mechanism and finger interaction in passive mode.

(b) Lifting mechanism: cam profile. Dimensions in mm.

(c) Finger interaction in active mode.

(d) Infrared sensor placement.

Fig. 4: W-FYD: mechanical description.

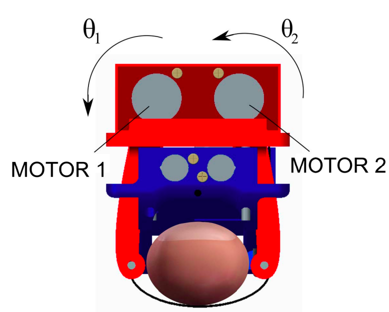


Fig. 5: Representation of a finger interacting with the W-FYD.

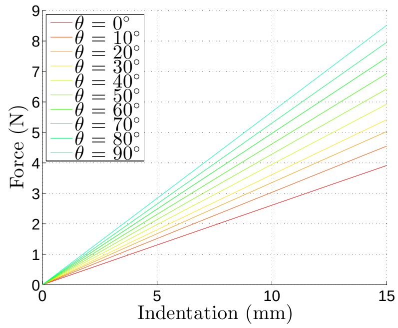


Fig. 6: Elastic fabric force indentation characterization.

B. Softness Rendering

To render a given level of softness, we refer to the force-indentation (i.e. $F(\delta)$) characteristics of the material to reproduce. We used a control architecture entirely based on system characterization reported in Section III. Without loss of generality, hereinafter we will consider the case of power $F(\delta)$ function, i.e. $F(\delta) = \lambda\delta^b$, which we adopted to describe the stiffness behavior of the silicone specimens we used in experiments with humans (see Section IV). As in [18], our signal reference is the value of λ we would like to reproduce through the W-FYD. Exploiting the characterization reported in Eq. (2), λ can be expressed as

$$\lambda = \frac{F}{\delta^b} = \frac{\sigma(\theta)\delta}{\delta^b} = \frac{m\theta + q}{\delta^{b-1}}. \quad (3)$$

The value of indentation δ corresponds to height variation, which can be obtained through the IR sensor measurement h_a in the *active* mode, and through the servo motor commanded h_p in the *passive* mode. After some algebra, we can obtain the motor position θ that allows to achieve the desired stiffness coefficient λ

$$\theta = \frac{1}{m}(\lambda\delta^{b-1} - q). \quad (4)$$

Note that the haptic rendering mechanism of W-FYD enables typical dynamic human interactions to probe for softness external objects, which basically consist of pressing the finger along the normal to the surface, as widely discussed in literature (see e.g. the exploratory procedures described in [25], or [26], where anisotropic or distortion effects due to lateral force exertion were observed in softness perception) and used to shape the design of softness displays (see e.g. [27], [28]).

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IV. Experiments with Humans

We performed experiments with humans to assess the capability of the system of eliciting different softness sensations in the user, considering both active and passive touch modes. Adopting the same procedures and naming as in [27], [18], we asked participants to perform relative and absolute softness cognition tasks: more specifically, in relative cognition tasks, participants were asked to touch three rendered silicone specimens, whose compliance was artificially simulated using W-FYD, and to rank them based on the perceived softness. In absolute softness recognition tasks, participants were asked to correctly associate the artificial silicone specimens with the real ones.

A. Experimental Setup

We used half elliptical silicone specimens (with middle principal axes of $20 \times 20 \times 35$ mm), which were made by mixing a given quantity of a commercial bicomponent, room temperature-curing silicone (BJB TC-5005A/B), with a variable percentage of plasticizer (BJB TC-5005C), acting as a softener. The amount of softener in the mixture was chosen as 0%, 30% and 50%. Hereinafter, we will refer to these specimens as SS1, SS2 and SS3, respectively. SH1, SH2, SH3 indicate their counterparts artificially rendered through W-FYD.

These silicone specimens are coherent with those used in [18] with the grounded version of W-FYD and offer a good representation of the system softness workspace. For an exhaustive psychophysical characterization of softness perception associated to the silicone objects, the reader is invited to refer to [18]. Future research will address a more in depth analysis of psychometric response associated to W-FYD.

Their stiffness characteristics, expressed in terms of force/indentation curves (see Fig. 7), were obtained through the characterization procedure previously described and using a conic shape indenter with a head radius of 2 mm. We imposed a total compression force of 10 N, at a velocity of 10 mm/min, while the indentation and compression force were continuously measured. Force/indentation data were interpolated with a power function, $F(\delta) = \lambda\delta^b$ (see Table I), with $R^2 > 0.99$.

	SS1	SS2	SS3
λ	0.239	0.067	0.024
b	1.67	1.74	1.87

TABLE I: Specimen characterization coefficients.

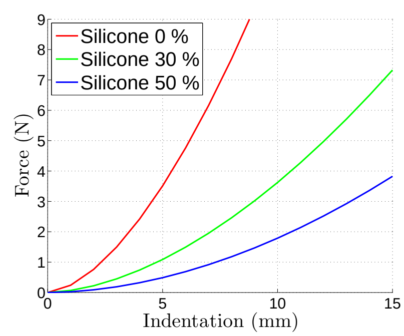

Fig. 7: The $F(\delta)$ characteristics of the three silicone specimens used for the experiments with humans. Silicone 0% corresponds to SS1, while Silicone 30 % and Silicone 50% can be referred to as SS2 and SS3, respectively.

We also conducted an experiment to verify if W-FYD can induce a reliable slipping sensation on the user's finger pad, when its motors are controlled to rotate in the same direction, an to verify whether the participants were able to correctly identify the direction of slipping.

At the end of this last experiment, we also asked the subjects to provide a value in bipolar Likert-type seven-point scale related to the effectiveness of the slippage sensation W-FYD was able to induce.

B. Participants

Fifteen right-handed healthy participants (8 Female, Age: 25.6 ± 1.7) gave their informed consent to participate to the experiment. No one had any physical limitation which would have affected the experimental outcomes. Their finger pads were free of calluses. The experimental procedure was approved by the Ethical Committee of the University of Pisa.

C. Passive Mode – Relative Cognition Task

In the passive mode, the fabric, whose stretching state is controlled to mimic different stiffness levels, was put in contact with the user's finger pad. The servo was fed with a sinusoidal input with frequency of 0.8 Hz, which is consistent with common active exploration tasks in humans. SH1, SH2 and SH3 were presented three times in a random order to the participants and then they were asked to sort them in terms of softness. They did not have time limitations since each rendered specimen was presented to the users as long as they wanted. Participants wore headphones with white noise, to prevent the usage of any auditory cue, and were blind-folded. Results of the ranking experiments are shown in Table II, where perceived softness is reported versus artificially reproduced softness, with the relative accuracy in discrimination for each specimen. Values on the diagonal express the amount of correct answers. The average cognition rate is 85.92% (chance level of 33.34%).

	SH1	SH2	SH3	Relative Accuracy
SS1	40	1	4	88.89%
SS2	4	38	3	84.44%
SS3	1	6	38	84.44%

TABLE II: Confusion Matrix for Relative Cognition Task (passive mode).

D. Passive Mode – Absolute Cognition Task

In this experiment, the task was similar to the one we used for the relative recognition tests in passive mode. SH1, SH2 and SH3 were presented three times in a random order to participants and then they were asked to associate them to their physical counterparts SS1, SS2 and SS3. One rendered specimen was randomly presented at one time to the user's right finger pad. At the same time, real specimens were positioned in a random order for each participant, on a nearby support on the desk (Fig. 8).

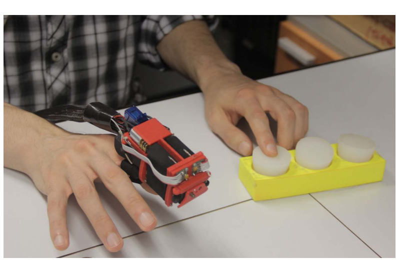

Fig. 8: Experimental setup.

Since participants were blind-folded, they were guided over the real specimens and required to consequently touch them one at a time with the left index finger, with the same frequency used for the artificial stimuli which was simultaneously conveyed to the right finger. We chose this strategy to minimize the effect of *time error* [29]. Participants were recommended to not perform movements of the finger across the surface and not to apply lateral forces, thus avoiding any anisotropic or distortion effect in softness perception [30]. Participants did not have time limitations, and were allowed to touch the silicone specimens, going back and forth between them as many times as they wanted.

We chose active mode for the exploration of the real silicone specimens relying on the results from [24], which showed no significant difference in softness discrimination between active and passive mode with real compliant deformable specimens. Results of the ranking experiments are shown in Table III, where the perception of artificial specimens was associated to the perception of real ones in a confusion matrix structure. Values on the diagonal express the amount of correct answers. The average cognition rate is 86.74% (chance level of 33.34%).

	SH1	SH2	SH3	Relative Accuracy
SS1	41	5	0	89.13%
SS2	1	36	8	80%
SS3	0	4	41	91.11%

TABLE III: Confusion Matrix for Absolute Cognition Task (passive mode).

E. Active Mode – Relative Cognition Task

In the active mode, participants were asked to actively probe and sort for softness the rendered specimens SH1, SH2 and SH3, by moving the Inter-Phalangeal and Distal-Inter-Phalangeal joints of their right finger wearing the W-FYD. In a preliminary task, they were instructed to perform a sinusoidal movement of their finger pad, with a frequency of 0.8 Hz, which was the same for the passive mode. SH1, SH2 and SH3 were presented three times in a random order to the participants and then they were asked to sort them in terms of softness. They did not have time limitations since each rendered specimen was presented to the users as long as they wanted. Participants wore headphones with white noise, to prevent the usage of any auditory cue and they were blind-folded. Results of the ranking experiments are shown in Table IV, where the perception of artificial specimens was associated to the perception of real ones in a confusion matrix structure. Values on the diagonal express the amount of correct answers. The average cognitive rate is 91.11% chance level of 33.34%.

	SH1	SH2	SH3	Relative Accuracy
SS1	43	1	1	95.56%
SS2	1	40	4	88.89%
SS3	1	4	40	88.89%

TABLE IV: Confusion Matrix for Relative Cognition Task (active mode).

F. Active Mode – Absolute Cognition Task

In this experiment, SH1, SH2 and SH3 were presented three times in a random order to participants and then they were asked to associate them to their physical counterparts SS1, SS2 and SS3. The procedure was analogous to the one used for the passive mode. Results of the ranking experiments are shown in Table V, where the perception of artificial specimens was associated with the perception of real ones in a confusion matrix structure. Values on the diagonal express the amount of correct answers. The average cognitive rate is 82.22%, chance level of 33.34%.

	SH1	SH2	SH3	Relative Accuracy
SS1	35	10	0	77.78%
SS2	0	34	11	75.56%
SS3	0	3	42	93.33%

TABLE V: Confusion Matrix for Absolute Cognition Task (active mode).

All these results indicate that the device is able to render different stiffness levels, which are well recognizable by the participants both in active and passive mode. These findings are comparable with the ones reported in [18] for the grounded version of the W-FYD. Furthermore, they are also comparable with values achieved through other grounded softness displays [27], [28].

G. Slipping Experiments and Likert-type scale

Participants placed their right finger into the W-FYD, slightly in touch with the surface of the fabric, and they were provided with 6 randomized stimuli. In this case, the motors were controlled to move synchronously ($\theta_1 = \theta_2$) to simulate a total slide length of 70 mm at a speed of 25 mm/s, in both right and left directions. In previous pilot experiments, we verified that with such a movement the finger maintains the contact with the fabric. More specifically, with reference to Fig. 5, we assume that with both motors rotating of a positive angle, the finger interacting with the fabric should experience a skin stretch in left direction, while a right direction skin stretch is induced by a synchronous negative rotation. Participants were asked to discriminate the direction of skin stretch on their finger. The average accuracy was 99% (chance level 50%), with only one erroneous classification (over 90 trials) for the right direction. This demonstrates a high effectiveness of the W-FYD in rendering tangential directional cues.

At the end of this experiment, we also asked the participants to assess the capability of the device of inducing a slipping sensation, using bipolar Likert-type seven-point scale. We noted that in the actual prototypical design, the weight of W-FYD can affect the naturalness of perception, especially when subjects had small index fingers. Excluding subjects with the smallest index fingers, i.e. subject 2 (M, 25), subject 10 (F, 27) and subject 15 (F, 24), who gave scores 3, 3 and 2, respectively, despite a good discrimination performance, we achieved an average score of 6.67 ± 0.65, which demonstrates a good reliability of W-FYD in eliciting a slippage sensation. Future studies will further investigate these results.

V. Conclusions and Future Works

In this paper, we have presented the W-FYD, a wearable fabric-based haptic display for active and passive softness rendering and tangential slipping cue delivery, which for the first time are all integrated together in this device. Furthermore, due to its architecture, W-FYD enables to change the stiffness level presented to the user and decouple it from the force exerted on the user. Results with human participants confirm the effectiveness of the approach presented here, and encourage us to investigate applications of the device in neuroscientific studies, e.g. to study the role of softness information for slip/grasp control or softness perception of non-uniform materials [20].

Future studies will aim at further reducing the dimensions of the device, thus increasing its wearability, the naturalness of haptic experience and enabling multi-digit implementation. At the same time, we will focus on the development of a virtual reality environment to increase user immersiveness in rendered haptic interactions.

Acknowledgments

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