

Review

A Fabric-Based Approach for Wearable Haptics

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Abstract: In recent years, wearable haptic systems (WHS) have gained increasing attention as a novel and exciting paradigm for human–robot interaction (HRI). These systems can be worn by users, carried around, and integrated in their everyday lives, thus enabling a more natural manner to deliver tactile cues. At the same time, the design of these types of devices presents new issues: the challenge is the correct identification of design guidelines, with the two-fold goal of minimizing system encumbrance and increasing the effectiveness and naturalness of stimulus delivery. Fabrics can represent a viable solution to tackle these issues. They are specifically thought “to be worn”, and could be the key ingredient to develop wearable haptic interfaces conceived for a more natural HRI. In this paper, the author will review some examples of fabric-based WHS that can be applied to different body locations, and elicit different haptic perceptions for different application fields. Perspective and future developments of this approach will be discussed.

Keywords: wearable haptic systems; fabrics; cutaneous feedback; softness rendering; force feedback; affective touch









1. Introduction

The sense of touch is one of the most fundamental sensory channels for humans. It represents the primary way of interacting with and exploring the external environment, and is one of the most effective channels for social communication [1]. Not surprisingly, a great deal of effort has been devoted to the development of artificial systems, or haptic devices, which enable users to feel external or virtual objects as if they were directly encountered, even if they are remote or not directly accessible by touch, by delivering different types of tactile information and can be used in many application fields (for a review, the interested reader can refer to reference [2]). In recent years, to increase device usability, a novel idea has gained increasing attention: i.e., to move from physically-grounded haptic interfaces, where haptic stimulation is provided with respect to (w.r.t.) operator’s ground, towards wearable systems, which can be worn by users while the body-grounded base is moved, as close as possible, to the point of stimulus application [2,3]. This new generation of wearable haptic systems (WHS) [3] can convey tactile cues in a more natural fashion, while being easily worn by users, carried around, and integrated in everyday life. This shift in system design has opened up exciting avenues in many application fields, such as virtual reality and assistive robotics [4–6]. One of the most convincing motivations for this change relies on the possibility to integrate WHS with the human body with minimal constraints [7], thus enabling a more natural investigation of human behavior and human–robot interaction (HRI). For the latter, tele-robotics represents an ideal application field. In this case, wearable devices can be easily worn by human operator and convey to her/him information from the tele-manipulated environment, thus significantly advancing the naturalness of performance. At the same time, the substitution of kinaesthetic force feedback with another form of feedback, such as the one provided by wearable cutaneous devices, represents a useful approach to overcome stability

issues in teleoperation. This method is called sensory substitution: Since no kinaesthetic force is fed back to the operator, the haptic loop is intrinsically stable and, thus, no bilateral controller is needed [8]. An additional method to improve the performance of passive teleoperation systems with force reflection integrates kinaesthetic haptic interfaces with wearable cutaneous haptic feedback. This approach proposes to scale down kinaesthetic feedback to satisfy passivity, at the expense of transparency: In this case, to recover performance, cutaneous force information is conveyed through wearable devices [9]. Human–robot co-working is also another promising scenario for WHS, where the cooperative manipulation of robots, together with a human partner, is envisioned. In this case, mutual knowledge of the current reality, achievable through wearable sensing systems and haptic feedback devices, represents a key component to ensure an effective and natural cooperation [10].

1.1. Wearable Haptic Systems: Technologies and Main Characteristics

Looking at the state-of-the-art, it is possible to observe a number of strategies for stimulus delivery through wearable systems, specifically developed to generate vibrations [4], apply forces [11], stimulate skin using pin-arrays [12] or using electrocutaneous feedback [13], and considering different body locations for stimulus application, such as arm [7,14], foot [15], finger [5,16], among the others; the interested reader may refer to references [16,17] (for a review of these topics see Figure 1).

Location	Devices
 Finger	[5,16,18]
 Wrist	[19,21]
 Arm and Forearm	[14,20,22,23]
 Tongue and Mouth	[24–26]
 Head	[27]
 Torso, Trunk, Shoulders	[28–30]
 Leg	[31,32]
 Foot	[15,33]

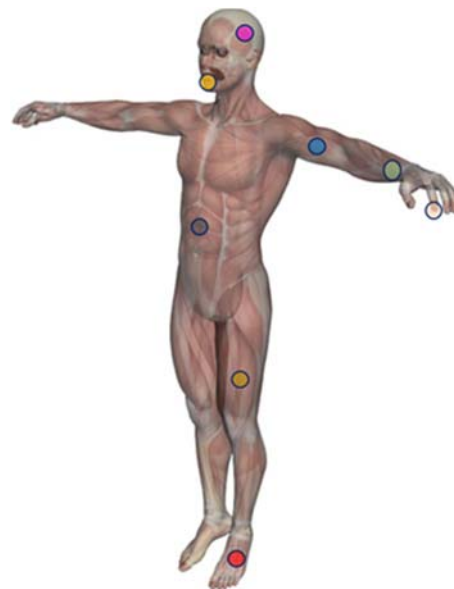


Figure 1. Wearable haptic systems and body locations. Finger [5,16,18]; wrist [19,21]; arm and forearm [14,20,22,23]; tongue and mouth [24–26]; head [27]; torso, trunk and shoulders [28–30]; leg [31,32]; foot [15,33].

From a technological point of view, different actuation strategies are usually employed to deliver haptic stimuli in wearable devices, the main ones are summarized in Table 1.

Table 1. Wearable haptic systems (WHS) main actuation types.

Stimulus/Actuation Type	Devices
Pin-arrays	[12,34]
Electrocutaneous	[13,22,35]
Vibration	[4,7,30]
Deformation/Forces	[5,16,36]
Pneumatic	[31,32]

Each of these strategies comes with pros and cons, which must be considered in light of the applications that WHS are designed for, such as rehabilitation, assistive robotics, guidance, among others—the interested reader can refer to reference [17] for further details. From a physiological point of view, different stimulation modes target the different mechanoreceptors of human skin, of which the main characteristics and response typologies are summarized in Table 2 (note that all contribute to guarantee stable precision grasp and manipulation [37,38])—for an exhaustive description of mechanoreceptor characteristics, the reader can refer to references [37–40].

Table 2. Human skin mechanoreceptors (adapted from [39,41]).

Mechanoreceptors	Primary Functions
Slowly Adapting type I (SAI)	Very-low-frequency vibration detection; coarse texture perception; pattern/form detection
Fast-adapting type I (FA I)	Low-frequency vibration detection
Fast-adapting type II (FA II)	High-frequency vibration detection; fine texture perception
Slowly Adapting type II (SAII)	Direction of object motion and force due to skin Stretch; finger position

Furthermore, low-threshold mechanosensitive C fibers that can be found in the hairy skin represent the neurobiological substrate for the affective properties of touch [42].

The main objective of this subsection is to provide the reader with a general, but useful, overview on WHS, which can provide the essential tools needed to understand the topics and issues introduced in the following sections.

1.2. Wearable Haptic Systems: Open Issues and Fabric-Based Approaches

The diffusion of WHS, of which the main characteristics are described in the previous subsection, has created new and challenging issues: (1) how to design systems with minimal encumbrance, and (2) how do design systems that allow a natural haptic interaction? To tackle these issues, the author proposes to leverage the intrinsic wearability of fabrics with the objective of engineering artificial devices, which can be easily worn and, at the same time, enable a highly natural HRI. These characteristics have been already widely used in the literature to develop sensors for monitoring human behavior, which can successfully handle the demands of on-body sensing and are also light-weight, such as knitted fabrics (e.g., [43–46]). For this reason, extensive research work has been performed for the definition of mechanical textile properties (which can affect haptic sensation), as well as subjective evaluation of haptic properties of fabrics and textiles (see references [47–50]). In reference [51] the authors integrated electroactive polymeric materials into wearable garments to endow them with sensing and actuation properties, with applications in post stroke rehabilitation and assessment. In reference [52], a textile-based glove with electroactive polymers, acting as force/position sensors and haptic feedback actuators, was presented. In reference [53], the authors proposed an air-inflatable vest that can be remotely triggered to create a sensation that resembles a hug. In reference [50], the authors presented BubbleWrap, a matrix of electromagnetic actuators enclosed in fabric. This system consisted of individually controllable cells, which can expand and contract, thus providing both active and passive haptic feedback. In reference [54], the authors described HAPI (Haptic Augmented Posture Interface) Bands, a set of user-worn bands instrumented with eccentric mass motors to provide vibrotactile feedback for the guidance of static poses. In reference [55], the authors introduced TableHop, a tabletop display that provided controlled self-actuated deformation and vibro-tactile feedback to an elastic fabric surface while retaining the capability of high-resolution visual projection. The surface was made of a highly-stretchable pure spandex fabric that was electrostatically actuated using electrodes mounted on its top or underside. In reference [56], the authors reported on a stretchable glove endowed with vibration motors and bend sensors, which was used to provide sensory feedback during rehabilitation training in a virtual reality environment.

While these examples show the effectiveness of textiles and fabrics as sensing tools or haptic devices, all of them require the integration of additional properties into the fabric structures (e.g., conductive, magnetic properties, or pneumatic, vibrotactile actuation). To the best of the author's knowledge, there is no evidence of wearable haptic systems that completely leverage pure mechanical changes of stress–strain fabric characteristics to deliver tactile cues.

This work aims at reviewing three examples of devices that have been developed by the author, which exploit the mechanical properties of a bi-elastic fabric for conveying tactile cues, at three different body locations, and targeting different application fields. The fabric is called Superbiflex HN, by Mectex S.P.A (Erba, Como, Italy), which exhibits a good range of elasticity and resistance to traction. Body locations, i.e., finger, forearm, and arm, can be used to define a taxonomy for devices, while a broad distinction of haptic systems for discriminative and affective touch can be also applied. Following these classifications, I will start with discriminative haptic devices, first describing W-FYD (Wearable Fabric Yielding Device), a tactile display for softness rendering and multi-cue delivery, which is worn on a user's finger [18] and can be profitably employed for virtual reality, neuroscientific studies, and tele-operation. Then, I will describe CUFF [14], a Clenching Upper-limb Force Feedback wearable device for distributed mechano-tactile stimulation of normal and tangential skin forces, which can be applied on a user's arm and used for prosthetics, tele-operation, and guidance for the blind. Finally, considering affective haptics, I will present a device that can simulate a human caress in terms of force and velocity [57], which can be worn on a subject's forearm, and was proven to effectively elicit an emotional response in users. Without any claim of exhaustiveness, these three systems offer an interesting perspective on the usage of the mechanical properties of simple elastic fabrics for wearable haptics, showing promise in different application domains. A discussion of these applications, and possible future directions, regarding the employment of fabrics as enabling ingredients for a successful development and usage of WHS are also reported.

2. W-FYD

Softness represents one of the most fundamental haptic properties [58], which plays a crucial role for task accomplishment in many contexts, from handling fruit to complex medical procedures. However, looking at WHS in the literature, none of the proposed solutions are able to provide controllable softness information to the user and enable both active and passive touch experiences. To bridge this gap, in reference [18], the author proposed W-FYD (Figure 2), which represents the wearable version of the grounded softness display described in references [59–62]. W-FYD controls 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 is inspired by the grounded version of the device and is also similar to the one reported in reference [36]. More specifically, two DC motors can vary the stiffness of the fabric and, if independently controlled, provide tangential force (Figure 3). 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. To enable the passive mode, an additional degree of freedom is implemented through a servomotor and a lifting mechanism, which puts the fabric into contact with the user's finger pad (Figure 4). 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 the 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, right and left, against the user's finger (which is still). The control of the stretching states of the fabric, and, hence, of the stiffness stimulus to be delivered, relies on the characterization of the system. In other terms, the stiffness workspace of the device was characterized at different DC motor positions (each corresponding to a given force-indentation curve, i.e., stiffness characteristic or fabric stretching state) (Figure 3b). When the device is used on the user's finger, DC motor positions were controlled to reproduce a given softness level, based on the value of fabric indentation (h_a , measured through an

infrared sensor, or via the commanded servo-motor position, h_p , in the active and passive modes, respectively (see Figure 4). More specifically, knowing the relation between DC motor position (θ , in our case $\theta_1 = \theta_2 = \theta$ (see Figure 3a)) and force-indentation curves obtained during the characterization phase, we can command motor positions as $\theta = \frac{1}{m} (\gamma \delta^{b-1} - q)$, where γ is the stiffness level to be reproduced, according to a generic power function, i.e., $\gamma = \frac{F}{\delta^b}$, F is the force, δ is the indentation, while m and q represent the coefficients that characterize device stiffness workspace for different stretching states (i.e., DC motor positions): $\sigma(\theta) = m\theta + q$ (see Figure 3b).

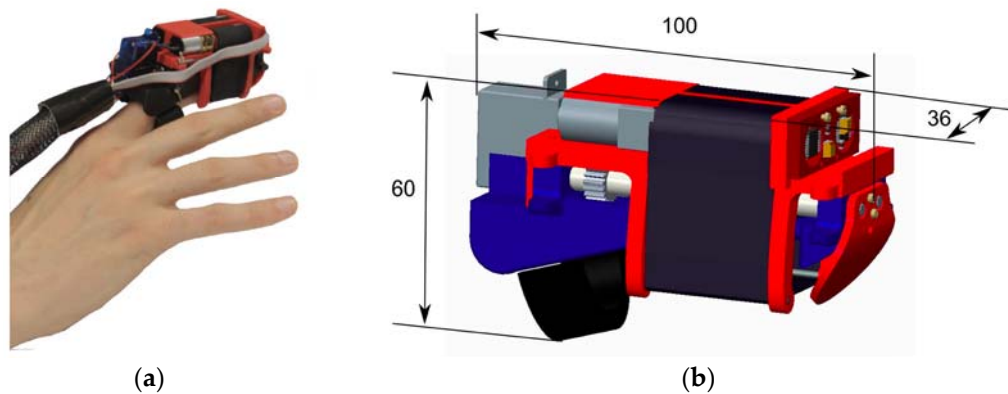


Figure 2. Wearable Fabric Yielding Device (W-FYD) on a user's finger (a); W-FYD CAD design and dimensions (in mm) (b). Reproduced from [18], Copyright 2016, IEEE.

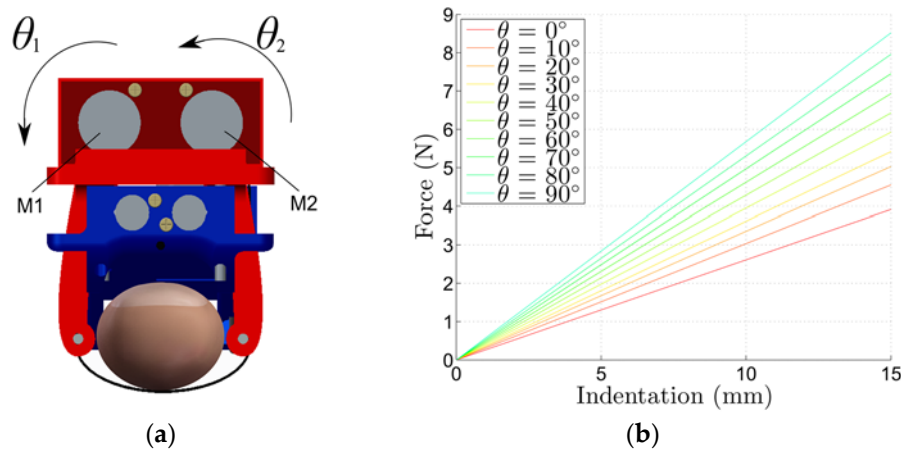


Figure 3. Representation of a finger interacting with the W-FYD (a); characterization curves for different motor positions (θ_1 and θ_2) (b). Reproduced from [18], Copyright 2016, IEEE.

W-FYD, of which the total mass is 100 g (and dimensions of which are reported in Figure 2), was proven to successfully enable a correct softness discrimination in users, in absolute and relative cognition tasks, as well as an effective identification of the direction of slipping [18].

These results are promising 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 (through multi-digit device implementation), virtual reality, and tele-operation. In the latter case, W-FYD acts as a display mounted on the user's finger for remote-robotic palpation of soft materials, e.g., in robot-assisted medical applications or surgeon training, where the correct rendering of tissue stiffness, and other haptic cues, is extremely important for the success of diagnostic or surgical procedures. In this regard, it is worth to mention that W-FYD was integrated into an augmented physical simulator that allows the real time tracking of artery

reproductions and the user's finger, and provides pulse feedback during palpation [63]. Preliminary experiments showed a general consensus among surgeons regarding the realism of the arterial pulse feedback and the usefulness of tactile augmented reality in open-surgery simulators.

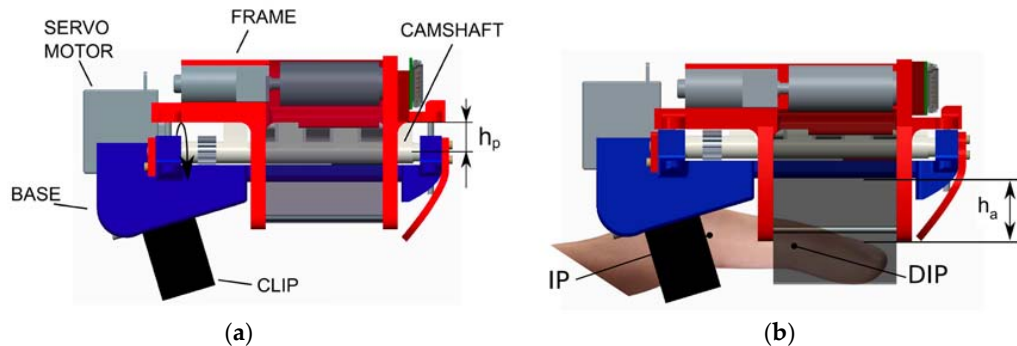


Figure 4. Passive mode: The fabric frame is put in contact with the user's finger by the camshaft lifting mechanism and servo-motor, inducing a variation of h_p (commanded servo motor position) of the frame (a); active mode: The user can indent the fabric by flexing the interphalangeal proximal joint of the index finger (IP), while fabric indentation h_a can be measured through a contactless infrared sensor (b). Reproduced from [18], Copyright 2016, IEEE.

In all these examples, wearability represents the key factor for successful task accomplishment, or to increase the immersiveness and naturalness of haptic interaction.

3. CUFF

The Clenching Upper-limb Force Feedback (CUFF) is comprised of two DC motors attached to a fabric cuff worn around the arm (Figure 5). The motors can spin in opposite directions to tighten or loosen the band on the arm, thus conveying normal force and pressure cues; they can also spin in the same direction in order to slide the band around the arm, thus inducing skin stretch cues that can easily be associated with directional and navigation information (see Figure 5).

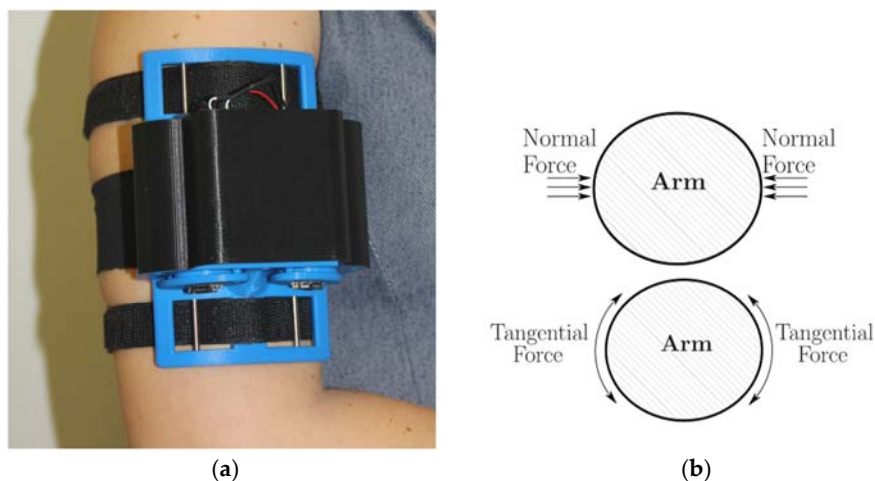


Figure 5. Clenching Upper-limb Force Feedback (CUFF) (a) and working modes (b). The total weight is 494 g and its overall dimensions are $14.5 \times 9.7 \times 11.6$ cm. Reproduced from [14], Copyright 2013, IEEE.

In the first mode, CUFF was used in association with Pisa/IIT SoftHand (SH), an anthropomorphic robotic hand, actuated through a single motor, but capable of adapting for grasping different objects [64]. Because the SH has no built-in force sensors, an estimation of applied force can be

obtained based on the current the motor draws. Briefly, the current that the SH absorbs while moving without obstacles is lower than that required to move following contact with an object. The difference between these two currents (residual current) can, thus, be exploited to drive the DC motors of CUFF and to provide force feedback. This is because residual current is proportional to grasp force (see Figure 6). This approach is motivated by the fact that there is a net difference in the absorbed current of the SH motor, in free motion (maximum value of ≈ 800 mA) or when the robotic hand grasps an external object (maximum value of ≈ 1200 mA). The reconstructed current represents the current absorbed by the motor in free hand motion, which will be subtracted from the current sensed by the μ -controller of the hand, which controls the opening/closing levels of the hand and acts on the current that drives the hand motor.

To achieve this goal, a Look Up Table was implemented as a function of the variables θ , $\dot{\theta}$, $\ddot{\theta}$ (where θ is the angular motor position of SH) and of which the output is the reconstructed free-hand motion current, I_{lut} . For the derivation of the terms of this function, please see reference [14]. The error of the reconstructed current for free-hand motions is under 5%. The *residual current term* rI was then used to compute the reference angular motor position of CUFF motors as: $\theta_{m,ref} = \beta_{CUFF} rI$. In this case, the two angular positions of the CUFF motors are $\theta_{m1} = \theta_{m2} = \theta_m$.

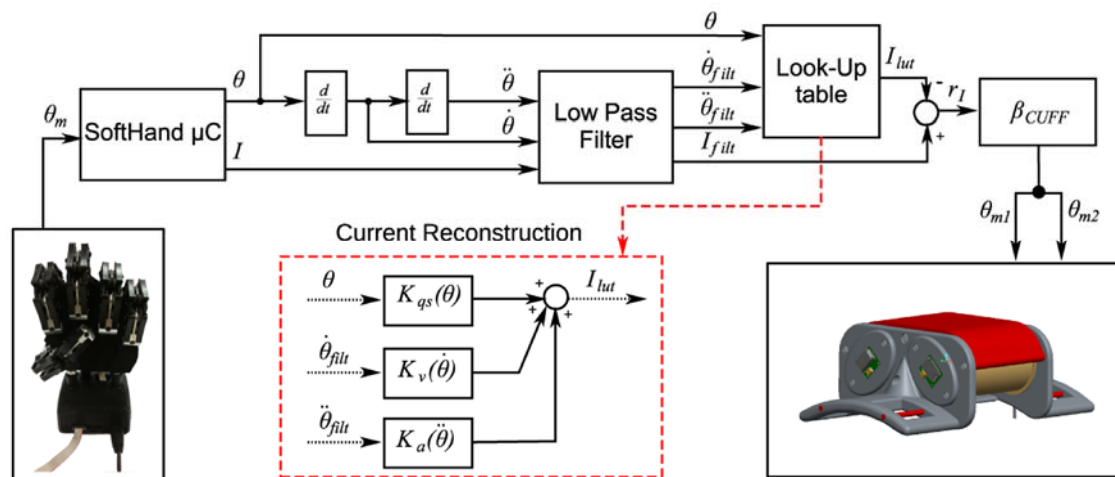


Figure 6. CUFF reproduces the estimated resultant force applied by SoftHand through belt stretching over a user's arm. The suffix *filt* on signals indicates the measured current, velocity, and acceleration of SH after low pass filtering. Reproduced from [14], Copyright 2013, IEEE.

The CUFF device was studied in applications to evaluate the role of force feedback with the usage of the prosthetic version of SH [65]. Thanks to its high wearability, the CUFF system can be used in conjunction with such a prosthetic device to provide haptic feedback in prosthetic applications or in tele-operation tasks where the modulation of grasping force is crucial. In reference [66], an early version of the device was connected to SH, operated by participants through a human–robot interface and surface electromyography signals. Leveraging the current-based disturbance observer, the interaction forces in contact with the grasped object were estimated and then converted and applied to the upper arm of the user via a custom-made pressure cuff. Such a tactile device was used together with vibrotactile feedback, based on surface irregularities and acceleration signals, which conveyed information on surface properties, contact, and detection of object slippage. Experiments in the evaluation of grasp robustness and intuitiveness of hand control suggested that incorporating these haptic feedback strategies facilitated the execution of safe and stable grasps. In reference [14], CUFF was tested in conjunction with the Pisa/IIT SoftHand, which was controlled using a handle to grasp objects with different stiffness properties. As reported in reference [67], the relationship between the indenting force and the overall rigid displacement (or indentation) between the two bodies can be regarded as an approximation of the kinaesthetic information involved in softness perception.

Therefore, in reference [14], participant had information on how much she/he indented the specimens, at least indirectly, through the control of the handle, while CUFF conveyed information on the grip force exerted by the hand. Results of ranking experiments, where softness specimens were sorted in terms of perceived softness, were highly accurate. Furthermore, the tangential skin stretch cue that the CUFF is able to deliver can represent potential directional information, to be investigated in applications where wearability is a mandatory requirement, e.g., the haptic guidance of blind people.

4. Caress-Like Haptic Stimulation

The devices presented in the previous sections are all devoted to elicit discriminative perception of haptic properties in users. In recent years, in parallel with the study of perceptual aspects of touch, the interest in investigating the role of haptic cues in communicating or evoking emotions in humans has also increased. This is not surprising, since touch represents one of the most ancestral human senses [1] and is a profound communication channel for humans, is highly emotionally charged [68], and has immediate affective consequences [69]. Of note, Autonomic Nervous System (ANS) dynamics are strongly affected by emotional changes [70].

The affective touch display in reference [57] exploits the elasticity of fabric to reproduce the haptic stimuli that are commonly conveyed through a human caress. More specifically, the user places a forearm on the forearm support under the fabric layer, of which the extremities are connected to two motors through two rollers. By controlling motor positions and rotation velocity, it is possible to vary the velocity and the strength of the artificial caress on the user's arm. The system is also endowed with a load cell that measures the normal force exerted by the fabric on the forearm. After a calibration phase, where the offset due to forearm weight is removed, the exerted force (i.e., the strength of the caress) can be varied by acting on the two motor positions, which determine how much the fabric is wrapped around the forearm, and, hence, the force exerted on it (maximum force 20 N). Once the desired level of force is achieved, and both motors are in the reference position, the velocity of the caress can be modulated by regulating the velocity of the motors, exploiting a built-in motor position controller and feeding the motors with a sinusoidal input reference trajectory. By setting the frequency and amplitude of the input, the velocity and the amplitude of motor rotation are controlled, respectively (see reference [57] for further details). The maximum angular displacement of the motors from the reference positions is set to 90 deg., while an entire control cycle lasts 1 ms. An overview of the system is shown in Figure 7. Psycho-physiological assessment tests were performed to characterize the capability of the device in eliciting tactually emotional states in humans, using different combinations of velocity and caress strength. The emotional state was expressed in terms of valence and arousal, which represent the two fundamental neurophysiological systems—one related to pleasure/displeasure (valence) and the other to alertness (arousal)—from which all affective states arise [71]. Moreover, the activation of the ANS was also demonstrated through analysis of the electro-dermal activity. Successive studies confirmed that such a caress-like stimuli can significantly affect the dynamics of other ANS-related physiological measurements, such as heart rate variability (HRV) and electro-encephalographic signals [72–74], thus, further demonstrating the effectiveness of this type of haptic stimulation in eliciting emotional responses in users. Of note, this system represents an interesting proof-of-concept, although its wearability needs to be improved to enable users to carry the device around in everyday life. In reference [75], evidence on how the caress-like haptic device can influence physiological measures related to the autonomous nervous system (ANS), which is intimately connected to evoked emotions in humans, were further discussed and related to self-assessment scores of arousal and valence through a pictorial technique known as SAM (Self-Assessment Manikin) [76]. Specifically, a discriminant role of electrodermal response and heart rate variability can be associated to two different caressing velocities, which can also be linked to two different levels of pleasantness. The paper also reported on the implications of these outcomes for HRI, creating a fascinating and novel perspective for the design of haptic interfaces. In this envisioned scenario, ANS-related measurements could be used to assess user's comfort and emotional state in interaction with a given

haptic device, and to devise design and control guidelines for the novel generation of haptic systems, which can be commanded to elicit a given emotional state in users. During the administration of haptic stimuli, physiological signals related to ANS dynamics (e.g., the HRV series, respiration dynamics, electrodermal response, etc.) can be recorded and analyzed to infer information on user's emotional status and other parameters, e.g., stress, fatigue, etc.). An interesting point is that these results are consistent across subjects, and, hence, they can be generalized and effectively employed for a large class of human-machine systems, with potential impact on healthcare and social and rehabilitation-assistive robotics. Regarding the latter case, one possible challenging application of the caress-like haptic stimulation might be in clinical rehabilitation scenarios, where it is crucial to have wearable devices to convey repeatable and controllable haptic stimuli. For example, the caress-like haptic system might be employed for patients with Disorders of Consciousness (DOC), where standardized tactile stimuli could evoke a response in the autonomic nervous system. For this reason, it would be important to further increase the wearability of the systems, in terms of portability and usability, for long-term monitoring [57].



Figure 7. An overview of the haptic system worn by a subject. Reproduced from [57], Copyright 2014, IEEE.

5. Discussion and Conclusions

In this paper, the author has reviewed three main applications of wearable fabric-based devices (Table 3) that can deliver haptic cues relying only on suitable mechanical modifications of fabric stress-strain characteristics. The reported technologies were validated in experiments with human subjects. W-FYD, for example, was tested in active and passive modes, in absolute and relative cognition tasks, for softness ranking. For the absolute cognition task, participants were asked to associate the stimulus artificially reproduced through W-FYD with its physical counterpart (silicone specimen). Results showed an average accuracy of 88.51% for relative cognition tasks and 84.48% in absolute cognition tasks. For the sliding mode, participants were asked to discriminate the direction of skin stretch on their fingers. The average accuracy was 99%. An average score of 6.67 ± 0.65 using a bipolar Likert-type seven-point scale for the assessment of device capability in inducing slippage sensation was observed. CUFF effectiveness was demonstrated in grasping experiments (in terms of grasp success rate) and softness recognition tasks (through confusion matrices) in conjunction with the SH, as previously described [66]. Finally, a caress-like haptic device was exhaustively investigated in terms of its capabilities in eliciting emotion-related stimulation in users.

These devices can have a significant impact in different fields of HRI. A natural application of wearable systems, given the high level of portability, is virtual and augmented reality, as witnessed for example by results presented in reference [63] for W-FYD. Other important examples can be assistive robotics, e.g., guidance for blind people and force feedback in prosthetics for CUFF, or clinical rehabilitative scenarios, where the possibility to have haptic stimuli conveyed in a controllable and repeatable fashion can be exploited to stimulate ANS—this is the case of caress-like haptic device [77],

which can be also used for social interaction through affective cue delivery. Finally, the integration of wearable systems in tele-operation and HRI could represent the key to advance the state-of-the-art and to enable a more natural information exchange from natural to artificial and back again.

Table 3. Main characteristics of reviewed devices.

Name	Dimensions (mm)	Weight (g)	Stimuli	Body Location	Touch	Force Range	Measurements Provided	Stiffness Range	Control Cycle
W-FYD	100 × 60 × 36	100	Active/passive softness; sliding	Finger	Discriminative	Up to 10 N	Force; motor position; indentation	Up to 0.8 N/mm	≤1ms
CUFF	145 × 97 × 116	494	Normal-tangential force	Arm	Discriminative	Up to 21 N	Force; motor position	-	≤1ms
Caress	150 × 150 × 80	560	Velocity; normal force (combination)	Forearm	Affective	Up to 20 N	Force; motor position	-	≤1ms @7Hz

Without any claim of exhaustiveness, the conclusion that can be drawn is that mechanical change of fabric stress–strain behavior can represent a viable and cost-effective solution for wearable haptics, for both discriminative and affective touch, presenting a high level of portability, with high potential impacts in different application fields. At the same time, fabrics can stimulate skin in a natural fashion, enabling an intuitive cue delivery with minimal effects on haptic perception—this opens up promising avenues in augmented reality, i.e., through the superposition of additional tactile cues during the exploration of real objects, as in reference [63]. Of course, to push forward this paradigm, it is important to further reduce device dimensions and encumbrance, and, at the same time, take into account user’s point of view and acceptability.

In an ideal future, we could have devices that are “transparent”. In other terms, as we are not aware of the cloths we wear, we should not be aware of the WHS we use. Only in this manner WHS can become a key part of our lives. To paraphrase the words of the well-known American industrialist H. Ford, the true progress is to put technology “on the body” of everyone.

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References

1. Aristotle. *A New Aristotle Reader*; Ackrill, J.L., Ed.; Princeton University Press: Princeton, NJ, USA, 1987; pp. 161–205.
2. Hannaford, B.; Okamura, A.M. Haptics. In *Handbook on Robotics*; Siciliano, B., Kathib, O., Eds.; Springer: Heidelberg, Germany, 2008; pp. 719–739.
3. Chinello, F.; Malvezzi, M.; Pacchierotti, C.; Prattichizzo, D. A three DoFs wearable tactile display for exploration and manipulation of virtual objects. In *Proceedings of the Haptics Symposium 2012*, Vancouver, BC, Canada, 4–7 March 2012; pp. 71–76.
4. Traylor, R.; Tan, H.Z. Development of a wearable haptic display for situation awareness in altered-gravity environment: Some initial findings. In *Proceedings of the 10th Symposium on Haptic Interfaces Virtual Environment and Teleoperator Systems*, Orlando, FL, USA, 24–25 March 2002; pp. 159–164.
5. Leonardis, D.; Solazzi, M.; Bortone, I.; Frisoli, A. A wearable fingertip haptic device with 3 dof asymmetric 3-rsr kinematics. In *Proceedings of the 2015 IEEE World Haptics Conference (WHC)*, Evanston, IL, USA, 22–26 June 2015; pp. 388–393.
6. Pacchierotti, C.; Chinello, F.; Malvezzi, M.; Meli, L.; Prattichizzo, D. Two finger grasping simulation with cutaneous and kinesthetic force feedback. In *Proceedings of the International Conference, EuroHaptics 2012*, Tampere, Finland, 13–15 June 2012; pp. 373–382.
7. Lieberman, J.; Breazeal, C. TIKL: Development of a wearable vibrotactile feedback suit for improved human motor learning. *IEEE Trans. Robot.* **2007**, *23*, 919–926. [[CrossRef](#)]

8. Prattichizzo, D.; Pacchierotti, C.; Rosati, G. Cutaneous force feedback as a sensory subtraction technique in haptics. *IEEE Trans. Haptics* **2012**, *5*, 289–300. [[CrossRef](#)] [[PubMed](#)]
9. Pacchierotti, C.; Tirmizi, A.; Bianchini, G.; Prattichizzo, D. Enhancing the performance of passive teleoperation systems via cutaneous feedback. *IEEE Trans. Haptics* **2015**, *8*, 379–409. [[CrossRef](#)] [[PubMed](#)]
10. Tomasello, M.; Carpenter, M.; Call, J.; Behne, T.; Moll, H. Understanding and sharing intentions: The origins of cultural cognition. *Behav. Brain Sci.* **2005**, *28*, 675–691. [[CrossRef](#)] [[PubMed](#)]
11. Kuchenbecker, K.J.; Ferguson, D.; Kutzer, M.; Moses, M.; Okamura, A.M. The touch thimble: Providing fingertip contact feedback during point-force haptic interaction. In Proceedings of the 2008 Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Reno, NE, USA, 13–14 March 2008; pp. 239–246.
12. Yang, G.H.; Kyung, K.U.; Srinivasan, M.A.; Kwon, D.S. Quantitative tactile display device with pin-array type tactile feedback and thermal feedback. *Proc. IEEE Int. Conf. Robot. Autom.* **2006**, *2006*, 3917–3922.
13. Buma, D.G.; Buitenweg, J.R.; Veltink, P.H. Intermittent stimulation delays adaptation to electrocutaneous sensory feedback. *IEEE Trans. Neural Syst. Rehabil. Eng.* **2007**, *15*, 435–441. [[CrossRef](#)] [[PubMed](#)]
14. Casini, S.; Morvidoni, M.; Bianchi, M.; Catalano, M.G.; Grioli, G.; Bicchi, A. Design and realization of the CUFF—Clenching upper-limb force feedback wearable device for distributed mechano-tactile stimulation of normal and tangential skin forces. In Proceedings of the 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hamburg, Germany, 28 September–2 October 2015; pp. 1186–1193.
15. Kim, H.; Seo, C.; Lee, J.; Ryu, J.; Yu, S.; Lee, S. Vibrotactile display for driving safety information. In Proceedings of the 2006 IEEE Intelligent Transportation Systems Conference, Toronto, Canada, 17–20 September 2006; pp. 573–577.
16. Prattichizzo, D.; Chinello, F.; Pacchierotti, C.; Malvezzi, M. Towards wearability in fingertip haptics: A 3-DoF wearable device for cutaneous force feedback. *IEEE Trans. Haptics* **2013**, *6*, 506–516. [[CrossRef](#)] [[PubMed](#)]
17. Shull, P.B.; Damian, D.D. Haptic wearables as sensory replacement, sensory augmentation and trainer—A review. *J. Neuroeng. Rehabil.* **2015**, *12*, 59. [[CrossRef](#)] [[PubMed](#)]
18. Bianchi, M.; Battaglia, E.; Poggiani, M.; Ciotti, S.; Bicchi, A. A Wearable Fabric-based Display for Haptic Multi-Cue Delivery. In Proceedings of the 2016 IEEE Haptics Symposium (HAPTICS), Philadelphia, PA, USA, 8–11 April 2016; pp. 277–283. [[CrossRef](#)]
19. Scheggi, S.; Aggravi, M.; Morbidi, F.; Prattichizzo, D. Cooperative human-robot haptic navigation. In Proceedings of the 2014 IEEE International Conference on Robotics and Automation (ICRA), Hong Kong, China, 31 May–7 June 2014. [[CrossRef](#)]
20. Sergi, F.; Accoto, D.; Campolo, D.; Guglielmelli, E. Forearm orientation guidance with a vibrotactile feedback bracelet: On the directionality of tactile motor communication. In Proceedings of the 2008 2nd IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechanics, Scottsdale, AZ, USA, 19–22 October 2008; pp. 433–438.
21. Van Wegen, E.; De Goede, C.; Lim, I.; Rietberg, M.; Nieuwboer, A.; Willems, A.; Jones, D.; Rochester, L.; Hetherington, V.; Berendse, H.; et al. The effect of rhythmic somatosensory cueing on gait in patients with Parkinson’s disease. *J. Neurol. Sci.* **2006**, *248*, 210–214. [[CrossRef](#)] [[PubMed](#)]
22. Witteveen, H.J.B.; Droog, E.A.; Rietman, J.S.; Veltink, P.H. Vibro- and electrotactile user feedback on hand opening for myoelectric forearm prostheses. *IEEE Trans. Biomed. Eng.* **2012**, *59*, 2219–2226. [[CrossRef](#)] [[PubMed](#)]
23. Bark, K.; Wheeler, J.; Shull, P.; Savall, J.; Cutkosky, M. Rotational skin stretch feedback: A wearable haptic display for motion. *IEEE Trans. Haptics* **2010**, *3*, 166–176. [[CrossRef](#)]
24. Vuillerme, N.; Chenu, O.; Demongeot, J.; Payan, Y. Controlling posture using a plantar pressure-based, tongue-placed tactile biofeedback system. *Exp. Brain Res.* **2007**, *179*, 409–414. [[CrossRef](#)] [[PubMed](#)]
25. Vuillerme, N.; Pinsault, N.; Chenu, O.; Fleury, A.; Payan, Y.; Demongeot, J. A wireless embedded tongue tactile biofeedback system for balance control. *Pervasive Mob. Comput.* **2009**, *5*, 268–275. [[CrossRef](#)]
26. Hui, T.; Beebe, D.J. An oral tactile interface for blind navigation. *Neural Syst. Rehabil. Eng. IEEE Trans.* **2006**, *14*, 116–123.
27. Mann, S.; Huang, J.; Janzen, R.; Lo, R.; Rampersad, V.; Chen, A.; Doha, T. Blind navigation with a wearable range camera and vibrotactile helmet. In Proceedings of the 19th ACM International Conference on Multimedia, New York, NY, USA, November 2011; pp. 1325–1328.

28. Wall, C.; Weinberg, M.S.; Schmidt, P.B.; Krebs, D.E. Balance prosthesis based on micromechanical sensors using vibrotactile feedback of tilt. *IEEE Trans. Biomed. Eng.* **2001**, *48*, 1153–1161. [[CrossRef](#)] [[PubMed](#)]
29. Nanhoe-Mahabier, W.; Allum, J.H.; Paman, E.P.; Overeem, S.; Bloem, B.R. The effects of vibrotactile biofeedback training on trunk sway in Parkinson's disease patients. *Park. Relat. Disord.* **2012**, *18*, 1017–1021. [[CrossRef](#)] [[PubMed](#)]
30. Van Erp, J. Presenting directions with a vibrotactile torso display. *Ergonomics* **2005**, *48*, 302–313. [[CrossRef](#)] [[PubMed](#)]
31. McKinney, Z.; Heberer, K.; Fowler, E.; Greenberg, M.; Nowroozi, B.; Grundfest, W. Initial biomechanical evaluation of wearable tactile feedback system for gait rehabilitation in peripheral neuropathy. *Stud. Health Technol. Inform.* **2014**, *196*, 271–277. [[PubMed](#)]
32. McKinney, Z.; Heberer, K.; Nowroozi, B.N.; Greenberg, M.; Fowler, E.; Grundfest, W. Pilot evaluation of wearable tactile biofeedback system for gait rehabilitation in peripheral neuropathy. In Proceedings of the 2014 IEEE Haptics Symposium (HAPTICS), Houston, TX, USA, 23–26 February 2014; pp. 135–140.
33. Velázquez, R.; Bazán, O. Preliminary evaluation of podotactile feedback in sighted and blind users. *Conf. Proc. IEEE Eng. Med. Biol. Soc.* **2010**, *2010*, 2103–2106. [[PubMed](#)]
34. Yang, T.H.; Kim, S.Y.; Kim, C.H.; Kwon, D.S.; Book, W.J. Development of a miniature pin-array tactile module using elastic and electromagnetic force for mobile devices. In Proceedings of the Third Joint EuroHaptics conference, 2009 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Salt Lake City, UT, USA, 18–20 March 2009; pp. 13–17.
35. Wentink, E.C.; Talsma-Kerkdijk, E.J.; Rietman, H.S.; Veltink, P. Feasibility of error-based electrotactile and auditive feedback in prosthetic walking. *Prosthet. Orthot. Int.* **2015**, *39*, 255–259. [[CrossRef](#)] [[PubMed](#)]
36. Minamizawa, K.; Fukamachi, S. Gravity grabber: Wearable haptic display to present virtual mass sensation. *ACM Emerg. Technol.* **2007**, *8*. [[CrossRef](#)]
37. Johansson, R.S.; Westling, G. Signals in tactile afferents from the fingers eliciting adaptive motor responses during precision grip. *Exp. Brain Res.* **1987**, *66*, 141–154. [[CrossRef](#)] [[PubMed](#)]
38. Westling, G.; Johansson, R.S. Responses in glabrous skin mechanoreceptors during precision grip in humans. *Exp. Brain Res.* **1987**, *66*, 128–140. [[CrossRef](#)] [[PubMed](#)]
39. Lederman, S.J.; Klatzky, R.L. Haptic perception: A tutorial. *Atten. Percept. Psychophys.* **2009**, *71*, 1439–1459. [[CrossRef](#)] [[PubMed](#)]
40. Johansson, R.S.; Westling, G. Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects. *Exp. Brain Res.* **1984**, *56*, 550–564. [[CrossRef](#)] [[PubMed](#)]
41. Wolfe, J.M.; Kluender, K.R.; Levi, D.M.; Bartoshuk, L.M.; Herz, R.S.; Klatzky, R.L.; Lederman, S.J.; Merfeld, D.M. *Sensation and Perception*; Sinauer Associates: Sunderland, MA, USA, 2006.
42. McGlone, F.; Wessberg, J.; Olausson, H. Discriminative and Affective Touch: Sensing and Feeling. *Neuron* **2008**, *82*, 737–755. [[CrossRef](#)] [[PubMed](#)]
43. Carbonaro, N.; Mura, G.D.; Lorussi, F.; Paradiso, R.; De Rossi, D.; Tognetti, A. Exploiting wearable goniometer technology for motion sensing gloves. *IEEE J. Biomed. Heal. Informatics* **2014**, *18*, 1788–1795. [[CrossRef](#)] [[PubMed](#)]
44. Windmiller, J.R.; Wang, J. Wearable Electrochemical Sensors and Biosensors: A Review. *Electroanalysis* **2013**, *25*, 29–46. [[CrossRef](#)]
45. Mukhopadhyay, S.C. Wearable sensors for human activity monitoring: A review. *IEEE Sens. J.* **2015**, *15*, 1321–1330. [[CrossRef](#)]
46. Zeng, W.; Shu, L.; Li, Q.; Chen, S.; Wang, F.; Tao, X.-M. Fiber-based wearable electronics: A review of materials, fabrication, devices, and applications. *Adv. Mater.* **2014**, *26*, 5310–5336. [[CrossRef](#)] [[PubMed](#)]
47. Darden, M.A.; Schwartz, C.J. Investigation of skin tribology and its effects on the tactile attributes of polymer fabrics. *Wear* **2009**, *267*, 1289–1294. [[CrossRef](#)]
48. Volino, P.; Davy, P.; Bonanni, U.; Luible, C.; Magnenat-Thalmann, N.; Mäkinen, M.; Meinander, H. From measured physical parameters to the haptic feeling of fabric. *Vis. Comput.* **2007**, *23*, 133–142. [[CrossRef](#)]
49. Mäkinen, M.; Meinander, H.; Luible, C.; Magnenat-thalmann, N. Influence of Physical Parameters on Fabric Hand. In Proceedings of the Workshop on Haptic and Tactile Perception of Deformable Objects, Leibniz Haus, Hanover, Germany, 1–2 December 2005; pp. 8–16.

50. Bau, O.; Petrevski, U.; Mackay, W. BubbleWrap: A Textile-Based Electromagnetic Haptic Display. In Proceedings of CHI '09 Extended Abstracts on Human Factors in Computing Systems, Boston, MA, USA, 4–9 April 2009; pp. 3607–3612. [[CrossRef](#)]
51. De Rossi, D.; Carpi, F.; Lorussi, F.; Scilingo, E.P.; Tognetti, A. Wearable kinesthetic systems and emerging technologies in actuation for upperlimb neurorehabilitation. *Conf. Proc. IEEE Eng. Med. Biol. Soc.* **2009**, *2009*, 6830–6833. [[PubMed](#)]
52. De Rossi, D.; Carpi, F.; Carbonaro, N.; Tognetti, A.; Scilingo, E.P. Electroactive polymer patches for wearable haptic interfaces. *Conf. Proc. IEEE Eng. Med. Biol. Soc.* **2011**, *2011*, 8369–8372. [[PubMed](#)]
53. Mueller, F.F.; Vetere, F.; Gibbs, M.R.; Kjeldskov, J.; Pedell, S.; Howard, S. Hug over a distance. In Proceedings of CHI EA '05 CHI '05 Extended Abstracts on Human Factors in Computing Systems, Portland, OR, USA, 2–7 April 2005; pp. 1673–1676. [[CrossRef](#)]
54. Rotella, M.F.; Guerin, K.; He, X.; Okamura, A.M. HAPI bands: A haptic augmented posture interface. In Proceedings of the 2012 IEEE Haptics Symposium (HAPTICS), Vancouver, BC, Canada, 4–7 March 2012; pp. 163–170.
55. Sahoo, D.R.; Hornbæk, K.; Subramanian, S. TableHop: An Actuated Fabric Display Using Transparent Electrodes. In Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, San Jose, CA, USA, 7–12 May 2016; pp. 3767–3780.
56. Sadihov, D.; Migge, B.; Gassert, R.; Kim, Y. Prototype of a VR upper-limb rehabilitation system enhanced with motion-based tactile feedback. In Proceedings of the World Haptics Conference (WHC), Daejeon, Korea, 14–17 April 2013; pp. 449–454.
57. Bianchi, M.; Valenza, G.; Serio, A.; Lanata, A.; Greco, A.; Nardelli, M.; Scilingo, E.P.; Bicchi, A. Design and preliminary affective characterization of a novel fabric-based tactile display. In Proceedings of the 2014 IEEE Haptics Symposium (HAPTICS), Houston, TX, USA, 23–26 February 2014; pp. 591–596.
58. Bergmann Tiest, W.M.; Kappers, A.M.L. Cues for haptic perception of compliance. *IEEE Trans. Haptics* **2009**, *2*, 189–199. [[CrossRef](#)]
59. Bianchi, M.; Scilingo, E.P.; Serio, A.; Bicchi, A. A new softness display based on bi-elastic fabric. In Proceedings of the Third Joint EuroHaptics Conference, 2009 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Salt Lake City, UT, USA, 18–20 March 2009; pp. 382–383.
60. Bianchi, M.; Serio, A.; Scilingo, E.P.; Bicchi, A. A new fabric-based softness display. In Proceedings of the 2010 IEEE Haptics Symposium, Waltham, MA, USA, 25–26 March 2010; pp. 105–112.
61. Serio, A.; Bianchi, M.; Bicchi, A. A device for mimicking the contact force/contact area relationship of different materials with applications to softness rendering. In Proceedings of the 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems, Tokyo, Japan, 3–7 November 2013; pp. 484–490.
62. Bianchi, M.; Serio, A. Design and Characterization of a Fabric-Based Softness Display. *IEEE Trans. Haptics* **2015**, *8*, 152–163. [[CrossRef](#)] [[PubMed](#)]
63. Condino, S.; Vigliani, R.; Fani, S.; Bianchi, M.; Morelli, L.; Ferrari, M.; Bicchi, A.; Ferrari, V. Tactile augmented reality for arteries palpation in open surgery training. *Med. Imaging Augment. Real.* **2016**, accepted.
64. Catalano, M.G.; Grioli, G.; Farnioli, E.; Serio, A.; Piazza, C.; Bicchi, A. Adaptive synergies for the design and control of the Pisa/IIT SoftHand. *Int. J. Rob. Res.* **2014**, *33*, 768–782. [[CrossRef](#)]
65. Godfrey, S.; Bianchi, M.; Bicchi, A.; Santello, M. Influence of Force Feedback on Grasp Force Modulation in Prosthetic Applications: A Preliminary Study. *IEEE Eng. Med. Biol. Mag.* **2016**, accepted.
66. Ajoudani, A.; Godfrey, S.B.; Bianchi, M.; Catalano, M.G.; Grioli, G.; Tsagarakis, N.; Bicchi, A. Exploring teleimpedance and tactile feedback for intuitive control of the Pisa/IIT SoftHand. *IEEE Trans. Haptics* **2014**, *7*, 203–215. [[CrossRef](#)] [[PubMed](#)]
67. Scilingo, E.P.; Bianchi, M.; Grioli, G.; Bicchi, A. Rendering softness: Integration of kinesthetic and cutaneous information in a haptic device. *IEEE Trans. Haptics* **2010**, *3*, 109–118. [[CrossRef](#)]
68. Field, T. *Touch*; MIT Press: Cambridge, MA, USA, 2003.
69. Huisman, G. A touch of affect: Mediated social touch and affect. In Proceedings of the the 14th ACM international conference on Multimodal interaction, Santa Monica, CA, USA, 22–26 October 2012; pp. 317–320. [[CrossRef](#)]
70. Calvo, R.; D’Mello, S. Affect detection: An interdisciplinary review of models, methods, and their applications. *Affect. Comput. IEEE Trans.* **2010**, *1*, 18–37. [[CrossRef](#)]

71. Posner, J.; Russell, J.; Peterson, B. The circumplex model of affect: An integrative approach to affective neuroscience, cognitive development, and psychopathology. *Dev. Psychopathol.* **2005**, *17*, 715–734. [[CrossRef](#)] [[PubMed](#)]
72. Valenza, G.; Greco, A.; Citi, L.; Bianchi, M.; Barbieri, R.; Scilingo, E.P. Inhomogeneous Point-Processes to Instantaneously Assess Affective Haptic Perception through Heartbeat Dynamics Information. *Sci Rep.* **2016**, *6*, 28567. [[CrossRef](#)] [[PubMed](#)]
73. Nardelli, M.; Valenza, G.; Bianchi, M.; Greco, A.; Lanata, A.; Bicchi, A.; Scilingo, E.P. Gender-specific velocity recognition of caress-like stimuli through nonlinear analysis of Heart Rate Variability. In Proceedings of the 2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Milan, Italy, 25–29 August 2015; pp. 298–301.
74. Valenza, G.; Greco, A.; Nardelli, M.; Bianchi, M.; Lanata, A.; Rossi, S.; Scilingo, E.P. Electroencephalographic spectral correlates of caress-like affective haptic stimuli. In Proceedings of the 2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Milan, Italy, 25–29 August 2015; pp. 4733–4736.
75. Bianchi, M.; Valenza, G.; Greco, A.; Nardelli, M.; Battaglia, E.; Bicchi, A.; Scilingo, E.P. Towards a Novel Generation of Haptic and Robotic Interfaces: Integrating Affective Physiology in Human-Robot Interaction. *IEEE Int. Symp. Robot Hum. Interact. Commun.* **2016**, accepted.
76. Bradley, M.; Lang, P.J. Measuring Emotion: The Self-Assessment Semantic Differential Manikin and the semantic differential. *J. Behav. Ther. Exp. Psychiatry* **1994**, *25*, 49–59. [[CrossRef](#)]
77. Bianchi, M.; Valenza, G.; Lanata, A.; Greco, A.; Nardelli, M.; Bicchi, A.; Scilingo, E.P. On the role of affective properties in hedonic and discriminant haptic systems. *Int. J. Soc. Robot.* **2016**. [[CrossRef](#)]



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