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Cutaneous/Tactile Haptic Feedback in Robotic Teleoperation: Motivation, Survey, and Perspectives

Claudio Pacchierotti, *Senior Member, IEEE*, and Domenico Prattichizzo, *Fellow, IEEE*

Abstract—Cutaneous haptic feedback has recently received great attention from researchers in the robotic teleoperation field, as it has been proven to convey rich information to the human operator while guaranteeing the safety and stability of the control loop. In fact, delivering ungrounded cutaneous cues keeps the teleoperation system stable even in the presence of time-varying destabilizing factors such as hard contacts or communication delays. This aspect is particularly relevant for all the applications and scenarios where the safety of the system is of paramount importance, as in medical robotics. This article presents an overview on cutaneous haptic interaction followed by a review of the literature on cutaneous/tactile feedback systems for robotic teleoperation, categorizing the considered systems according to the type of cutaneous stimuli they can provide to the human operator. The paper ends with a discussion on the role of cutaneous haptics in robotics and the perspectives of the field.

Index Terms—cutaneous feedback, tactile feedback, robotic teleoperation, robot-assisted teleoperation, taxonomy, survey

I. INTRODUCTION

Rich sensory feedback is of paramount importance during robotic teleoperation, as it allows the human operator to perceive the remote environment and react accordingly, enhancing the operator's situational awareness and ability to perform complex tasks. The attainment of a convincing sense of telepresence – the illusion of feeling physically present at the remote site [1] – is a matter of technology. If the remote robotic system transmits sufficient information to the human operator, displayed in a sufficiently natural way, the illusion of telepresence can be compelling. Various forms of sensory feedback can facilitate this objective, enabling information to flow from the remote environment to the human operator. Haptic feedback is an important component of this flow, as it provides the human operator with information about the forces exerted at the remote side of the system.

Haptic feedback has been proven to be a valuable and effective tool for improving robotic teleoperation [2]–[4]. It has been shown to enhance operators' performance in several robotic applications, including microrobotics [5]–[7], needle and catheter insertion [8]–[11], surgical robotics [9], [12]–[15], training [16], [17], assembly [5], [18]–[20], cutting [21], [22], grasping [23]–[25], mobile robotics [26], [27], and palpation [11], [22], [28]–[30]. The benefits of haptic feedback

in such scenarios include increased manipulation and perception accuracy, reduced completion time, decreased peak and mean force applied to the remote environment. The inclusion of haptic feedback is also usually supported by the majority of users [11], [30]–[33]. However, despite these expected benefits, current commercially-available telerobotic systems provide very limited haptic feedback. This omission and mismatch between good research results and poor industry adoption is due to different reasons, including the high cost of haptic-enabled consoles and the harmful effect that haptic force feedback may have on the stability of the teleoperation loop. Outputting grounded forces with the haptic console can indeed lead to undesired oscillations of the system, which interfere with the operation and may be dangerous for the remote environment [4], [34]–[36]. To address such stability issues, researchers have proposed a broad variety of transparency- and stability-optimized controllers [37], [38], but it has always been challenging to achieve a good trade-off between these two objectives. In this respect, passivity has been considered an effective tool for providing a sufficient condition for stable teleoperation in many controller design approaches [39]–[43].

Given the expected benefits of haptic feedback, the high cost of haptic interfaces, and the challenges of a stable and safe implementation, engineers have often looked towards sensory substitution techniques, in which force feedback is presented via an alternative sensory channel, such as through auditory or visual stimulation. For example, Kitagawa et al. [44] compared applied forces during surgical knot-tying under four sensory substitution conditions: auditory, visual, and combined auditory-visual feedbacks. Forces provided through sensory substitution techniques more closely approximated suture tensions achieved under ideal feedback conditions (i.e., direct hand tying) than forces applied without such feedback. Similarly, Gwilliam et al. [45] used sensory substitution to augment the visual display recorded by a da Vinci stereoscopic camera with a graphical representation of the applied force at the tool-tip. Thanks to the fact that no haptic force is provided to the human operator through the console, sensory substitution techniques make robotic teleoperation systems intrinsically stable [20], [34]. However, even if the stability of the system is guaranteed, the sensations provided are substantially different from those that are being substituted (e.g., a beeping sound instead of force feedback). Therefore, depending on the application at hand, sensory substitution usually performs worse than unaltered force feedback [20], [46], [47].

Haptic feedback is provided to the human operator as a combination of cutaneous and kinesthetic stimuli. Cutaneous stimuli (sometimes also referred to as tactile stimuli) are detected by receptors located in the skin, enabling humans to perceive and recognize various local properties of objects, such

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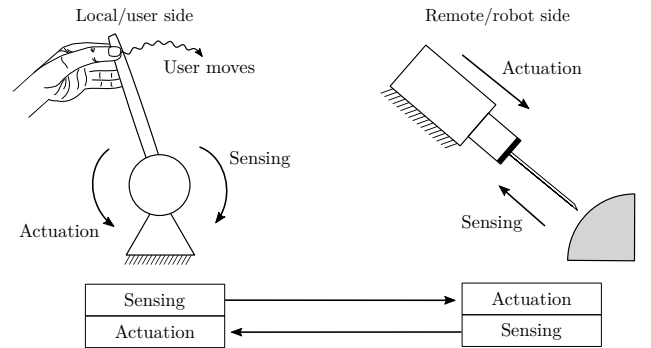
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as their shape, edges, temperature, and texture. On the other hand, kinesthetic stimuli come from the afferent information originating from the muscles, joints, and skin; they provide information about the position and velocity of neighboring parts of the body, as well as the applied force and torque [48]–[50]. In this respect, cutaneous feedback has recently received great attention from researchers looking for an alternative to sensory substitution techniques in robotics. Delivering ungrounded cutaneous sensations has been indeed proven to provide rich and distributed feedback information in teleoperation. Cutaneous feedback enhances movement and weight perception [51], [52], fine manipulation [53], precision grasping [54], space resolution [55], and shape recognition [56]. Furthermore, cutaneous stimuli provide a smart way to reduce the form factor of haptic devices: the high density of mechanoreceptors in the skin and their low activation thresholds [51] allow for the development of cutaneous displays that are compact, comfortable, and inexpensive [57]. As cutaneous stimuli are already part of any haptic interaction [58]–[60], substituting haptic feedback with cutaneous feedback (i.e., removing the kinesthetic part of the interaction) has been often considered a more natural choice with respect to other sensory substitution techniques [46]. Moreover, as for other sensory substitution techniques, providing cutaneous feedback to the human operator does not affect the position of the user’s local end-effector, making the teleoperation loop as stable as it would be in an open-loop configuration, i.e., as if we provide no haptic feedback [32], [46], [47] (see also Sec. II-B).

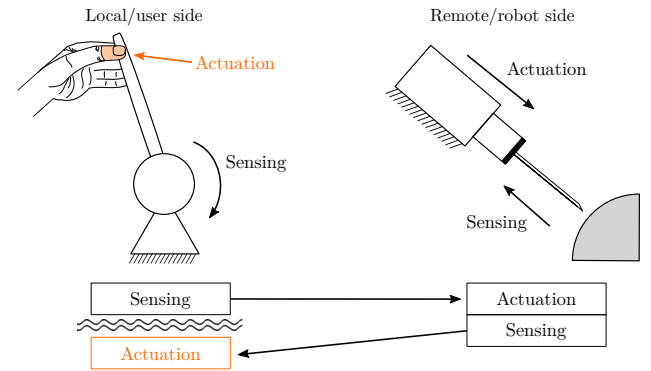
For all these reasons, in the last years we have witnessed a growing interest toward ungrounded cutaneous/tactile feedback solutions for robotic teleoperation. This article presents an overview on cutaneous haptic interaction followed by a review of the literature on cutaneous/tactile feedback systems for robotic teleoperation. However, this article does not include work in which the feedback system (i) is not focused on providing cutaneous stimuli (e.g., a grounded kinesthetic interface), (ii) is used for purposes other than robotic teleoperation (e.g., interaction with virtual environments, psychophysics studies, prosthetics, rehabilitation), or (iii) is employed to provide information different than the physical properties of the remote environment (e.g., guidance, active constraints, robot pose). In the remainder of this paper, we first recall the different types of haptic stimuli the human skin can perceive as well as present the main motivations for introducing cutaneous feedback solutions in robotic teleoperation. Then, we introduce our review of the state-of-the-art, categorizing the different cutaneous/tactile systems according to the type(s) of stimuli they provide to the human operator. The paper ends with a discussion on the perspectives of the field.

II. CUTANEOUS/TACTILE HAPTIC FEEDBACK

“Haptic” is a synonym of the term “touch-based,” which originates from the Greek *haptikós* and means “able to touch or grasp.” Haptics technology refers to the capability of designing artificial systems that can sense and transmit the different pieces of information we receive when physically interacting with the surrounding environment [61]. In robotic teleoperation, haptics technology enables human operators to virtually relocate their sense of touch at a place other than their true location, *touching*



(a) Common approach for haptic-enabled teleoperation systems. The force feedback provided to the operator is directly applied at the end-effector of the local device, which is also in charge of controlling the motion of the remote robot. In this situation, a control action is usually needed to avoid unstable behaviors.



(b) Cutaneous-only teleoperation system. Cutaneous feedback is applied to the operator’s skin, so it does not affect the position of the local interface. Sensing and actuation are thus decoupled at the user’s side, leaving the teleoperation system as stable as if no haptic feedback was applied. In this example, the cutaneous feedback is applied at the fingertips of the human operator [20]; many other options exist.

Figure 1: Comparison between the standard haptic-enabled and cutaneous-only approaches for robotic teleoperation.

remote objects through the action of one or multiple remote robots. In this context, haptic actuation and sensing technologies play an analogous role to video cameras and display screens, which register moving images and feed them to our eyes, or microphones and speakers, which register sounds and play them to our ears, respectively.

A. Haptic feedback: a composition of cutaneous and kinesthetic stimulation

The human haptic sense comprises two sensory sub-modalities, cutaneous and kinesthetic (see also Sec. I), which can be differentiated from their sensory inputs. Loomis and Lederman [62] define cutaneous perception as the “perception mediated solely by variations in cutaneous stimulation,” kinesthetic perception as the “perception mediated exclusively or nearly so by variations in kinesthetic stimulation,” and haptic perception as the “perception in which both the cutaneous sense and kinesthesia convey significant information.”

We can therefore consider haptic feedback as a *combination* of cutaneous and kinesthetic (haptic) feedback components. For this reason, since cutaneous stimuli are already a component of the full haptic interaction, substituting haptic feedback with cutaneous feedback in robotic teleoperation can be considered a

more natural and promising choice with respect to other sensory substitution techniques (e.g., substituting haptic feedback with audio or visual cues). Prattichizzo et al. [63] called this cutaneous sensory substitution approach “sensory subtraction,” to highlight the removal of the possibly-dangerous kinesthetic part from the full haptic interaction.

B. Cutaneous haptic feedback in robotic teleoperation

The richness of information that cutaneous (haptic) feedback can convey is directly related to the great variety of sensations our skin can register, taking advantage of the plethora of receptors distributed throughout our body. As Sec. II-D details, there are indeed several cases in which cutaneous perception even dominates or improves on the kinesthetic one. For this reason, to enhance teleoperation performance and user experience, many researchers have started to substitute (or complement) classic kinesthetic interfaces with innovative cutaneous displays, able to provide informative cues about local geometry, compliance, and texture of the remote environment. Another reason for choosing cutaneous feedback is that it does not affect the stability of the teleoperation loop, leaving it as stable as it would be if no cutaneous feedback was applied. Therefore, if cutaneous feedback is the only type of haptic feedback provided to the human operator, the teleoperation system is as stable as it would be in an open-loop configuration (when no force feedback is applied). Intuitively, this property can be explained by the fact that applying ungrounded cutaneous stimuli to the operator’s skin does not affect the position of the local interface controlling the remote robot. Figure 1 is inspired from Pacchierotti et al. [20] and illustrates this decoupling concept for a representative teleoperation scenario: if the haptic feedback is applied locally at the operator’s skin through a cutaneous-only device, its actions will never affect the local interface, de facto opening the teleoperation loop. In this sense, cutaneous feedback behaves as any other sensory substitution technique, decoupling sensing and actuation at the local side. As we will see below, this interesting feature made cutaneous teleoperation particularly popular in all those applications and scenarios where the safety of the system is a requirement of paramount importance, e.g., medical robotics [64]. Indeed, this feature significantly reduces the negative effects of latency in the communication channel, which are anyway an issue in the presence of large visuotactile temporal discrepancy [65], [66], i.e., when the user perceives a delay between the movement of the robot and the corresponding haptic feedback received.

C. Cutaneous perception

Cutaneous sensations are elicited by the spatiotemporal perception of various external stimuli, mediated by the large number of cutaneous receptors distributed throughout our body, e.g., mechanoreceptors sense mechanical stimuli, thermoreceptors sense temperature, nociceptors sense pain and damage [67]. Mechanoreceptors are the most interesting for our objectives, as they provide information about the applied pressure, shape, distortion, and vibration. Mechanoreceptors are present in different density across our body, and they can be categorized according to their receptive fields and rates of adaptation [48], [68], [69]. Fast-adapting (FA) mechanoreceptors react to bursts

of action potentials when the stimulus is applied the very first time and when it is removed (e.g., making/breaking contact sensations). On the other hand, slow-adapting (SA) mechanoreceptors remain active throughout the period during which the stimulus contacts their receptive field (e.g., a varying pressure sensation). FA and SA receptors constitute the 56% and 44% of all the cutaneous units in the hand glabrous skin [70], respectively. Johansson and Balbo [71] estimate the density of these mechanoreceptors at the fingertip and palm to be 241 and 58 units per square centimeters, respectively, explaining the high cutaneous sensibility shown by our fingertips.

Another set of cutaneous receptors interesting for our purposes are thermoreceptors. Differently from mechanoreceptors, these receptors code absolute and relative temperature changes in the non-dangerous range ($\sim 15 - 45^\circ\text{C}$), and they can be classified as either cold or warm [72], [73]. When the skin is at its normal temperature, in the range $30-36^\circ\text{C}$, both cold and warm thermoreceptors are naturally active. Nonetheless, there is no sensation of cold or warmth. This temperature range is commonly referred to as the neutral thermal region. Receptive fields of warm and cold thermoreceptors are only a few millimeters in diameter, they are distributed independently of each other, and cold receptive fields are significantly more common than warm ones. Strughold and Porz [74] estimate the density of cold receptors on the volar surface of the finger and palm to be 2–4 and 1–5 units per square centimeters, respectively. On the other hand, Reins [75] estimates the density of warm receptors on the volar surface of the finger and palm to be 1.6 and 0.4 units per square centimeters, respectively. For a detailed study and analysis on cutaneous receptors and their perceptual importance in humans and robots, the reader can refer to [48], [68]–[70], [76].

When one (or more) of the aforementioned cutaneous stimuli is applied to our skin, our body processes a variety of complex mechanical, perceptual, and cognitive phenomena. As soon as we contact an object with our fingertip, its skin rapidly deforms to match the shape of the object’s surface, projecting this deformation to the large number of underlying mechanoreceptors. At the same time, thermoreceptors register the sudden change in skin temperature due to this new contact. Each receptor then elicits a cutaneous sensation according to its specific function, encoding the contact and thermal information regarding a small portion of the object in the form of action potential spikes. Finally, all these pieces of contact information are transmitted to the central nervous system for higher-level processing and interpretation, to provide a coherent tactile sensation of the considered object. This integration process is analogous to how our brain is able to use visual information from both eyes to create a single, coherent visual image. A more in-depth discussion on how the central nervous system processes and combines this plethora of information to get a coherent tactile sensation of the environment can be found in [69], [77].

D. Types of cutaneous interaction

This Section reports on the types of haptic interaction eliciting sensations principally mediated by mechano and

thermoreceptors. Biggs and Srinivasan [78] define a list of four primitives of mechanical cutaneous interactions with objects: normal indentation, lateral skin stretch, relative tangential motion, and vibration. The variety of mechanical tactile sensations humans experience can be considered combinations of these few building blocks. This characterization will be later used in Sec. III to classify the considered cutaneous systems.

1) *Normal indentation*: Normal indentation devices are composed of one (or multiple) moving factors, which convey spatially-distributed cutaneous stimuli by indenting into the skin. Variable pressure, compliance, and large-radius curvature displays fall into this category [57].

Variable pressure and softness display. The fingertip skin can be described as a non-linear spring which stiffens when being compressed, reaching its maximum compression at small loads. This fast increase in the contact area enables the activation of a growing number of mechanoreceptors as the contact area increases, also explaining the high sensitivity of the fingertip to small pressures [79]. The temporal change of contact area is indeed known to help stiffness perception [80]–[82], even without the related proprioceptive cue. For example, when probing an object to estimate its compliance, we measure the penetration of our finger into the object’s surface. However, studies show that humans can distinguish compliance even when relying solely on cutaneous cues [83]. We can justify this result by considering that the temporal change of contact area and the consequent skin deformation are correlated with the applied normal pressure, as a compliant object deforms around the finger. Moreover, the total area of contact has been proven more important than the exact shape of the pressure distribution [82]. The softness and compliance features of our skin have indeed a relevant role on sensing mechanical interactions. Adapting to the object’s shape provides more contact area for sensory perception and improves grasp performance through friction [76], [84]. Finally, we want to highlight the importance of making and breaking contact sensations. As such sudden sensations activate a high number of mechanoreceptors, they can significantly improve the feel of virtual and remote environments [67], [85].

Proprioception illusions. As mentioned above, when probing an object to estimate its compliance, we establish a relationship between contact area (cutaneous cue) and finger displacement (proprioceptive cue). Moreover, we can elicit softness sensations by modulating the contact area on the fingertip. Similarly, it is also possible to modulate the contact area to induce an erroneous estimation of finger displacement [86]. Properly modulating these two relations, contact area–fingertip displacement and contact area–softness sensation, can therefore elicit push-button and other illusionary movement percepts, suggesting that cutaneous stimulation may have a significant role in proprioception [51].

Large-radius curvature display. When our finger interacts with a curved surface having a radius larger than a finger, we follow a 2-D trajectory while the surface normal angle changes with respect to the finger’s surface. Wijntes et al. [87] shows that cutaneous information dominates the proprioceptive one when exploring such large-radius curvature, meaning that subjects are good at differentiating curvatures when provided with local orientation information (cutaneous cue) but perform poorly

when only height information is provided (proprioceptive cue).

2) *Lateral skin stretch and relative tangential motion*: Lateral skin stretch devices provides shear/tangential stimuli to the skin, exploiting the skin’s high sensitivity to lateral stretches. Lateral skin stretch can be also combined with tangential motion stimuli to convey the illusion of slippage. Caress, friction, and small-radius curvature displays fall into this category [57].

Caress and stroke stimuli. As affective haptics is gaining more and more interest [88], we have witnessed an increasing number of displays aiming at delivering affective sensations, such as caresses and hugs. Caress-like sensations can greatly benefit from cutaneous stimulation of the hairy skin (e.g., stroking the forearm), exploiting the pervasive presence of unmyelinated fibers, which are known to respond to light touch [89].

Friction display. Rendering friction stimuli is quite common in robotic teleoperation to provide information about the weight and material of remote objects. While it is common to render friction sensations through kinesthetic feedback, providing lateral skin stretch has been proven to significantly improve friction perception [90]. However, although quite difficult to apply in practice, friction rendering at the fingertip should also take into account for the humidity of the skin [91], the sliding velocity [92], and the mechanics of fingerprints (i.e., presence of ridges and valleys). In fact, the presence of irregularities on the skin, such as the intermediate and fingerprint ridges, helps concentrating the applied forces onto the mechanoreceptors and improves human’s texture discrimination capabilities [91], [93].

Small-radius curvature. Lateral stresses are also used for determining surface geometry, e.g., to detect the presence of (finger-sized) bumps in a surface. Providing strain patterns correlated with position has been indeed shown to elicit sensation of divots and bumps [94].

Proprioception illusions. As anticipated in Sec. II-D1, cutaneous skin stimulation seems to play a significant role in proprioception, including stretch stimulation related with the hairy skin at the joints during flexion. For example, Edin and Johansson [51] showed that humans with anesthetized index fingers were still able to detect finger position by exploiting skin stretch information sensed at the borders of the anesthetized regions. These proprioception illusions may be used to overcome the lack of kinesthetic feedback in cutaneous-only robotic systems.

3) *Vibration*: Vibrotactile feedback devices have always been very popular in haptics and robotics, as the small and lightweight form factor of vibrotactile actuators enables researchers to develop inexpensive, uncomplicated, yet informative interfaces.

Texture, material, notification display. Vibrations are important for recognizing and differentiating materials and textures, as vibratory stimuli with frequency scaled according to scanning velocity are elicited when a finger moves across a surface [95]–[97]. It is also important to correlate the vibrotactile stimuli with the exploration conditions, as it has been proven difficult to identify similar textures rendered at different velocities in passive touch conditions (i.e., when the surface is moved across a stationary finger or when

the subject's hand is moved by the experimenter across a stationary surface) [98]. Moreover, vibration cues are not only present where the interaction takes place (e.g., the fingertip), but they have been proven to propagate at least up to the forearm [99]–[101]. Non-local stimulation may therefore be a valid option [102], as long as real-time correlates are guaranteed.

Proprioception illusions. Another cutaneous-related proprioceptive effect is the induction of angular estimation errors by providing vibrations at the tendons [103], [104]. However, quite large amplitudes are necessary to elicit such illusion. Further proprioceptive effects may be attainable by correlating vibrations and limb movements [105].

4) *Thermal:* Thermal devices are able to provide changing temperature and wetness sensations. Although thermal-only devices are not common in the literature, they have been successfully used in combination with other types of cutaneous stimuli.

Temperature display. An increasing amount of cutaneous devices are being equipped with thermoelectric (Peltier) coolers at their end-effectors [106]. Peltier elements are composed of two sides, and they are able to transfer heat from one side to the other depending on the direction of the current flowing through them. This feature makes possible to display warm and cold sensations to the user's skin.

When designing thermal devices, it is important to consider the thermal thresholds of the skin under stimulation as well as spatial and temporal aspects. The rate at which skin temperature changes also influences how we detect temperature. If the temperature changes very slowly, e.g., $<0.001^\circ\text{C/s}$, a change of 5°C in temperature can go easily unnoticed. On the other hand, if the temperature changes more rapidly, e.g., 0.1°C/s , we are able to detect changes in skin temperature. However, thermal thresholds do not further decrease for rates higher than 0.1°C/s [107]. Finally, it is also important to consider that our skin tends to adapt quite quickly to continuous warm and cold stimuli, with rates as high as 60 s for changes of $\pm 1^\circ\text{C}$ in skin temperature within the neutral thermal region [108].

Wetness display. Afferent signals arising from cold thermoreceptors have been shown to also play an interesting role in the perception of wetness [109], [110], which may enable the development of cutaneous devices able to render this property. In fact, humans are not equipped with specific receptors for sensing wetness. Therefore, we learn what “wet” means through the multisensory integration of thermal and mechanical signals generated by the interaction of our skin with moisture. Indeed, wetness perception is significantly reduced when cutaneous sensitivity is diminished, proving a strong interconnection between wetness sensations and the stimuli registered by thermoreceptors and mechanoreceptors.

5) *Electrotactile:* Electrotactile sensations are elicited by providing low-level electrical current pulses to the skin. They differ from all the other cutaneous stimuli since their perception is not mediated by any receptor. Instead, they directly stimulate cutaneous afferent nerve fibers. Cutaneous information can be conveyed to the human user by properly changing the quality and intensity of the elicited sensations, by modulating the stimulation parameters (i.e., pulse width, amplitude, and frequency) and the location of the active channel [111], [112].

Electrotactile stimulation is usually delivered using concentric electrodes providing sequence of pulses at a certain frequency. This shape of the electrodes enables the generation of surface currents, avoiding the unwanted activation of deeper sensory-motor structures such as nerve trunks and muscles [113]. On the other hand, changing the rate of pulse delivery directly influences the perceived cutaneous sensations, from discrete tapping to sustained vibrations [114]. Finally, a positive correlation between electric pulse frequency and perceived magnitude of sensations has been found, meaning that increasing the pulse frequency also increases the perceived magnitude of the resulting sensation [115]. This result suggests that we should use the lowest pulse frequency possible that still has the desired effect, in order to minimize pain and increase comfort.

III. REVIEW OF THE STATE OF THE ART

This Section reviews the literature on cutaneous/tactile feedback systems used for robotic teleoperation, categorizing them according to the type of cutaneous stimuli they provide to the human user. Five tables summarizing the characteristics, features, and envisioned applications of the considered cutaneous systems are included as supplemental material, see Tables I, II, III, IV, and V. In addition to these Tables, we have created a *visual* survey database, where the surveyed articles can be intuitively browsed through a webpage. It is accessible from <https://www.rego-project.eu/survey-cutaneous-teleop>, reporting the same information of the Tables in a more flexible and versatile format. This visual survey tool is inspired by the work of the *ISOVIS* group (Sweden), who originally developed it for other surveys [116], [117].

A. Normal indentation

Normal indentation displays convey cutaneous stimuli through one or multiple moving factors, providing spatially distributed tactile information through the indentation of the factors into the skin. Peeters et al. [120] claimed that this is “the preferred stimulation method for tactile feedback systems to be used in minimally invasive surgery”. Table I in the Appendix summarizes the characteristics of these haptic systems.

1) *Pin-array displays:* An example of haptic devices providing this kind of cutaneous stimuli are pin-array displays. Already in 1995, Howe et al. [121]–[124] developed a pin-array device able to provide cutaneous feedback in teleoperated manipulation. The display raises pins against the human fingertip skin to approximate a desired shape. It is composed of a 6×4 array of pins actuated via shape memory alloy (SMA) wires, with a center-to-center pin spacing of 2.1 mm. The authors validate the system by carrying out different experiments, including one of remote palpation. Similarly, Fischer et al. [125] presented a pin-based cutaneous system for endoscopic surgery applications. At the remote side, a force-moment sensor is mounted into the distal shaft of a laparoscopic forceps, and a 12×15 mm tactile sensor array is attached on one of the forceps jaws. At the local side, 64 pins, actuated by three electromagnetic units, provide the clinician with the registered tactile sensations, applying either static pressure or vibrations up to 600 Hz. Four years later, Chang et al. [126],

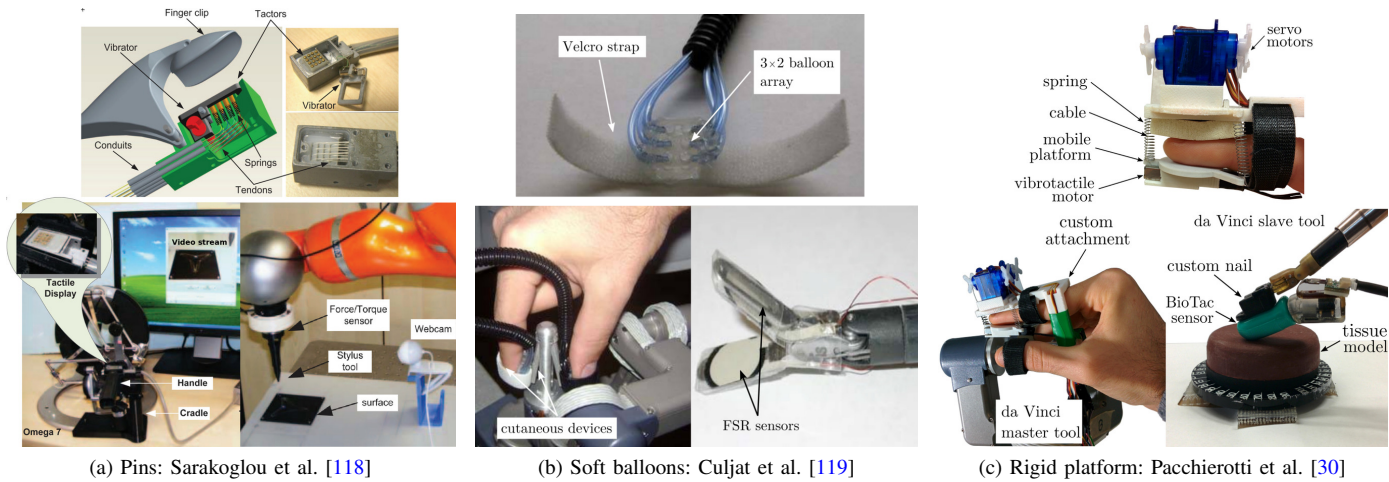


Figure 2: Three representative cutaneous systems for robotic teleoperation providing normal indentation feedback through (a) pins, (b) soft balloons, or (c) a rigid platform. Pictures adapted from the original articles.

[127] developed an arm exoskeleton equipped with a fingertip cutaneous module, composed of a 4×5 array of pins actuated using electromagnets. The authors carried out a teleoperation experiment, in which a human user teleoperated a two-armed humanoid robot to manipulate dangerous chemical materials.

Shen et al. [128] presented a teleoperated five-fingers robotic hand, controlled by a CyberGlove (Cyber Glove Systems, USA) endowed with one cutaneous fingertip module. The module is composed of a 6×4 array of pins actuated via DC solenoids, with a center-to-center pin spacing of 2.5 mm. At the remote side, tactile sensors mounted on the robotic hand measure the contact area using the optical principle of total internal reflection. Feller et al. [129] built a 6×6 pin-array device for remote palpation, actuated via RC servo motors. The center-to-center pin spacing is 3 mm and the diameter of each pin is 1 mm. In the experimental evaluation, subjects teleoperated an instrumented manipulator using a Phantom haptic interface with their right hand. At the same time, they received tactile feedback through the pin-array device worn on the left index finger. Sarakoglou et al. [118], [130], [131] developed a 4×4 fingertip pin-array device for robotic teleoperation, actuated via DC servo motors (see Fig. 2a). The center-to-center pin spacing is 2 mm and the diameter of each pin is 1.5 mm. The tactors are spring loaded and actuated remotely through a flexible tendon transmission. In addition to the cutaneous feedback provided by the pin array, this device also provides vibrotactile stimuli through an Eccentric Rotating Mass (ERM) motor placed next to the fingertip. The cutaneous device is mounted on the end-effector of an Omega 7 grounded haptic interface (Force Dimension, Switzerland), to provide additional kinesthetic feedback and control the motion of a remote 7-DoF LWR manipulator (Kuka, Germany). Hergenhan et al. [132] presented a pin-array display for remote palpation. It consists of seven pins attached to compression springs that can be pre-loaded with servo motors. The pins have a stroke of 10 mm with a maximum counter-force of 7 N altogether. Each pin rests on one compression spring that can be pushed 10 mm downwards with linearly increasing force. Additionally, the basis of the spring can be pushed upwards by the servo motor

for additional force. At the remote side, a single point force sensor and a laser distance sensor register the forces applied on the remote environment.

More recently, Saudrais et al. [133] presented a 8×8 array of pins, driven by piezoelectric bimorphs and with a center-to-center spacing of 3 mm, for providing needle-tissue interaction feedback during needle insertion in soft tissue. Alagi et al. [134] used a 4×4 array of pins, driven by servo motors and with a center-to-center spacing of 2 mm, to provide information about the proximity of target objects to a remote telemanipulator, equipped with a capacitive proximity sensor array.

2) *Soft displays*: Similarly to pin arrays, another popular set of cutaneous systems providing stimuli via normal indentations of mobile tactors are pneumatic balloon-based systems. Both pin and air balloon arrays provide spatially distributed tactile information through multiple moving tactors. This means that, in addition to normal stresses, they can also provide tactile information by changing the contact area between the skin and the display, which is known to elicit changing compliance sensations (see Sec. II-D1).

As early as 1983, Calden [135] presented a pneumatic fingertip device for robotic teleoperation. It is composed of small rubber air balloons placed inside a rubber glove, in contact with the finger pad, each connected to a pressure source by a pneumatic tube. The pressure in each balloon is controller by pressure transducers that, in turn, control air valves placed on an arm band. Ten years later, Cohn et al. [136] presented a cutaneous display consisting of a 5×5 array of pneumatic actuators. The stimulators lie on 2 millimeter centers, in a hexagonal close-packed configuration. Each stimulator consists of a cylinder with a vertically-traveling piston. Solenoid valves are used to control the pressure behind each piston. At the remote side, a force sensor is made out of a 5-mm-thick layer of soft isoprene rubber over a layer of harder silicone rubber. Bicchi et al. [82], [137] used a pneumatic device to convey softness information by changing the contact area spread rate between the finger and the display. The cutaneous display consists of ten cylinders of different radii posed in a telescopic arrangement. The cylinders are subjected to controlled air

pressure on one side, while the operator's finger interacts with the other side. The length of the cylinders is designed in a way that, in the absence of any external forces from the operator, the active surface of the display resembles a cone with a series of gradual steps. As the force applied increases, the contact area with the skin increases. In a later work [138], the same device is attached to the end-effector of a Delta Haptic interface (Force Dimension, Switzerland), with the objective of combining softness and kinesthetic feedback. The same concept was also used by Kimura et al. [139], who presented a device made of a silicone rubber sheet, whose ends are attached to an actuated plastic fork. When the sheet ends are pulled up, the silicone wraps around the finger, increasing the contact area between the sheet and the skin. Differently from [82], the device in [139] use DC motors instead of pneumatic actuators.

King et al. [119], [140]–[145] developed a modular pneumatic cutaneous feedback system to improve the performance of the da Vinci Surgical System (Intuitive Surgical Inc., USA). The system is composed of two piezoresistive force sensor mounted onto the Cadiere graspers of the robot and two pneumatic balloon-based cutaneous displays mounted on the robot's local console (see Fig. 2b). Each cutaneous display is composed of a 3×2 element array of 3 mm balloons with 1.5 mm spacing. The same system was also used on live tissue [146]. A similar cutaneous approach was recently proposed by Fischel et al. [147] for providing feedback during the fine teleoperation of a high-end bimanual telemanipulation system. The remote system is composed of two 6-DoF UR10 robotic arms, each equipped with a Shadow Dexterous Hand with BioTac sensors at the fingertips. The operator wears two HaptX Gloves, providing resistive force at each fingertip via a pneumatically-actuated tendon-breaking system. The gloves also features pneumatically-actuated cutaneous taxels distributed over the palm and fingertips that can be independently controlled with up to 2 mm of deflection. Similarly, Li et al. [148] also used controllable air chambers at the user's fingertip to provide feedback about the contact forces registered at the remote side by a pneumatic anthropomorphic soft hand.

Uddin et al. [149] presented a one-finger exoskeleton providing both kinesthetic and cutaneous sensations. Kinesthetic feedback is provided by three rigid links, grounded on the back of the palm and attached to the dorsal side of the proximal and distal phalanges of the index finger. Cutaneous feedback is provided by an air chamber placed all along the volar surface of the index finger. Users were asked to teleoperate a remote two-fingered robotic gripper endowed with FSR sensors. Park et al. [150] developed a haptic ring composed of a proportional pressure valve, a balloon with Magnetorheological (MR) fluid, and an electromagnet. The proportional valve controls the amount of fluid in the balloon, providing changing pressure sensations to the proximal phalanx of the user's finger. At the same time, the compliance of the MR fluid can be controlled by changing the electromagnetic field, providing different softness sensations. This device was used during the teleoperation of a robotic gripper endowed with FSR and optical distance sensors.

Abd et al. [151] presented an armband able to provide both pressure and vibrotactile stimuli to the upper arm. It is made of flexible silicone rubber, and it houses five inflatable air chambers as well as five vibrotactile motors. It was used during

the teleoperation of a Dexterous Shadow Hand (Shadow Robot Company, UK) endowed with three BioTac tactile sensors (Syntouch, USA) at the fingertips. The contact deformations, DC pressure, and AC pressure (vibrations) registered by the BioTac were mapped at runtime into pressure and vibratory stimuli provided by the air chambers and vibrotactile motors, respectively. More recently, Ham et al. [152] used a bending ionic electromechanically active polymer (iEAP) actuator to provide the user with wearable cutaneous feedback about the grasping force applied to a remote soft gripper.

3) *Rigid moving platforms*: Finally, rigid platforms in contact with the skin can move and orient to provide different shape and contact sensations.

In 2012, Pacchierotti et al. [153] presented a two-fingertips cutaneous device for teleoperated needle insertion. The device is composed of two static platforms and two mobile platforms, placed in contact with the nail and finger pad of two fingers, respectively. The mobile platforms are actuated by servomotors and apply pressures normal to the finger pads. The device is attached to the end-effector of an Omega.3 grounded haptic interface (Force Dimension, Switzerland), to provide additional kinesthetic feedback and enable the control of a remote 6-DoF KR3 manipulator (Kuka, Germany), endowed with a needle.

In the following years, the same group at the University of Siena developed a wide range of platform-based cutaneous devices [24], [154], [155]. Similarly to [153], these devices are composed of a static platform placed on the nail and a mobile platform placed on the finger pulp, acting as the end-effector. They have been used in many different applications, ranging from gaming to robotic teleoperation. In the latter scenario, the devices have been employed to either substitute [20], [30], [156]–[158] or complement [159] the complete haptic feedback provided by grounded haptic interfaces (see Sec. II-B). Pacchierotti et al. [20] attached two 3-DoF cutaneous devices to the end-effectors of two Omega.3 grounded interfaces. Users were asked to wear the cutaneous devices on the thumb and index fingers and control the motion of a 6-DoF Kuka KR3 manipulator equipped with a DLR-HIT Hand II. Meli et al. [156] controlled the same robotic system using an ungrounded version of the above cutaneous device. The user's hand is tracked using a Leap Motion controller (Leap Motion, USA). Users wear three cutaneous devices on their right hand. The system is used to introduce an object-based mapping between positions/forces in teleoperation, useful in the presence of different number of contact points at the local and remote sides of the system. More recently, Ferro et al. [158] compared the use of pressure stimuli, provided either at the fingertips or at the proximal finger phalanx, vs. vibrotactile stimuli on the forearm to provide feedback during teleoperated needle insertion in soft tissue. Results indicate that pressure feedback is more suited for rendering the elastic components of the needle-tissue interaction with respect to the vibrotactile one. Providing delocalized sensations, e.g., feedback at the proximal finger phalanx instead that on the fingertip, do not significantly degrade performance, confirming that delocalized cutaneous sensations can be an effective solution [102].

Musić et al. [157] more recently used the same ungrounded cutaneous devices of [156] to interact with a bimanual robotic system in a teleoperated pick-and-place manipulation task. A

human operator controls the motion of two KUKA LWR4+ manipulators to grasp and lift a 1-kg box, while receiving feedback about the applied grasping force through two cutaneous devices worn on the thumb and index fingers. Pacchierotti et al. [30] adapted the above cutaneous devices for use on a da Vinci Surgical System. At the surgeon's side, one cutaneous device is mounted on the da Vinci's operator's interface. With respect to [20], [156], this device is also endowed with a vibrotactile motor placed directly below the mobile platform. At the patient's side, a BioTac sensor is attached to a surgical tool (see Fig. 2c). As the user interacts with the remote environment, the contact deformations, DC pressure, and AC pressure (vibrations) registered by the BioTac are converted into motor commands for the cutaneous device using a data-driven algorithm that relies on look-up tables [160]. Brown et al. [161] extended this approach to two-fingered pinching palpation. The same teleoperated palpation scenario was considered by Chinello et al. [155], who presented a modular wearable interface composed of a 3-DoF fingertip cutaneous device and a 1-DoF finger kinesthetic exoskeleton. The 3-DoF device makes and breaks contact with the fingertip and re-angle to render contacts with slanted surfaces (similar to [20]); the 1-DoF finger exoskeleton conveys kinesthetic stimuli to the proximal and distal interphalangeal finger articulations through one servo motor placed at the proximal phalanx. Finally, Pacchierotti et al. [159] used the same ungrounded device of [156] to complement the kinesthetic feedback provided by a grounded haptic interface in teleoperated needle insertion. Users wear cutaneous devices on the thumb and index fingers while holding the end-effector of an Omega.3 interface. At the remote side, a needle is attached to the end-effector of a Kuka KR3 robot (as in [153]). The ideal force feedback registered at the remote environment is actuated via the grounded haptic device as long as a stability condition is not violated. As the stability controller detects a violation, kinesthetic feedback is decreased according to a time-domain passivity-preserving algorithm, while the cutaneous device delivers an appropriate level of cutaneous stimuli to restore transparency.

Khurshid et al. [162], [163] presented a wearable cutaneous device capable of providing kinesthetic grip feedback, as well as fingertip contact, pressure, and vibrotactile stimuli. It is composed of a rotational joint, whose axis is aligned with the MCP joint of the index finger, and two rigid links. The first link is secured around the proximal phalanx of the thumb, while the second link is fastened to the index finger. A DC motor actuates the revolute joint, providing kinesthetic feedback to the hand, while one voice-coil actuator per fingertip provides cutaneous stimuli. The device was used to control the grip aperture of a remote PR2 robotic gripper (Willow Garage, USA) in a pick-and-place task. A similar setup was recently presented by Palagi et al. [164], who developed a mechanical hand-tracking system with cutaneous pressure feedback. A wearable wide-bandwidth haptic motor, based on an electromagnetic voice coil, is mounted on the thumb and index fingers. Potentiometers were used to sensorize the thumb, index, and middle fingers, so as to teleoperate a 4-DoF anthropomorphic robotic hand attached to a 6-DoF Panda robot arm. Pressure feedback from grasping remote objects was provided to the user during robotic pick-and-place tasks.

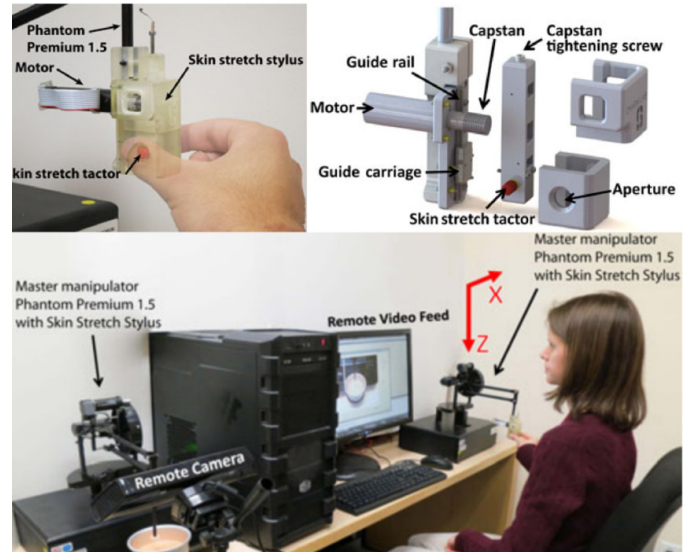


Figure 3: A representative cutaneous systems for robotic teleoperation providing lateral skin stretch feedback [165]. Picture adapted from the original article.

B. Lateral skin stretch and relative tangential motion

Lateral skin stretch is a feedback modality in which a shear force is applied to the user's skin. It exploits the high sensitivity of human skin to tangential lateral stretches and can provide the user with directional information. Skin stretch and tangential motion cutaneous stimuli can be then combined together to provide the illusion of slippage. Of course, providing these stimuli requires the device's end-effector to contact the skin. For this reason, these systems often also provide variable pressure sensations. Table II in the Appendix summarizes the characteristics of these haptic systems.

In 2013, Roke et al. [166] investigated the benefits of lateral skin stretch on the detection and localization of lumps embedded in soft tissue. They used a custom fingertip cutaneous device able to provide both shape sensations via normal indentation of pins and lateral skin stretch. The device is composed of a 4×4 pin array remotely actuated by servomotors, mounted on a 2-DoF plate able to drive the array in the longitudinal and sideways directions of the finger. The plate is in turn mounted on a Falcon grounded interface (Novint Technologies, USA), to provide additional kinesthetic feedback and control the motion of the remote robot. At the remote side, a 7-DoF Whole Arm Manipulator (Barrett Technologies, USA) is endowed with an iCub force/torque sensor (Italian Institute of Technology, Italy) and a TACTIP tactile sensor (Bristol Robotics Laboratory, UK).

Schorr et al. [165], [167] evaluated the potential of skin stretch feedback for robotic teleoperated palpation. They presented a 1-DoF fingertip skin stretch feedback device that imposes tangential skin stretch proportionally to the intended level of force feedback (see Fig. 3). The skin stretch device is designed as a stylus to imitate interaction with an object surface via a hand-held tool. The stylus consists of two dome-shaped, 7-mm-diameter tactors actuated by a geared DC Motor. Users place their fingertips on two conical apertures housing the tactors. The device is attached to the end-effector of a Phantom Premium grounded device, to provide additional kinesthetic

feedback and control the motion of a second remote Phantom Premium. Quek et al. [168] combined the abovementioned skin stretch feedback approach of [165] with normal cues, presenting a 6-DoF cutaneous device capable of providing tangential and normal skin deformation on three fingerpads. The system was tested in two teleoperated manipulation tasks, peg transfer and tube connection, using a da Vinci Surgical robot, comparing kinesthetic feedback, skin stretch, and the combination of both. A similar approach was also recently presented by Zhu et al. [169], that integrated a two-finger cutaneous display into the gripper of an Omega.7 kinesthetic haptic interface. Each cutaneous display is composed of two five-bar linkage mechanisms moving two spherical factors on the index and thumb fingerpads. The system was used to provide feedback information of grasping force, shear force, and friction during the teleoperation of a simulated Panda robotic arm (Franka Emika, DE) during in-hand pivoting manipulation tasks.

Lim et al. [170] devised a haptic system able to convey both cutaneous and kinesthetic feedback during robot-assisted surgery. Kinesthetic feedback is provided by a PHANToM Premium (3D Systems, USA) grounded interface. Cutaneous feedback is provided by two balloon-based displays mounted on the end-effector of the kinesthetic interface. Each display is composed of five balloons. Four move a tactor tangentially to the skin surface, and one, placed on the tactor itself, provide normal stimuli to the skin. At the remote side, a 6-DoF serial robot equipped with a force/torque sensor, a grasper, and optical fiber Bragg grating sensors mimics a surgical robot arm. Casini et al. [171], [172] presented a wearable device for providing skin stretch and normal pressure to the upper arm. It consists of two DC motors moving an elastic belt. When motors rotate in opposite directions, the belt compresses the arm; when motors rotate in the same direction, the belt applies a tangential force. The device was used to provide haptic feedback during the control of a Pisa/IIT SoftHand. Fani et al. [173] used the same cutaneous device during the teleoperation of a Lightweight Kuka arm equipped with the Pisa/IIT SoftHand. The grasping force exerted by the robotic hand was delivered through the cutaneous device on the operator's arm.

Clark et al. [174] employed this device for the teleoperation of two 7-DoF Kuka LWR robots for peg-in-holes tasks. A similar solution has been also presented by Meli et al. [175]. It is composed of two bracelets connected by a linear stage. As in [171], each bracelet consists of two motors moving an elastic belt wrapped around the arm. The linear actuator can change the relative distance between the bracelets and produce translational cues. The device is used during the teleoperation of a Sawyer manipulator (Rethink Robotics, US) to provide information about the forces exerted by the Sawyer gripper on the remote environment. Han et al. [176] developed a two-finger MR-compatible haptic device to display needle tip forces during MR-guided needle procedures. It produces localized skin stretch at the tips of the index finger and thumb using multilayer electroactive polymer films.

C. Vibration

Thanks to the small form factor, low mass, reduced power consumption, availability, and cost of vibrotactile actuators,

haptic systems providing vibrotactile cutaneous feedback have been introduced very early and they are nowadays still popular. Table III in the Appendix summarizes the characteristics of these haptic systems.

Already in 1971, Hill and Bliss [179], [180] presented a cutaneous multi-finger device for teleoperation. It is composed of a 4×12 array of vibrating pins uniformly spaced on 0.25-cm centers. Each vibrator is a piezoelectric transducer tipped with a metal pin protruding through holes in a recessed plastic sensing plate. At the remote side, a 7-DoF robotic manipulator endowed with a parallel gripper interacts with the remote environment and register vibratory sensations. Later on, in 1992, Michael J. Massimino presented his Ph.D. thesis on "Sensory substitution for force feedback in space teleoperation [181], [182]." He tested the effectiveness of using vibrotactile stimuli to provide force feedback in robotic teleoperation. The haptic display consists of vibrating voice coils placed on the fingertips, palm of the hand, and wrist. An E2 manipulator was used to carry out peg-in-hole experiments and FSR sensors were used to register the force exchanged at the remote side. The magnitude of vibration was dependent on the magnitude of the force, while its frequency was fixed at 250 Hz.

Vibrotactile feedback is also used in the teleoperation hand system developed by Kontarinis and Howe [183], [184]. Local and remote manipulators are identical two-fingered hands with 2 DoF in each finger. Sensors in the fingertips of the remote manipulator measure the vibrations generated during the task, and high-frequency vibrotactile displays relay these vibrations to the human operator. The cutaneous displays consist of loudspeakers attached to the local manipulator, near the operator's fingers. Similarly, Dennerlein et al. [185], [186] developed a single-channel vibrotactile system for the deep sea manipulator Schilling Robotic Systems TITAN-II. At the remote side, a vibration sensor consisting of a pair of steel plates is mounted on the gripper fingers. At the user's side, a vibrotactile device is attached to the local interface. It consists of a voice coil motor mounted on an aluminum base. The moving motor coil actuates a 13-mm-long strip of spring steel projected from the aluminum base.

Tokashiki et al. [187], [188] used a DC buzzer vibrating at 400 Hz to notify the user the contact with a remote object in a teleoperated micrograsping task. Using vibrotactile feedback on top of kinesthetic feedback reduced grasp forces by as much as 40%. Sano et al. [189] developed a soft tactile sensor coupled with a fingertip ultrasonic display able to render changing friction sensations. Two ultrasonic vibrators having resonance frequency of 40 kHz are used as the source of oscillation, changing the user's perceived friction coefficient as they change the amplitude of their oscillation: as the amplitude became larger, the surface feels smoother [190]. Similarly, Aleotti et al. [191], [192] employed a CyberTouch glove (CyberGlove Systems, USA) to control a PUMA 560 robotic manipulator endowed with a parallel gripper. The CyberTouch was equipped with one vibrotactile motor per finger, providing information about making/breaking contact with remote objects. Lathan and Tracey [193] used a vibrotactile bracelet to provide information about the presence of obstacles during the teleoperation of a Pioneer 2-DX mobile robot (Omron, USA). Seven sonar elements on the robot provide obstacle proximity data, which

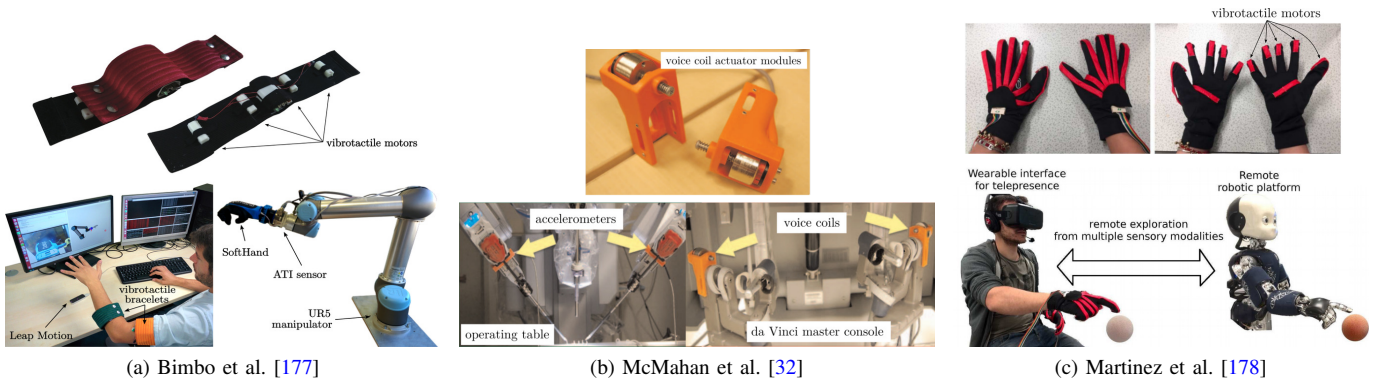


Figure 4: Three representative cutaneous systems for robotic teleoperation providing vibrotactile feedback. Pictures adapted from the original articles.

are then mapped into stimuli for the five vibrotactile motors on the bracelet. Vibrotactile bracelets have been used to provide information about the forces exerted at the remote side of the system also in [177], [194]–[199]. Tsetserukou and Tachi [194], [195] used a bracelet with six motors equally distributed around the forearm, Liarokapis et al. [196] used a bracelet with five motors, Khasnobish et al. [197] and Bimbo et al. [177] used two bracelets with four motors each (see Fig. 4a), Baker and Rolf [198] used used four bracelets with one motor each, and Aggravi et al. [199] used one bracelet with four motors.

Murray et al. [200] developed a vibrotactile glove containing miniature voice coils providing continuous, proportional force information. The device was used during two teleoperation experiments to convey information about the forces registered by a 4-fingered Utah/MIT robotic hand attached to a 6-DoF Puma 560 manipulator. Vibrotactile gloves to provide contact information from teleoperated robotic hands or grippers have been also used in [178], [201]–[205]. Dascalu et al. [201] used 20 ERM motors for the teleoperation of an anthropomorphic five-fingered MechaTE Robot Hand. At the remote side, the robotic hand was instrumented with 20 FSR sensors registering contact pressures at the fingers and palm. Sartori et al. [202] used six vibrating motors for receiving feedback from a three-fingered ReFlex robotic hand (RightHand Robotics, USA). The robotic hand was endowed with 11 tactile sensors on the palm and 9 on each finger. Martinez et al. [178] used two gloves, each endowed with six vibrating motors, during the teleoperation of an iCub humanoid robot (Italian Institute of Technology, Italy). At the remote side, the iCub robotic hands were instrumented with matrix capacitive sensors (see Fig. 4c). The same glove was also used during the teleoperation of a Pioneer LX mobile robot [206]. Similarly to [193], the front sonar elements provided obstacle proximity data, which were then mapped into stimuli for the six vibrotactile motors on the glove. Xu et al. [203] used two vibrating motors placed on the upper forearm to provide the human operator with grasping force feedback registered by a remote two-finger gripper during a pick-and-place task. Zhu et al. [204] used a Cyber-touch glove, which embeds vibrotactile motors at the fingertips, to provide feedback about the contact forces registered by an anthropomorphic robotic hand at its fingertips. More recently, Park et al. [205] used a hand exoskeleton able

to provide kinesthetic and vibrotactile feedback at three fingers to teleoperate a dexterous humanoid robot during the handling of brittle objects.

Kuchenbecker and Niemeyer [207] improved the user’s perception of high-frequency information at the remote environment (e.g., textures) through the approach of acceleration matching. High-frequency accelerations are combined with standard low-frequency position feedback using a Phantom Premium grounded haptic interface. During teleoperation, an accelerometer measures accelerations at the remote end effector, and the proposed real-time controller re-creates these signals at the local handle. Hulin et al. [208] developed a wearable fingertip cutaneous device composed of three shape memory alloy wires wrapped around the finger pad. The wires are commanded through a pulse width modulation (PWM) signal and they can either vibrate or apply constant pressure. Users wear three of these devices on the thumb, index, and middle fingers. Optical tracking is used to register the position of the fingers and control a remote robotic system composed of a DLR robot hand II mounted on a DLR Light Weight Robot III. Cutaneous feedback at the fingertips is driven by the error between commanded and measured positions of the robotic hand’s fingertips. Hayashi and Tamura [209] modified the user’s controller of an hydraulic excavator to provide vibration bursts when the bucket is about to touch the ground. A laser rangefinder, mounted on the bucket wrist, registers the distance between the bucket and the ground, and a vibrotactile motor notifies the operator 150 ms before contact. Similarly, and more recently, Nagano et al. [210] used a vibrotactile-enabled joystick to control the motion of an instrumented industrial robotic shovel as well as a dual-arms construction robot. The system provides the human operator with information about the collision vibrations in the remote environment, mapping the measured vibrations into the human sensitive range.

Mochiyama et al. [211] presented a macro-micro tele-manipulation system able to provide visual, cutaneous, and audio feedback to the operator. It is composed of two micro-manipulators (Narishige MMO-202ND, Japan) hydraulically connected to two joysticks. A voice coil motor is attached to one of the two joysticks, providing vibratory stimuli whenever the remote tool contacts the environment. The effectiveness of the system was demonstrated in a micro-drawing task. Also in

applications at the microscale, Pacchierotti et al. [212] used vibrotactile and kinesthetic feedback during the teleoperation of self-propelled magnetic microjets. At the remote side, a wireless magnetic control system regulates the orientation of the controlled microjet to reach the target position. At the user's side, an Omega.6 grounded interface provides the user with kinesthetic and vibrotactile stimuli about the inertia of the microjet and its collisions with the remote environment, respectively. A similar approach was also used for the teleoperation of magnetic microgrippers [213].

Okamoto et al. [214]–[216] developed a teleoperation system for texture rendering in the presence of communication delays. The local system masks the delay by building a local model of the remote surface and synchronizing the vibratory texture feedback with the motion of the local operator. Vibratory stimuli are provided by a piezoelectric stack actuator [214], [215] or a voice coil [216]. At the remote side, a fingertip-like silicon body is instrumented with strain gauges to register vibratory information. Vibrotactile feedback was also used in [217]–[220] for texture rendering in teleoperation. Gurari et al. [217] used a C2 tactor mounted either on the fingertip, foot, or upper arm, McMahan et al. [218] and Konyo [219] used a voice coil mounted on the end-effector of a Phantom interface, and Lin and Smith [220] used piezoelectric motors on a wearable fingertip device. Along this line of research, McMahan et al. [32], [221] presented one of the most notable systems employing vibrotactile feedback in robot-assisted surgery. They developed a high-frequency acceleration sensing and actuating system for the da Vinci Surgical System, able to provide auditory and vibrotactile feedback of tool contact accelerations (see Fig. 4b). The high-frequency accelerations of the da Vinci tools are measured with MEMS-based accelerometers, attached to the robotic manipulators below the interchangeable tool mounting points. At the user's side, off-the-shelf stereo speakers provide audio feedback, while voice coil actuators provide vibrotactile sensations. The speakers are mounted on the sides of the user's console, while the voice coils are mounted on the platform wrist joints of the same console. The system was even successfully tested in vivo, during two transperitoneal nephrectomies and two mid-ureteral dissections with uretero-ureterostomy on a porcine model [222]. More recently, 114 surgeons and non-surgeons tested the system in drylab manipulation tasks and expressed a significant preference for including this type of cutaneous feedback [31]. A similar approach has been also explored by Thiem et al. [223], who presented a single-port surgical robotic system providing high-frequency and kinesthetic haptic feedback. Kinesthetic forces are measured with strain gauges and force/torque sensors, and they are displayed through a Delta-type haptic interface. Cutaneous signals are acquired with an accelerometer placed close to the robotic grasper and conveyed to the user's palm by a vibrating cylinder. Instead, Massari et al. [224], [225] used a piezoelectric-enabled vibrotactile glove to provide users with information about the stiffness of a remote silicon phantom. The normal force information recorded by a remote robot while sliding over the surface of the phantom was converted into temporal patterns of spikes through a neuronal model, and delivered to the fingertip via the vibrotactile glove.

Surface haptic technology also conveys vibration stimuli

to the human user. While it has mostly been employed for rendering virtual textures on touch screens [226], it also has some applications to robotic teleoperation. For example, Takasaki et al. [227] presented a haptic-enabled surface able to reproduce the texture of remote surfaces scanned by a 3-dimensional profile scanner. It employs an active surface acoustic wave device that exploits ultrasonic vibrations to convey diverse temporal distribution of shear force and friction sensations on the target surface. Similarly, Yamamoto et al. [228]–[230] developed an electrostatic device for texture rendering in teleoperation. The display is composed of a stator plate and a slider film. A flexible printed circuit film is glued to the stator, which houses 50 parallel electrodes measuring 37×0.8 mm. Users place their finger on the slider film and then move the finger together with the slider to explore the stator surface. At the remote side, a linear stage is endowed with a bimorph piezoelectric sensor formed into a fingertip-like shape. When scanning a surface, the tip of the sensor is dragged backward and forward due to friction, deforming accordingly. This information is relied to the human operator through the such surface display.

We also include in this Section a haptic teleoperation system employing mid-air ultrasound haptic feedback, as the primary mechanoreceptors stimulated by ultrasound haptic sensations are indeed Pacinian corpuscles [231]. In this respect, Liu et al [232] proposed to use ultrasound haptic feedback to provide a human operator with feedback about the overall contact force registered by a pneumatic anthropomorphic hand mounted on a robotic arm. The amount of ultrasound feedback was modulated according to the amount of contact force registered at the remote side.

D. Thermal

Although providing thermal feedback for teleoperation is not as popular as other modalities, it is recently gaining attention from researchers trying to convey all-round cutaneous sensations. Thermal feedback is often presented together with other types of cutaneous stimuli, and all systems we found used technologies based on the Peltier effect. Table IV in the Appendix summarizes the characteristics of these haptic systems.

Caldwell and Gosney [233], [234] developed an instrumented finger able to register multi-modal tactile sensations, including contact texture, pressure, and temperature. A wearable tactile glove is then in charge of providing the operator with the diverse stimuli registered by the multi-modal sensor. Texture and pressure sensations are conveyed to the fingertip by a 10-mm-large piezo-electric lead-zirconate-titanate ceramic disc. The disc is driven from a high voltage source transforming texture inputs into motion of the ceramic. Thermal sensations are provided using a Peltier element. The instrumented finger is mounted on a Puma 560 manipulator, and outputs from the remote sensory modules are transmitted to the user through the tactile glove. An application of the same device to the teloperation of a two-armed mobile robot is presented in [235]–[237]. Kron and Schmidt [238] combined vibrotactile and thermal displays to provide multiple cutaneous stimuli to the user's fingertips. Vibrotactile feedback is generated using

miniaturized DC motors with a freewheeling out-of-balance mass at top of the motor shaft, able to produce vibrations at 166 Hz with amplitudes $> 3\mu\text{m}$. Thermal feedback is generated by four serially-connected Peltier elements, able to generate temperatures in the range $[8^\circ\text{C}, 80^\circ\text{C}]$. Combining the integrated cutaneous display with a CyberGrasp glove (CyberGlove Systems, USA), users can control and receive rich haptic feedback from a remote manipulator. Drif et al. [239] developed a robotic system for thermal rendering of remote objects. It uses two heat-controlled elements, each composed of a Peltier pump, temperature sensor, heat flux sensor, and dedicated electronics. The local interface uses the Peltier pump as a thermal display for the operator's fingertip, while the remote interface uses its to heat the touched object. The two pumps are commanded according to the temperature and/or heat flux observed at the other side of the teleoperation system, according to the chosen coupling.

More recently, Lee et al. [240] presented a wearable thermal feedback system using a thermal glove at the user's side and an instrumented Kinova JACO manipulator with a robotic hand at the remote side, so as to enable the human operator to feel a remote object's temperature. The glove is composed of four flexible thermoelectric devices, based on Peltier's elements, that provide thermal feedback at the user's palm, thumb, index, and middle fingers.

E. Electrotactile

Electrotactile devices directly excite the mechanoreceptive afferent nerve fibers, producing sensations that have been described as tingle, vibration, pressure, pulsation, fizz, pinprick, and buzz depending on the stimulus variables [111], [241], [242]. Table V in the Appendix summarizes the characteristics of these haptic systems. Clear advantages of these displays are that they can provide well-localized and controlled sensations of touch, they contain no moving components, are silent, very responsive, compact, and energy efficient [242], [243].

Shen et al. [128], [244] presented a teleoperated five-fingered robotic hand controlled by a CyberGlove (Cyber Glove Systems, USA) equipped with custom electrotactile fingertip modules. Optical tactile sensors mounted on the robotic fingers measure the contact area with the remote environment. This information is then transformed into triggers for the electrotactile modules at the fingertips, to notify the operator when contacts with the remote environment happen. Droessler et al. [245] developed an electrotactile tongue stimulation system to provide shape information about remote objects. Six conductive polymer force sensors are attached to the gripper of a commercial 6-DoF robotic manipulator. Five sensors are located in a 24-mm-diameter pentagonal pattern, with the sixth located at the center. The registered information is then converted into electrotactile stimulations through a Tongue Display Unit (Wicab, USA), a commercial tactile pattern generator with tunable stimulation parameters. Sato et al. [246]–[249] combined four electrotactile fingertip devices with a kinesthetic hand exoskeleton to teleoperate an anthropomorphic robotic hand. Each electrotactile device is 12×17 mm, and it is composed of a 5×3 array of electrodes with a center-to-center pin spacing of 2.5 mm. A finger-shaped GelForce

sensor is mounted on one of the remote robotic fingertips and sense the distribution, magnitude, and direction of the contact force. The distribution of the force is rendered via the electrocutaneous display, while its magnitude and direction is rendered through the kinesthetic exoskeleton. The teleoperation system was successfully tested by more than 1000 people during conferences and exhibitions, including the 2007 ACM SIGGRAPH in San Diego, USA. Pamungkas and Ward [250], [251] used cutaneous feedback to provide information about the presence of obstacles during the teleoperation of a mobile robot. At the user's side, a five-fingers P5 data glove (Essential Reality, USA) is endowed with six Transcutaneous Electro Neural Stimulation (TENS) electrodes, placed on the volar surface of the middle phalanges of the fingers and the palm. Pamungkas and Ward also used the same electrotactile glove for the teleoperation of a 6-DoF robotic manipulator [252], [253].

Very recently, Trinitatova et al. [254] combined kinesthetic and electrotactile feedback for accurate liquid dispensing during the dexterous telemanipulation of deformable objects. An Omega.7 kinesthetic interface houses two arrays of 4×5 electrodes, one per fingertip. Kinesthetic and electrotactile feedback provide information about the grasping force and local shape of the remote objects, respectively.

IV. DISCUSSION

Robotic teleoperation has been central in the technological advances of the past decade. Teleoperated robots perform over 700,000 surgeries per year [255], they are currently exploring the surface of Mars, they help our public forces during natural calamities, they navigate our oceans and sort our waste. This article has reported on how the benefits of haptic feedback are significant and consistent across teleoperation domains, including increased accuracy, repeatability, and user's experience, as well as decreased completion time and damage to the remote environment.

However, despite these well-proven benefits, current commercial telerobotic systems provide very limited haptic feedback. This surprising omission and mismatch between good research/lab results and poor industry/field adoption is mainly due to three barriers: (i) the negative effect grounded kinesthetic feedback may have on the safety of teleoperation systems; (ii) the high cost and complexity of currently-available haptic-enabled consoles; and (iii) the challenge of devising effective, viable, and general haptic rendering policies. Cutaneous feedback represents a very promising solution for addressing the two first points, as it provides rich and safe feedback information through interfaces that are often rather inexpensive and easy to integrate in currently-available consoles. Indeed, as also mentioned in [57], one of the great advantages of cutaneous interfaces is their reduced form factor with respect to standard kinesthetic devices. This feature not only means reduced prices but also the possibility of more easily engaging in multi-contact interactions, e.g., full-hand feedback. Multi-contact *cutaneous* feedback does not require anymore complex and expensive systems such as those needed for multi-contact *kinesthetic* feedback, but rather multiple instances of small similar (cutaneous) devices. For example, let us compare the 5-fingers cutaneous feedback system used in [256] vs. a CyberGrasp or a Haption

HGlove system. While they – of course – provide very different types of feedback, the significantly reduced prize, form factor, and weight of the former might represent an interesting solution for many scenarios. This feature seems especially promising for manipulation and grasping applications, where having feedback information delivered at multiple contact points is particularly beneficial. The intrinsic stability of cutaneous feedback is another feature that makes it so promising, especially in those applications in which the safety of the system is a non-negotiable requirement, e.g., surgical robotics. Indeed, as discussed in Sec. II-B, providing cutaneous feedback directly to the user’s skin opens the force feedback loop, making the system as stable as it would be in an open-loop configuration, thus significantly reducing the common safety issue linked to communication delays and stiff contacts.

As it is clear from our review in Sec. III, vibrotactile feedback solutions are the most popular. This is of course not a surprise, as vibrotactile motors benefit of small form factors, limited power needs, and are inexpensive. A notable commercial example of this technology is the TactGlove by bHaptics (Korea), which features 12 vibrotactile motors spread around the palm and fingers, addressing mostly VR gaming applications. On the other hand, the Nova glove by SenseGlove (The Netherlands) combines vibrotactile and (passive) kinesthetic haptic sensations; it houses one voice-coil motor on the palm and two Linear Resonance Actuators (LRA) on the index and thumb. While it mainly targets virtual training applications, this glove has also been used for robotic teleoperation [257]. A previous version of this glove (SenseGlove DK1) has been used to teleoperate the iCub 3 humanoid robot [258] as well as two 7-DoF Panda robotic arms equipped with instrumented anthropomorphic robotic hands during the ANA Avatar XPRIZE finals [259]. Vibrotactile feedback at the fingertips provided information about the rugosity and local geometry of the remote environment.

The second most popular way of providing cutaneous feedback was through the indentation of single or multiple tactors. With respect to vibratory feedback, the distributed indentation of the skin can provide much richer information in a sustained and comfortable way. A notable commercial example of this technology is the HaptX G1 glove (USA), which includes 135 soft microfluidic actuators distributed throughout the glove, each providing up to 1.5 mm of indentation. As for the SenseGlove device, two of the HaptX gloves have been used to control two 6-DoF robotic arms equipped with anthropomorphic robotic hands and biomimetic fingertip tactile sensors during the ANA Avatar XPRIZE finals [260].

The type of envisaged application directly affects the type of haptic feedback and technology in use. Most research targets generic robotic telemanipulation, focusing on the feedback rendering more than in validating its use in a specific set of applications. When an application scenario is identified, medical ones are the most popular, especially targeting palpation and needle insertion, probably due to their high-potential impact and historical lack of haptic feedback. However, as also mentioned above, the recent ANA Avatar XPRIZE highlighted the great potential of (cutaneous) haptics for the teleoperation of humanoid robots. The target of the contest was to “create avatar systems that can transport human presence to remote locations

in real time,” for which attaining effective haptic sensations is of course paramount. Indeed, out of the ten tasks considered during the competition finals, five comprised interacting and manipulating the remote environment [259], as teams were asked to develop systems with the following capabilities: “gestures, lifting, pulling or pushing objects”, “lifting, turning, placing objects”, “use of tools, knobs, levers, etc.”, “identifying weights of objects,” and “determination of textures, pressures.” On a similar note, cutaneous haptic feedback has also been used to provide feedback about supernumerary anthropomorphic limbs [261]–[263], e.g., an additional arm or finger, mostly for applications of rehabilitation and human augmentation.

A whole new range of applications will become possible thanks to the advent of the Tactile Internet, which will enable rich real-time transmission of haptic information over the Internet, in addition to conventional audiovisual sensory cues [264]: in healthcare, surgeons will safely and effectively perform remote surgeries; in education, students will engage with digital models physically and collaboratively; in automotive, distributed tactile warnings about hazards will improve driver alerts, reducing accidents; in rehabilitation, remote physical therapy with haptic guidance will accelerate recovery. Mark Zuckerberg (Meta, USA) has referred to this next phase of our online presence as the “embodied Internet” [265], enabling a perfect sense of presence in remote and virtual settings, i.e., where real and artificial environments become indistinguishable. The facility and comfort to use and wear cutaneous interfaces can become a clear advantage for their use in these contexts.

V. CHALLENGES AND PERSPECTIVES FOR THE FUTURE

Despite the promising results and applications, there are still many aspects of (cutaneous) haptic feedback for robotic teleoperation that need further research. An important one is the challenge of devising general and effective rendering techniques. Indeed, haptic feedback can convey a wide range of feedback information (e.g., contact sensations, active constraints, guidance) using different types of stimuli (e.g., kinesthetic, skin stretch, vibration, normal indentation, temperature). It is however challenging to understand *how* to best convey the necessary information through haptic feedback, i.e., defining the best haptic rendering approach for a given situation and task. Currently, empirical choices based on personal experience are the standard, leading to suboptimal policies and forcing engineers to devise ad-hoc rendering algorithms for each task. To overcome this limitation, we need to achieve a deeper understanding of our sense of touch as well as a better knowledge about how each haptic sensation is processed and interleaved with the other sensory feedback coming from the remote environment. Already in 1992, Thomas B. Sheridan asserted that a deeper understanding of the sense of presence and agency is paramount to develop better haptic-enabled teleoperation systems [1]. In this respect, recent advancements in Large Language Models (LLM), such as GPT (OpenAI, USA), can significantly facilitate the communication between human operators and teleoperated systems, even regarding the definition of the haptic feedback. For example, operators can describe target haptic sensations in natural language, especially where there is a virtual component in the interaction (e.g., “I want to interact with a leather cushion”), analyze haptic data to

identify the source of the interaction (e.g., the system verbally describes the environment to the user), or better understand the operator intent and suggest appropriate haptic responses in ambiguous situations (e.g., to devise shared control techniques).

Nowadays, another important barrier for the adoption of cutaneous haptic technologies is their added value in many applications, which is sometimes unclear to companies and developers. Such devices must bring a significant value to the user's life, justifying an investment in terms of money (i.e., to purchase the haptic system) and effort (e.g., to learn how to use it). A notable example has been the experience of Novint Technologies, which developed an inexpensive desktop haptic interface intended to replace the mouse in video games and other applications; for example, it was used in first-person-shooter games such as *Half-Life 2* and *Team Fortress 2* to provide the sensation of recoil after shooting – unfortunately, this device is not available anymore. In this respect, one of the mistakes might be trying to endow already-existing non-haptic applications with haptic capabilities. For example, the inexpensive grounded kinesthetic interface Novint Falcon was designed to provide the sensation of recoil after shooting in popular first-person-shooter games. However, applications that have originally been developed without haptics in mind feature interactions that are designed to work well without the haptic component, making its impact minor at best. Adding haptics to these applications might be seen innovative for those trying such a technology for the first time, eliciting the so-called “wow-effect”, but it might not always bring a long-term benefit. On the other hand, addressing tasks and scenarios that are only possible *because* of the haptics component, e.g., teleoperated fine manipulation, would show a clear and significant added value of haptic feedback. In this respect, a general framework (or a set of rules) to evaluate the benefits of these systems would be useful, e.g., in terms of performance with respect a given task, match between the forces exerted at both sides of the system (transparency), user's comfort and experience, effectiveness in providing haptic sensations. For example, Fazlollahi and Kuchenbecker [266] presented a benchmarking framework for grounded kinesthetic interfaces, assessing them in terms of workspace shape, global free-space forces and vibrations, local dynamic forces and torques, frictionless surface rendering, and stiffness rendering.

Another fascinating challenge is providing rich multisensory haptic stimulation. Indeed, due to design constraints, most haptic device are capable of only providing a (very) small subset of haptic sensations. This is also clear from our survey of the literature, where most systems focus on providing a single type of cutaneous feedback. However, throughout our life, we have always been used to experiencing a coherent and complete haptic representation of the environment, as we discussed in Sec. II-C. Failing to fulfill such a sensory expectation might result in a significant degradation of the experience and, thus, of its expected performance in the considered scenarios. Fortunately, we have seen how even an incomplete delivery of haptic information (e.g., one type of cutaneous feedback only) still significantly enhance the performance and feeling of presence in remote environments. Of course, the more coherent and complete sensations are available the better, taking also into account the importance of

cross-modal sensory coherence [267].

Adding haptic feedback in telerobotics also means effectively acquire force information at the remote side, which can sometimes be challenging [268]–[271]. For example, incorporating touch sensors into surgical instruments can be difficult due to strict operating room requirements regarding size, robustness, and sterilization [4], [64], [272]. The requirements of such sensors design vary based on parameters such as the desired number of measured degrees of freedom and sensor placement. For example, in minimally invasive procedures, the sensor is typically placed externally on the instrument, but this setup introduces additional forces and disturbances that can affect the measurement. Placing the sensor close to the interaction region (e.g., at the instrument tip) improves measurement accuracy but at the same time imposes design limitations due to insulation and size constraints. Sterilization is another critical concern in this context, with steam and chemical agents being common approaches. Sensors must indeed withstand heat, pressure, and humidity during sterilization. Equipment that cannot be sterilized needs to be disposable (and therefore less expensive). Similarly, whenever using untethered interfaces (e.g., haptic gloves), the reduced quality of the user's position wireless tracking can significantly affect the effectiveness and precision of the haptic feedback. Indeed, popular hand tracking cameras (e.g., the LeapMotion) are not made for tracking hands equipped with, e.g., wearable haptic interfaces, severely limiting the use of these technologies. These two points show how sensing techniques are of paramount importance for the effective application of haptic feedback systems.

Finally, research in haptics is highly interdisciplinary, requiring knowledge from various fields, including human perception, design of physical interfaces, automatic control, human-robot interaction. To reach a significant breakthrough in the implementation of haptic feedback in robotic teleoperation and other related fields, these disciplines must be contemplated from an integral perspective, leading to insights in each of the separate aspects and feedback between one another, taking advantage of opportunities for cross-field collaboration and interaction. The great results of cutaneous haptics are proof that, sometimes, less is really more and that, by better understanding the underlying mechanisms of our sensory system, we can achieve results that might seem counter-intuitive at first. Indeed, *just enough* haptics [273] might be the right answer to finally bring haptic technologies to the robotic teleoperation market and beyond.

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APPENDIX

Stimuli: N = normal indentation, S = lateral skin stretch and/or relative tangential motion, V = vibration, T = thermal, E = electrotactile
 Body parts: F = finger, H = whole hand, A = arm (including wrist), T = tongue

TABLE I: CUTANEOUS SYSTEMS FOR ROBOTIC TELEOPERATION PROVIDING NORMAL INDENTATION. WE REPORT THE TYPES OF CUTANEOUS STIMULI THEY CAN PROVIDE, THE TYPE OF END-EFFECTOR AND ACTUATION TECHNOLOGY THEY USE TO APPLY THESE STIMULI, AND THEIR FIELD OF APPLICATION.

	Work	Stimuli	Body area	End-effector	Main actuation technology	Application
Pin arrays	Howe et al. [121]	N	F	6×4 pin array, 2.1 mm spacing	Shape Memory Alloy (SMA)	palpation in MIS (artery and tumor localization)
	Fischer et al. [125]	N, V	F	64 pins	electromagnetic actuation	palpation
	Chang et al. [126], [127]	N	F, A	4×5 pin array	electromagnetic actuation	telemanipulation of dangerous materials via a humanoid robot
	Shen et al. [128]	N	F	6×4 pin array, 2.5 mm spacing	DC solenoids	telemanipulation of a multi-fingered hand
	Feller et al. [129]	N	F	6×6 pin array, 3 mm spacing	servo motors	palpation
	Sarakoglou et al. [118], [130], [131]	N, V	F	4×4 pin array, 2 mm spacing	servo motors	teleoperation of a 7-DoF KUKA LWR manipulator
	Hergenhan et al. [132]	N	F	7 pins in a circle, 2 mm spacing	servo motors	palpation
	Saudrais et al. [133]	N	F	8×8 pin arrays, 3 mm spacing	piezoelectric bimorphs	needle insertion in soft tissue
	Alagi et al. [134]	N	F	4×4 pin arrays, 2 mm spacing	servo motors	teleoperation of a UR10e robotic manipulator
Soft displays	Calden [135]	N	F	1 rubber air balloon per finger	stepper motors controlling pressure transducers	remote touch
	Cohn et al. [136]	N	F	5×5 array of pneumatic actuators	solenoid valves	remote touch
	Bicchi et al. [82]	N	F	ten cylinders of different radii in a telescopic arrangement	servo pneumatic actuators	palpation
	Kimura et al. [139]	N	F	silicone rubber sheet attached to an actuated plastic fork	DC motor with a rack-and-pinion mechanism	palpation
	King et al. [119], [140]–[145]	N	F	3×2 air balloon array, 1.5 mm spacing	electropneumatic pressure actuators	telemanipulation using a da Vinci Surgical System
	Fischel et al. [147]	N	F, H	130 pneumatic cutaneous actuators	N/A	teleoperation of two UR10 arms equipped with Shadow Hands and BioTacs
	Uddin et al. [149]	N	F	pneumatic cylinders	solenoid DC valves	teleoperation of a two-fingered robotic gripper
	Li et al. [148]	N	F	elliptical air chambers	programmable air compressor	teleoperation of a pneumatic anthropomorphic soft hand
	Park et al. [150]	N	F	balloon with MR fluid	programmable pressure valve	teleoperation of a robotic gripper
	Abd et al. [151]	N, V	A	band with five air chambers and five vibromotors	programmable air compressor	teleoperation of a Shadow Hand equipped with three BioTacs
	Ham et al. [152]	N	F	soft plate at the fingerpulp	ionic electro-mechanically active polymers (iEAP)	remote grasping

	Work	Stimuli	Body area	End-effector	Main actuation technology	Application
Rigid platforms	Pacchierotti et al. [153]	N	F	two 1-DoF rigid mobile platforms (one per finger)	servo motors	needle insertion with a KUKA KR3 robot
	Pacchierotti et al. [20]	N	F	two 3-DoF rigid mobile platforms (one per finger)	servo motors	peg-in-hole using a DLR-HIT Hand II on a KUKA KR3 robot
	Meli et al. [156]	N	F	three 3-DoF rigid mobile platforms (one per finger)	servo motors	peg-in-hole using a DLR-HIT Hand II on a KUKA KR3 robot
	Musić et al. [157]	N	F	three 3-DoF rigid mobile platforms (one per finger)	servo motors	teleoperation of two KUKA LWR manipulators for grasping and lifting
	Pacchierotti et al. [30]	N, V	F	one 3-DoF rigid mobile platform	servo motors	palpation using a da Vinci Surgical System equipped with a BioTac sensor
	Chinello et al. [155]	N	F	one 3-DoF rigid mobile platform	servo motors	palpation using a UR5 robotic manipulator
	Pacchierotti et al. [159]	N	F	one 3-DoF rigid mobile platform	servo motors	needle insertion with a KUKA KR3 robot
	Khurshid et al. [162], [163]	N, V	F	two 1-DoF rigid mobile platforms (one per finger)	voice-coils actuators	teleoperation of a PR2 robotic gripper for pick-and-place
	Palagi et al. [164]	N	F	two 1-DoF rigid mobile platforms (one per finger)	voice-coils actuators	teleoperation of a Prensilia MIA anthropomorphic hand for pick-and-place

TABLE II: CUTANEOUS SYSTEMS FOR ROBOTIC TELEOPERATION PROVIDING LATERAL SKIN STRETCH AND/OR RELATIVE TANGENTIAL MOTION. WE REPORT THE TYPES OF CUTANEOUS STIMULI THEY CAN PROVIDE, THE TYPE OF END-EFFECTOR AND ACTUATION TECHNOLOGY THEY USE TO APPLY THESE STIMULI, AND THEIR FIELD OF APPLICATION.

System	Stimuli	Body area	End-effector	Main actuation technology	Application
Roke et al. [166]	S, N	F	4×4 pin array on a 2-DoF plate that moves laterally	servo motors	palpation using a 7-DoF Whole Arm Manipulator with iCub and TACTIP sensors
Schorr et al. [165], [167]	S	F	stylus with two rounded 7-mm tactors	DC motors	palpation using a Phantom Premium 1.5 interface
Quek et al. [168]	S, N	F	stylus with four rounded 7-mm tactors	DC motors	telemanipulation using a da Vinci Surgical System for peg transfer and tube connection
Zhu et al. [169]	S, N	F	two tactors per finger	DC motors	telemanipulation using a Panda robot for in-hand pivoting
Lim et al. [170]	S, N	F	two displays each with five balloons	N/A	teleoperation of a 6-DoF robot for pulling in MIS
Casini et al. [171], [173]	S, N	A	band made of soft elastic fabric	DC motors	teleoperation of a KUKA LWR robot with a SoftHand for grasping and drilling
Clark et al. [174]	S, N	A	band made of soft elastic fabric	DC motors	teleoperation of two KUKA LWR robots for pick-and-place
Meli et al. [175]	S, N	A	two bands made of soft elastic fabric	servo motors and a linear actuator	teleoperation of a Sawyer manipulator for grasping
Han et al. [176]	S	F	two 10-mm-wide tactors	electroactive polymer films	MR-guided needle procedures

TABLE III: CUTANEOUS SYSTEMS FOR ROBOTIC TELEOPERATION PROVIDING VIBRATION FEEDBACK. WE REPORT THE TYPES OF CUTANEOUS STIMULI THEY CAN PROVIDE, THE TYPE OF END-EFFECTOR AND ACTUATION TECHNOLOGY THEY USE TO APPLY THESE STIMULI, AND THEIR FIELD OF APPLICATION.

System	Stimuli	Body area	End-effector	Main actuation technology	Application
Hill and Bliss [179], [180]	V	F	4×12 pin array, 0.25 cm spacing	piezoelectric transducers	teleoperation of a Rancho Arm
Massimino et al. [181], [182]	V	F, H, A	vibrating tactors	voice coils	teleoperation of a E2 manipulator equipped with FSR sensors
Kontarinis and Howe [183], [184]	V	F	two thimbles (one per finger)	voice coils	teleoperation of two-fingered hands with 2 DoF in each finger
Dennerlein et al. [185], [186]	V	F	13-mm-long strip of spring steel	voice coils	teleoperation of deep sea manipulator Schilling TITAN-II
Tokashiki et al. [187], [188]	V	F	one thimble	DC buzzer	teleoperated micrograsping
Sano et al. [189]	V	F	two aluminum plates (one per finger)	ultrasonic vibrators	teleoperated pick-and-place
Aleotti et al. [191], [192]	V	F	five cylindrical motor casings (one per finger)	ERMs	teleoperation of a PUMA 560 robot for peg-in-hole and stacking
Lathan and Tracey [193]	V	A	five cylindrical motor casings in a bracelet	ERMs	teleoperation of a Pioneer 2-DX mobile robot
Bimbo et al. [177]	V	A	four cylindrical motor casings in two bracelets	ERMs	teleoperation of a SoftHand attached to a UR5 6-DoF robotic arm
Aggravi et al. [199]	V	A	four cylindrical motor casings in one bracelet	ERMs	teleoperation of a flexible needle attached to a 6-DoF robotic arm
Murray et al. [200]	V	F	five coin-like motor casings (one per finger)	voice coils	teleoperation of a 4-fingers robot hand on a Puma 560 for sorting
Dascalu et al. [201]	V	F, H	twenty distributed vibromotors (fingers and palm)	ERM	teleoperation of a 5-fingers robot hand on a robotic arm
Sartori et al. [202]	V	F	six distributed vibromotors (two per finger, three fingers)	ERM	teleoperation of a 3-fingers robot hand
Martinez et al. [178], [206]	V	F, H	six vibromotors per hand (fingers and palm, two hands)	ERM	teleoperation of an iCub humanoid or a Pioneer LX mobile robot
Xu et al. [203]	V	F	two vibromotors	ERM	teleoperation of a 2-fingers gripper during pick-and-place
Zhu et al. [204]	V	F, H	six vibromotors (fingers and palm, CyberTouch)	N/A	teleoperation of an anthropomorphic robotic hand
Park et al. [205]	V, K	F	three vibromotors (one per finger)	ERM	teleoperation of an arm of a humanoid robot
Kuchenbecker and Niemeyer [207]	V	F	stylus of a Phantom interface	DC motors driven by a high-frequency linear amplifier	remote touch of different materials using a Phantom interface
Hulin et al. [208]	V, N	F	three actuated wires wrapped around each fingertip (three fingers)	shape memory alloys	teleoperation of a DLR-HIT Hand II on a DLR LWR III robot
Hayashi and Tamura [209]	V	F	joystick of the excavator control console	N/A	teleoperation of a hydraulic excavator in pointing tasks
Nagano et al. [210]	V	A	bracelet	voice coil	teleoperation of a robotic shovel and a dual-arms construction robot
Mochiyama et al. [211]	V	F	joystick of the micro-macro system console	voice coil	teleoperation of two micro-manipulators MMO-202ND for drawing

Pacchierotti et al. [212], [213]	V	F	stylus of a Omega.6 interface	DC motors	teleoperation of self-propelled magnetic microjets or microgrippers
Okamoto et al. [214]–[216]	V	F	cylindric vibrator or 0.5-mm thick acrylic plate	piezoelectric stack actuator or voice coil	remote touch for texture rendering with communication delays
McMahan et al. [32], [221], [222]	V	F	standard surgeon console of da Vinci Surgical System	voice coils	telematipulation using a da Vinci Surgical System for drylab tasks and procedures on a porcine model
Thiem et al. [223]	V	H	hand-held cylinder with embedded springs	voice coil	teleoperation of a custom single-port MIs surgical system
Massari et al. [224], [225]	V	F	glove with one vibrator at the fingertip	piezoelectric actuators	remote palpation for telemedicine
Yamamoto et al. [228]–[230]	V	F	stator plate with 50 parallel electrodes and a slider film	voltage waveform generator	remote touch through a linear stage for texture identification
Takasaki et al. [227]	V	F	surface acoustic wave tactile display	voltage waveform generator	remote touch through 3d a tactile scanner for texture identification
Liu et al [232]	V	H	mid-air interaction through a 16×16 ultrasound array	40 kHz ultrasound transducers	teleoperation of a RobotAnno manipulator equipped with a soft pneumatic hand

TABLE IV: CUTANEOUS SYSTEMS FOR ROBOTIC TELEOPERATION PROVIDING THERMAL FEEDBACK. WE REPORT THE TYPES OF CUTANEOUS STIMULI THEY CAN PROVIDE, THE TYPE OF END-EFFECTOR AND ACTUATION TECHNOLOGY THEY USE TO APPLY THESE STIMULI, AND THEIR FIELD OF APPLICATION.

System	Stimuli	Body area	End-effector	Main actuation technology	Application
Caldwell and Gosney [233]–[237]	T, V, N	F	one thermal and one pressure/vibration module embedded in a glove	Peltier element and piezoelectric actuator	remote touch through a PUMA 560 manipulator and a two-armed mobile robot
Kron and Schmidt [238]	T, V	F	five thermal and vibration modules in a CyberGlove (one per finger)	Peltier elements and DC motors	remote touch
Drif et al. [239]	T	F	rectangular contact pad	Peltier elements	remote touch
Lee et al. [240]	T	H	silicone glove with four thermal patches	flexible thermoelectric elements	telematipulation with a Kinova JACO

TABLE V: CUTANEOUS SYSTEMS FOR ROBOTIC TELEOPERATION PROVIDING ELECTROTACTILE FEEDBACK. WE REPORT THE TYPES OF CUTANEOUS STIMULI THEY CAN PROVIDE, THE TYPE OF END-EFFECTOR AND ACTUATION TECHNOLOGY THEY USE TO APPLY THESE STIMULI, AND THEIR FIELD OF APPLICATION.

System	Stimuli	Body area	End-effector	Main actuation technology	Application
Shen et al. [128], [244]	E	F	five soft copper electrodes (one per finger) integrated in a CyberGlove	electrotactile pulse generator	teleoperation of a five-finger Yaskawa robotic hand
Droessler et al. [245]	E	T	12×12 electrodes array	electrotactile pulse generator	remote touch through a Robix RCS-6 robot for shape identification
Sato et al. [246]–[249]	E	F	four electrotactile units (one per finger), each a 5×3 electrode array with 2.5 mm spacing	electrotactile pulse generator	teleoperation of an anthropomorphic robotic hand for remote grasping
Pamungkas and Ward [250]–[253]	E	F	five electrodes (one per finger) in a P5 data glove	electrotactile pulse generator	teleoperation of mobile robot and a robotic manipulator
Trinitatova et al. [254]	E	F	two 4×5 electrodes arrays (one per finger) in a Omega.7 interface	electrotactile pulse generator	teleoperated pipetting