Wearable Haptic Systems for the Fingertip and the Hand: Taxonomy, Review, and Perspectives

Claudio Pacchierotti, *Member, IEEE*, Stephen Sinclair, *Member, IEEE*, Massimiliano Solazzi, *Member, IEEE*, Antonio Frisoli, *Member, IEEE*, Vincent Hayward, *Fellow, IEEE*, and Domenico Prattichizzo, *Fellow, IEEE*

Abstract—In the last decade, we have witnessed a drastic change in the form factor of audio and vision technologies, from heavy and grounded machines to lightweight devices that naturally fit our bodies. However, only recently, haptic systems have started to be designed with wearability in mind. The wearability of haptic systems enables novel forms of communication, cooperation, and integration between humans and machines. Wearable haptic interfaces are capable of communicating with the human wearers during their interaction with the environment they share, in a natural and yet private way. This paper presents a taxonomy and review of wearable haptic systems for the fingertip and the hand, focusing on those systems directly addressing wearability challenges. The paper also discusses the main technological and design challenges for the development of wearable haptic interfaces, and it reports on the future perspectives of the field. Finally, the paper includes two tables summarizing the characteristics and features of the most representative wearable haptic systems for the fingertip and the hand.

Index Terms—Wearable haptics, fingertip haptics, hand exoskeletons, wearable devices, wearable interfaces, cutaneous force feedback, tactile force feedback, taxonomy, review

1 Introduction

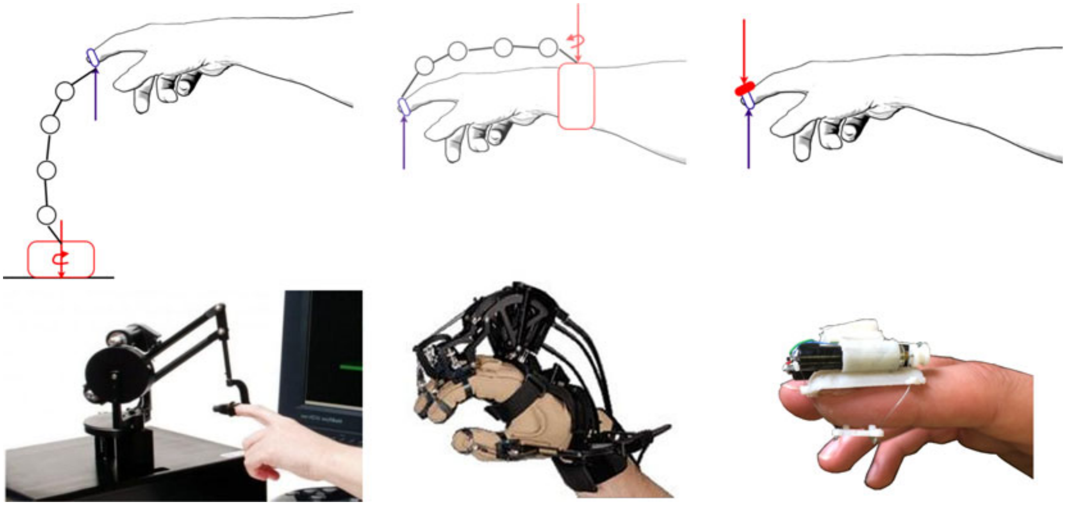
TECHNOLOGY for touching remote objects has typically been used in teleoperation. A robot is controlled as a slave in the remote scenario and a haptic interface feeds back the registered contact forces at the master side, enabling the user to perceive the remote environment. Current technology for teleoperation is very advanced [1], [2], [3], but it is usually neither wearable nor portable, significantly affecting the growth of this field. Despite the fact that haptic interfaces are now widely used in laboratories and research centers, their use still remains highly underexploited. One of the main reasons is that, traditionally, they have been mechanically grounded, and portable uses of haptics have been limited to notification using simple eccentric motors in telephones and pagers. Only recently, more sophisticated haptic systems have started to be designed with *wearability* in mind.

- *C. Pacchierotti is with the CNRS at Irisa and Inria Rennes Bretagne Atlantique, Rennes 35042, France. E-mail: claudio.pacchierotti@irisa.fr.*
- *S. Sinclair is with Inria Chile, Santiago 7630412, Chile. E-mail: stephen.sinclair@inria.cl.*
- *M. Solazzi and A. Frisoli are with the PERCRO Laboratory, TeCIP Institute, Scuola Superiore Sant'Anna, Pisa 56124, Italy. E-mail: {m.solazzi, a.frisoli}@sssup.it.*
- *V. Hayward is with the Institut des Systèmes Intelligents et de Robotique, UPMC University Paris 06, Paris 75005, France. E-mail: hayward@isir.upmc.fr.*
- *D. Prattichizzo is with the Department of Information Engineering and Mathematics, University of Siena, Siena 53100, Italy, and the Department of Advanced Robotics, Istituto Italiano di Tecnologia, Genova 16163, Italy. E-mail: prattichizzo@dii.unisi.it.*

Manuscript received 20 Nov. 2016; revised 17 Mar. 2017; accepted 25 Mar. 2017. Date of publication 0 . 0000; date of current version 0 . 0000.
(Corresponding author: Claudio Pacchierotti.)
Recommended for acceptance by V. Patoglu.
For information on obtaining reprints of this article, please send e-mail to: reprints@ieee.org, and reference the Digital Object Identifier below.
Digital Object Identifier no. 10.1109/TOH.2017.2689006

To this end, a variety of new devices, the so-called "wearables," have been developed specifically for this purpose. Notable commercial examples of wearables are the Google Moto 360, the Asus ZenWatch, the Samsung Gear Live, and the Apple Watch. They are easy and comfortable to wear, they often feature a touch screen, and they have functions similar to smartphones. Google and Apple even developed dedicated operating systems, which provide functions and applications customized for their wearable devices. This market stems from the need for wearability, which is a key element for a natural interaction with today's technology [4], [5]. Wearability of robotic devices is envisioned to enable novel forms of communication, cooperation, and integration between humans and robots. Specifically, wearable haptics will enable devices to communicate with the human wearer during his or her natural interaction with the environment they share. For example, the Apple Watch features a linear actuator able to make the watch vibrate. The actuator can provide different amounts and patterns of vibration for different events, e.g., during navigation using the Maps app, different vibrations are used to indicate whether the wearer needs to take a left or a right turn. Apple calls this technology "taptics", which is a portmanteau of tactile and haptics. There are even applications specifically designed to exploit the haptic capabilities of the wearables. For example, in Android systems, the "Feel The Wear" app enables the user to create custom vibration patterns by simply tapping the screen; and in iOS systems, the "Touch Room" app enables users that are far away to feel each other's touch through the screen of the device.

Nonetheless, the haptic stimuli provided by these wearables are still limited to vibrations, reducing the possibility of simulating rich contact interactions. Toward a more realistic feeling of touching virtual and remote environments, researchers have historically focused on grounded haptic



(a) Grounded haptics (e.g., Phantom Premium)

(b) Exoskeletons (e.g., CyberGrasp)

(c) Fingertip devices (e.g., 3-DoF cable-driven device [5])

Fig. 1. From grounded haptics to more wearable and portable designs. (a) A Phantom Premium, (b) a CyberGrasp, and (c) a fingertip device [5]. As we move from (a) to (c), the wearability of the system is improved at the cost of losing part of the kinesthetic component of the interaction.

interfaces, such as the Sigma or Phantom devices, and glove-type haptic displays, such as the CyberGrasp or the Rutgers Master. Although these devices provide compelling force sensations, they are nonetheless quite complex and too expensive in consumer terms. For example, the Sigma.7 haptic interface (Force Dimension, CH) and the CyberGrasp (CyberGlove Systems LLC, USA) sell for around 70,000 USD. For this reason, it is important to find a trade-off between providing a realistic feeling of touch and the cost, wearability, and portability of the system.

2 Wearable Haptics and the Role of Cutaneous Stimuli

In the previous section, we called the Apple Watch a wearable technology, while we referred to a Phantom device as a non-wearable device. However, the definition of what is wearable and what is not is not always so intuitive and straightforward. The Cambridge University Press dictionary defines a wearable object as something which is simply *"suitable for wear or able to be worn."* According to this definition, it seems correct to consider the Apple Watch to be wearable, since it can be easily worn as a normal wristwatch. On the other hand, a tablet PC cannot be considered a wearable object. In the case of audio technologies, modern media players (e.g., the Apple's iPod) can be considered portable objects, but only wireless headphone sets seem to also fit in the wearable objects category.

What about haptic technologies?

As already mentioned before, most haptic devices now available on the market cannot be considered wearable. Consider, for example, the Omega 3 haptic interface by Force Dimension (7 kg of weight for dimensions $27 \times 39 \times 35$ cm), or to the Phantom Premium 1.5 by Geomagic (9 kg of weight for dimensions $25 \times 33 \times 36$ cm, shown in Fig. 1a). These types of haptic devices are very accurate and able to provide a wide range of forces. They are commonly referred to as *grounded* interfaces, since their base is fixed to the ground. The pursuit of more wearable haptic technologies lead researchers to the development and design of *exoskeletons*, a type of haptic interface which is grounded to the body [6], [7]. The robotic system is *worn* by the human operator, who feels both the contact force simulating the interaction and the undesired reaction force, which counterbalances the first one (see Fig. 1b). In grounded haptic interfaces this undesired reaction force is counterbalanced by the ground and not felt by the user, thus increasing the illusion of telepresence provided by these devices [5], [8] (see Fig. 1a). An example of commercially-available hand exoskeleton is the CyberGrasp, shown in Fig. 1b.

Although exoskeletons can be considered wearable haptic systems, they are often quite heavy and cumbersome, reducing their applicability and effectiveness. For this reason, we seek to *extend* the definition of "wearable interface" beyond something that is merely suitable to be worn. A wearable haptic interface should also be small, easy to carry, comfortable, and it should not impair the motion of the wearer. In this respect, we embrace the idea of service technology that Parviz, Lee, and Thrun shared while presenting Google Glass: "We think technology should work for you— to be there when you need it and get out of your way when you don't" [9]. Following this line of thought, the *level of wearability* of haptic interfaces can be defined by their form factor, weight, shape, area of interest, and ergonomics. For example, we consider the fingertip haptic device shown in Fig. 1c more wearable than the hand exoskeleton shown in Fig. 1b, which we consider in turn more wearable than full-body exoskeletons such as the Raytheon Sarcos's XOS 2 robotic suit or the ActiveLink's Dual Arm Power Amplification Robot. It is also important to highlight that the level of wearability of a device is only related to its design features, and it does not depend on its performance or actuation capabilities. Section 4 will discuss more in detail the factors that, in our opinion, mostly affect the wearability of haptic interfaces.

A promising approach to increase the wearability of such devices consists of moving the grounding of the system (in red in Fig. 1) closer to the point of application of the stimulus (depicted in blue in Fig. 1). However, as this happens, the kinesthetic component of the interaction is progressively lost, leaving intact only the cutaneous part of the interaction [8], [10], [11]. At the extreme of this process, when the base of the interface is placed at the point of application of the stimulus, the haptic interface is only capable of providing cutaneous cues. This is the case of the fingertip device shown in Fig. 1c. Cutaneous feedback provides indeed an effective and elegant way to simplify the design of wearable haptic interfaces: the high density of mechanoreceptors in the skin and their low activation thresholds [12], [13] allow researchers to develop effective cutaneous-only displays that are compact, comfortable, and inexpensive [5], [14], [15] (as the one in Fig. 1c). Cutaneous feedback has been also proven to play a key role in enhancing the performance and effectiveness of teleoperation and immersive systems [15], [16], [17], [18], [19], [20], [21]. Cutaneous cues have even been found to be more informative than kinesthetic cues in discrimination of surface curvature [22] and fine manipulation [23].

3 Classification and Taxonomy of Wearable Haptic Interfaces

This section categorizes wearable haptic systems according to the type of tactile stimuli they provide to the wearer, the area where they apply these stimuli, the technologies they employ to apply and sense haptic cues, and their level of wearability. This characterization will be used in Section 5 to classify the systems included in our review and in Tables 2 and 3 to summarize their features and performance.

We have restricted our selection to devices that provides mechanical stimulation, taking advantage of cutaneous phenomena. Thus, we have excluded devices based on non-mechanical principles (e.g., electro-stimulation). We have also excluded a discussion of sensing and rendering techniques, both important components of the haptic servo. In this respect, we note briefly that many devices may include built-in sensors, such as inertial or force sensors (e.g., FSRs or fingernail sensors), while others may depend on external position sensing, which is often accomplished via marker-based or markerless methods using infrared or visible light (RGB) cameras. We do not go into detail on these here, as a full treatment would require a dedicated survey, and exact requirements are often device- and application-specific.

3.1 Type of Tactile Interaction

As mentioned in the previous section, due to the necessity of relocating actuators toward the effector positions, wearability often restricts haptic interfaces to cutaneous feedback, i.e., grounded on the body itself, close to the point of contact. It follows that we should design interfaces to fully exploit somatosensory cues possible to activate through cutaneous-only stimulation. Fortunately, from the somatosensory literature, we can identify several categories of feedback that are possible without resorting to grounded, kinesthetic cues.

3.1.1 Contact and Pressure Display

Although contact/non-contact and pressure display against the finger pulp can be considered as a "simple" form of feedback, requiring only for example a solenoid actuator to press a plate against the fingertip, contact between the finger pad and a surface represents complex biomechanics worth some consideration.

The finger pad is an inhomogeneous material whose compression can be likened to a non-linear spring which stiffens with displacement, reaching its maximum compression at small loads. The quick increase in contact area leads to a recruitment of mechanoreceptors correlated with contact force, which partly explains high sensitivity for small forces [24]. Apart from statics, deformation dynamics should also be considered, as the normal loading changes significantly with speed of impact [25]; such facts may affect sensation of pressure, stiffness and other material properties to be displayed.

3.1.2 Curvature Display

When feeling a surface with a radius of curvature larger than the finger, the position of the finger follows a 2-dimensional trajectory (proprioceptive cue), and the angle of the surface normal changes relative to the finger (cutaneous cue). It has been shown that this cutaneous cue dominates in haptic perception of large-radius curvature [26]—that is to say, when scanning a surface horizontally, subjects could identify differences in virtual surface curvature comparably well to the real surface when orientation was displayed via surface normal rotation, but performed poorly when only height information was provided. Such large-radius curvature cues based on surface orientation could be mounted in a wearable fashion similar to contact cues discussed above, with a platform controllable in orientation.

3.1.3 Vibrations, Textures, and Materials

In many portable devices, haptic vibrations are used in open loop as icons for notification or to indicate device state. However, vibrations with frequency scaled according to scanning velocity are produced when a finger runs along a surface, and thus form strong perceptual cues for recognizing and differentiating materials and textures. Correlation with exploration conditions is important, as indicated by our difficulty in recognizing similar textures at different velocities under a passive condition [27]. Roughness, but also dryness, and material friction properties may be indicated by correlation with the finger and material states, and the non-linearities thus involved [28]. Additionally, it should be noted that vibration information is present not only at the cutaneous site of interaction, but is in fact available at least up to the forearm [29], [30]. Non-local stimulation may thus be an option, as long as real-time correlates are well maintained. Finally, it has been shown that with clever signal design, it is even possible to produce an illusion of attraction forces at the fingertips using only vibration cues [31].

3.1.4 Softness/Hardness

When we judge the compliance of an object by probing with a finger, one intuitive explanation is that we estimate the penetration distance of the finger into the object. However, studies show that we are able to distinguish objects of varying compliance using only cutaneous information [32]; an explanation is that contact area pressure distribution, and therefore skin deformation, are correlated with normal force as a compliant object deforms around the finger probing it. Nonetheless, the exact shape of the pressure distribution is unimportant, compared with simply the total area of contact [33].

3.1.5 Caress

As an alternative to highly precise cutaneous stimulation on the glaborous skin, for wearable applications it is important to consider the possibilities of the substantial hairy skin. One way is by exploiting the unmyelinated fibers, which are pervasive in hairy skin. These have been shown to respond to "soft" and light touch [34], are slowly conducting compared to myelinated fibers, and have only very limited somatotopic organization [35], suggesting that stimulation location is less important than for myelinated fibers. However, velocity of caress or stroke does play a role in apparent pleasantness of the stimulation; for low velocities, no difference between sites featuring both myelinated and unmyelinated fibers were found, but for faster velocities, pleasantness was greater in the palm area [36]. Slow and light touch is therefore recommended if pleasant stimulation of the hairy skin is the goal.

3.1.6 Friction Display

In manipulation tasks using force feedback devices, it is typical to render friction using forces on the operator's grasping hand at the end effector. However, it has been shown that adding a small amount of skin stretch at the finger pad, even 0.25 mm, can enhance the perception of friction [37] in such applications. We note however that fingerpad friction is a complex phenomenon; it can be approximated in a dry state as an elastic polymer, but becomes highly plastic and dissipative under wet conditions due to even small amounts of sweat, increasing area of contact and modifying the mechanics of the ridges [38]. This leads to an increase in the friction coefficient; conversely, excess wetness will reduce it. The friction coefficient also varies greatly with sliding velocity, as does stick-slip behaviour [39]. The ridged areas are also highly anisotronic in their mechanics [40]. Such behaviour should be considered not only in modeling realistic friction conditions, but also in rendering them using an effector.

3.1.7 Indentation

Small indentations in the skin create lateral forces as well as normal forces. A simple demonstration can show that the lateral component of the forces is sufficient to give a percept of a bump: applying the index finger along the teeth of a comb and brushing them with a hard object gives a clear impression of a moving indentation under the finger [41]. This effect has been reproduced using a desktop lateral pin display. The same apparatus has been used to additionally show that such strain patterns reliably stimulate correlated neural patterns [42]. Therefore lateral pin displays, if made wearable, may be a good candidate for precise display of small indentation stimuli, interesting for example in Braille applications, among other categories.

3.1.8 Push-Button

Related to softness cues already discussed, the contact area of a probing gesture implicitly defines a finger displacement–contact area relationship. In the softness cue interpretation, it was proposed to modulate the contact area relationship to present sensations of different hardnesses. However, a dual view is that the deformation represents a relationship between contact area and finger displacement. If the contact area relationship is modified, an erroneous estimation of finger displacement may be induced [43]. Modulating such relations in real time can create push-button or illusionary movement percepts that could be exploited.

3.1.9 Proprioception

The above push-button effect is one example of a proprioceptive illusion induced by skin stretch. In fact, there is evidence to suggest that skin has an important role in proprioception, including the stretch associated with the hairy skin at the joints during flexion. It has been shown that participants with anaesthetized forefingers could nonetheless detect finger position associated with skin stretch at the edges of the anaesthetized regions [44]. Thus, manipulating skin laterally around joints may be a useful way to induce position or motion illusions.

Another proprioceptive effect that has been known since at least the 1970's is induction of angular estimation errors by means of vibration at the tendons [45], however large amplitudes are required, limiting exploitability for smooth user experiences. It is also possible that certain proprioceptive and kinesthetic effects are achievable by correlating vibration with limb movement [46].

3.1.10 Surface Geometry

A final example of the importance of lateral forces is that we use them during active exploration for determining surface geometry, that is to say, the existence of large-scale (size of a finger) bumps and dents in a surface. Indeed, it has been shown that it is possible to overcome shape cues of a real surface by modifying the associated lateral-only forces during interaction [47]. Therefore inducing friction-related strain patterns correlated with position can lead to the perception of bumps or divets. This differs from the display of large-radius curvature, Section 3.1.2, in that there is no need for an orientable platform.

The above perceptual cues represent exploitable illusions achievable through cutaneous stimulation. The apparatus in many cases that was used to demonstrate them is too bulky for wearable applications, requiring grounded or desktop devices. However, overcoming these constraints and discovering new methods to generate comparable stimuli using wearable hardware is considered as a design challenge for wearable haptics—to bring the plethora of options for cutaneous interaction from the lab to the portable, wearable world.

3.2 Mechanical Properties

One approach to characterize haptic devices is to group them according to their mechanical properties. Considerations on how these properties affect the wearability of these systems are reported in Section 4. Although the following mechanical characterization is necessary, it is probably not sufficient to guide the development of wearable haptic interfaces. For example, a device might perform extremely well at displaying large-radius surface curvature, but if this parameter is not relevant to the considered task, it may actually perform worse than others in experimental conditions. Measures of the *perceptual* importance of force and position stimuli at the contact point(s) during different tasks are required to ascertain what stimuli are worth providing to the human user [6].

3.2.1 Degrees of Freedom

A prominent feature of a haptic device is the number and the nature of the degrees of freedom at the end-effector. In general, a device is underactuated in rendering forces when it provides less than 3-dimensional force feedback and it is underactuated in rendering torques when it provides less than 3-dimensional torque feedback. A fully actuated haptic device would therefore be able to render 3-degrees-of-freedom (3-DoF) forces and torques at each contact point. However, underactuation is one of the major tools to reduce the form factor and complexity of haptic interfaces. For this reason, it is important to study and understand which force/torque information is more important for the considered task. In addition to active degrees of freedom, passive DoF are important for tracking and comfort purposes, especially in body-grounded exoskeletons. Wearable interfaces should in fact limit the motion of its wearer as little as possible (see also Section 2).

3.2.2 Workspace

In the case of wearable low-DoF devices, we can describe the operating volume inside which all other measures are taken as simple geometrical shapes, parallelepideds, spheres, encompassing the reachable locations of the end-effector [48], [49]. Since a wearable haptic interface often has a specific shape defining a preferred axis of operation, Hayward and Astley [48] propose to specify the motion range with three orientations, which are a combination of a solid angle, angle inside which the preferred axis may reach, with an angle specifying the amount of rotation around the preferred axis. Once the nature of the solid angle is defined, the orientation motion range can be expressed in steradians.

3.2.3 Peak Force

Hayward and Astley [48] propose three specifications for peak force: long term, short transient, and persistent transient peak force. The long term peak force is defined as the peak force achieved at the thermal equilibrium of the system, i.e., when the heat created by the actuation system matches the heat dissipated by the dissipation system (actively or passively). The short transient peak force is defined as a 10 ms square pulse, and a persistent transient is defined as a square signal of 1 s duration.

3.2.4 Inertia and Friction

Inertia specifications are very important in the characterization of haptic interfaces. Inertia is even more important when considering wearable interfaces, which may be worn during daily activities and should therefore impair the motion of its wearer as little as possible (see Section 2). For this reason, inertia can be defined in terms of *perceived* mass at the device end-effector over the various areas of contact and regions of the workspace [48], [50]. Reduction of the inertia can be achieved by mechanical design [51], [52], [53] or, at least for grounded devices, by control [54], [55].

3.2.5 Precision and Resolution

The precision of a haptic interface can be defined as the difference between the target coordinate and the center of the distribution curve of the actual coordinates of the end-effector over multiple trials. It describes the reproducibility of the commanded action. Precision can be evaluated in rendering both forces and positions. The resolution of a haptic interface can be expressed in two ways: (1) as the ratio between the maximum signal measured to the smallest part that can be resolved, or (2) as the degree to which the smallest deviation from the system equilibrium can be detected. Again, this can be evaluated both for forces and positions. While resolution is a critical feature for a haptic interface, precision seems to matter less [48].

3.2.6 Bandwidth

Bandwidth can be described as the rate at which a system is able to successfully track a given reference. For (wearable) haptic devices, however, it is still not clear which quantities are more important. In some cases, the force applied on the skin seems to be the most relevant quantity, in others the skin indentation. Hayward and Astley [48] proposed to specify the load as a piece of defined material, crafted to resemble a fleshy tissue. The frequency response and the bandwidth can be then measured with the interface loaded by the sample at multiple levels of force.

3.3 Area of Interest

The term "wearable haptics" concedes application of sensing and actuation to many areas of the body. While finger- and hand-related haptics, the focus of the majority of this article, naturally leads to ideas regarding interactivity for grasping and manipulation tasks, wearability indeed can lend itself to feedback applied to a variety of interface locations on the whole surface of the skin—anywhere, in fact, that clothing can be worn. Therefore, in this section we briefly cover areas of interest beyond only the fingers and hands.

Of course, the nature of haptic feedback necessitates tight fitting clothing using flexible and elastic materials, or adjustable straps, so as to allow for maximum force transmission to the skin. For example, a sports strap such as a velcro arm-band can turn a mobile phone or portable music player into a worn device. A wearable haptic device needs in fact to be expressly designed to take advantage of feedback applied to a certain area of the body. For instance, in the case of exoskeletons, force feedback may be applied to articulated joints, by means of motors or locking mechanisms. However, similar cues may usefully be applied to the backs of finger joints, the wrist, or the elbow, by applying lateral skin stretch, inducing a proprioceptive effect [44], e.g., a sense of movement or resistance to motion [56], [57]—without actually causing obstruction, see Section 3.1.9. Depending on the application this may provide a more convenient and sufficient cue for user interaction scenarios.

Vibration applied at or near the joints, in correlation with motion, may additionally provide sensation of angle change [58] or viscoelastic material effects (e.g., stick-slip joint friction) [59]. This can be done not only at the fingers, but at the elbows and knees as well [60].

Apart from the joints, skeletal links (arms, legs) provide a good-sized surface for squeeze [61], twist [62], and caress [63] cues, see Section 3.1.5.

The back also provides a large surface that has been exploited in the past in chair designs [64], but has also been embedded in wearable systems as far back as 1998 [65]. Back cues combined with squeezing effects have been embedded in jacket and suit designs in order to provide hugging feedback via vibration [66] or pneumatic force [67]. The jacket provides a convenient form factor for thermal and vibration cues covering the torso and neck, which has been used for affective feedback [68]. Full-body suits (legs, torso, arms) have also been explored for haptic stimulation in relation to musical applications [69], [70].

The neck provides a convenient stimulation location, particularly for headband/headphone [71] and helmet form factors.

Finally, one finds a plethora of belt designs in the haptics literature, for informing users of distance cues [72], [73], non-verbal social cues [72], directional/navigational cues [73], [74]. A belt design can also incorporate a squeeze effect, similar to the jacket designs intended for hugging feedback [75].

We note here that the majority of devices applied to the back, torso, neck, and waist strictly makes use of open-loop vibrational cues, with the exception of squeeze for hugging devices. There appears therefore to be plenty of low-hanging fruit for designs that take advantage of other haptic modalities, such as skin stretch, and also for designs that incorporate action-perception feedback more significantly.

4 Design Guidelines for Wearability

From the previous sections, we begin to see some characteristics of devices that may be considered wearable and how to categorize them according to their mechanical features, area of interest, and sensing/actuation capabilities. We will now discuss in detail which aspects make these haptic devices more or less wearable, with the objective of defining target requirements and guidelines for the design of wearable interfaces (see Table 1). In our opinion, the wearability of haptic systems can be defined as a combination of the following factors.

4.1 Form Factor

When we judge the wearability of a system, an important aspect is its form factor. Intuitively, small and compact devices are more wearable than big and large devices. However, the absolute form factor of a wearable system may be misleading—rather, it needs to be compared to the part of the body to which it is attached; i.e., a device that is considered unobtrusive if worn on the forearm may become cumbersome if worn on the fingertip. Moreover, it is also important to take into account how the device is shaped and fits the body. Smooth designs that follow the natural shape of the body rather than protrude and get in the way of natural movement should be preferred.

In this respect, choice of actuators is critical, since they are usually the bulkiest (and heaviest) components. This is particularly challenging for finger- and hand-mounted devices, since the amount of force that fingers can exert with respect to their dimension is higher than any other limb. On the other hand, wearable fingertip devices for providing normal indentation, lateral skin stretch, and relative tangential motion stimuli have different requirements of transparency as compared to haptic interfaces for providing kinesthetic feedback: kinesthetic devices have to be highly backdrivable to allow free active motion of the user, while fingertip devices, regardless of the actuation system, do not obstruct the movement of the finger, since they act only on the fingerpad. For this reason, small servomotors coupled with high-ratio reduction systems can be suitable for fingertip devices. In different applications, for providing vibrotactile feedback, researchers can employ eccentric, resonant mass, voice coil, or solenoid actuators. Eccentric and resonant mass actuators are usually simpler, but they often suffer from slow spin-up time, and they cannot separately control frequency and amplitude of the vibration (eccentric mass) or change the frequency of the vibration at all (resonant mass). Voice coils and solenoids represent a more versatile solution, since they can reproduce any vibration profile within their dynamical limits. Moreover, they have the advantage of being capable of applying a constant force.

4.2 Weight

Intuitively, lightweight devices are more wearable than heavy devices. However, the absolute weight of a system may again be misleading. Rather, it needs to be compared to the strength of the musculo-skeletal support of the part of the body on which it is worn. A device that is considered lightweight if worn on the leg may become too heavy to carry if worn on the wrist.

TABLE 1
Target Objectives for the Design of Wearable Interfaces

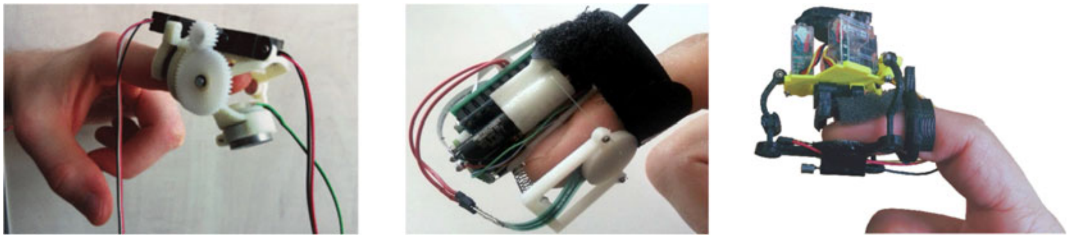
Form factor	Wearable devices should alter the body size of the wearer as little as possible.
Weight	Wearable devices should tire the wearer as little as possible.
Impairment	Wearable devices should limit the motion of its wearer as little as possible.
Comfort	Wearable devices should be comfortable to wear and easy to adapt to the wearer limb size and shape.

4.3 Impairment

Zatsiorsky and Prilutsky [76] found 230 joints in the human body, controlled by 630 skeletal muscles, which lead them to a grand total of 244 degrees of freedom for a human. Many of these may be considered partial, or debated, but regardless of the real numbers, it is important to consider the impairment caused by wearable haptic systems. Wearable interfaces must be able to naturally fit the human body without impairing it or interfering with its actions, they should ensure the correct kinematic compatibility with the considered human limb [77], and they should be able to function without requiring any additional voluntary action [78]. For example, many wearable fingertip devices place their actuators on the back of the finger, but actuate thin and light linkages placed in contact with the finger pulp (as in Figs. 1c, 2a, and 3c). This configuration minimizes interference during multi-finger simulation of grasping; on the other hand, since the end effector of such devices is always placed in proximity of the fingertip, grasping a real object with bare fingers is often difficult. Similarly, hand exoskeletons usually occupy the space over the back of the hand and fingers, to enable users to clench their fist or grasp real objects while wearing the device (as in Fig. 4c). Similar considerations apply also to arm and leg exoskeletons, with the general consequence that wearable devices always cover a part of the body, and the interaction of that part with the real environment is severely limited. Finally, in exoskeletons, the kinematics design is driven by human anatomy, and mechanical joints are constrained to follow those of the wearer. To adjust these devices for different limb sizes, a good approach is to adopt kinematics with variable link lengths and remote center rotation mechanisms. A further requirement for exoskeletons is to assure the same range of motion of human articulations: if, for some joints, this is not a challenging requirement, for the most complex ones, such as the shoulder or the thumb articulations, this result is very difficult to achieve. In these cases, the approach used by designers is to assure the range of motion used by humans in the most common tasks.

4.4 Comfort

Wearing a haptic device for long periods can often result in major discomfort. Sharp edges, tight fabric bands, rough surfaces, and hot parts are some of the causes of discomfort when wearing haptic systems. In our opinion, one of the



(a) Gabardi et al. [85] (b) Pacchierotti et al. [86] (c) Chinello et al. [94]

Fig. 2. Three representative wearable haptic devices providing normal indentation to the fingertip through a moving platform.

(a) Minamizawa et al. [14] (b) Tsetserukou et al. [112] (c) Leonardis et al. [113], [114]

Fig. 3. Three representative wearable haptic devices providing lateral skin stretch and/or relative tangential motion to the fingertip.

(a) In et al. [141], [142] (b) Khurshid et al. [143], [144] (c) Iqbal et al. [145]

Fig. 4. Three representative wearable haptic devices providing kinesthetic stimuli to the hand.

most relevant and common discomfort factors with wearable haptic systems is the pressure exerted by the worn device. This is particularly relevant when the wearer use the device for long periods. Unfortunately, most haptic devices need to be fastened tightly to convey the requird haptic cues at the given point of application. Moreover, it is also important to consider the high variability in the size and shape of human limbs [79], [80]. To be comfortable to wear, wearable interfaces should be adaptable to different limb sizes. In this respect, a good solution is to use ergonomically-shaped shells, made of a deformable material, with soft padding and adjustable straps. Comfort considerations should be also involved when designing end-effectors: applying high torques and shear forces to the skin is not easy, as slip and unpleasant feelings may arise. A proper design of the end-effectors in contact with the skin can ensure better feedback and kinematic precision.

5 A Review of Wearable Haptic Devices

This section reviews the literature on wearable haptics, categorizing the considered systems according to their area of interest and the type of cutaneous stimuli they can provide to the human user. In this respect, Biggs et al. [6] provide an in-depth review of haptic interfaces and define a list of four primitives of cutaneous sensation: normal indentation, lateral skin stretch, relative tangential motion, and vibration. The large variety of tactile sensations that humans experience can be considered combinations of these few building blocks.

5.1 Fingertip

Wearable devices for the hand often focus their attention on the fingertip, since it is the most sensitive part and the one that is most often used for grasping, manipulation, and probing the environment. We divide this section into three sections, categorizing the devices according to the cutaneous stimuli they can provide. Table 2 summarizes the features of the devices reviewed in this section.

5.1.1 Normal Indentation

Normal indentation displays convey cutaneous stimuli through one or multiple moving tactors, providing spatially distributed tactile information through the indentation of the tactors into the skin. Contact/pressure, curvature, and softness/hardness display, as described in Section 3.1, fall under this category.

Moving Platforms. A popular technique to provide cutaneous feedback to the fingertips is through a moving platform, that can orient and/or translate on the finger pulp.

In 2008, Frisoli et al. [81], [82] presented first the concept of a fingertip haptic display for improving curvature discrimination through a moving platform. The device is designed to bring a plate into contact with the fingertip at different orientations, defined by the normal to the virtual surface at the point of contact. The system is composed of a parallel platform and a serial wrist; the parallel platform actuates a translation stage for positioning the plate relatively to the fingerpad, while the wrist is in charge of adjusting its orientation. The device is actuated via sheathed

TABLE 2
Wearable Haptic Devices for the Fingertip Considered in Section 5.1

Device	End-effector	Actuation technology	Type of provided stimuli	Weight at the fingertip (g)	Dimensions at the fingertip (mm)
Solazzi et al. [83]	rigid circular platform	4 DC motors	contact, pressure, curvature	56	$55 \times 45 \times 35$
Gabardi et al. [85]	rigid circular platform	2 servo motors + 1 voice coil	contact, pressure, curvature, vibration	30	$66 \times 35 \times 38$
Prattichizzo et al. [5]	rigid triangular platform	3 DC motors	pressure, curvature	30	$45 \times 24 \times 31$
Scheggi et al. [91]	rigid circular platform	1 servo motor	contact, pressure	20	$30 \times 26 \times 35$
Chinello et al. [94]	rigid circular platform	3 servo motors	contact, pressure, curvature	25	$45 \times 35 \times 43$
Kim et al. [98]	8 × 4 pin array	linear ultrasonic actuators	pressure, curvature	.	$18 \times 25.5 \times 13.5^{\ddagger}$
Sarakoglou et al. [100], [101]	4 × 4 pin array	DC motors	pressure, curvature	30	$32 \times 12 \times 15$
Caldwell et al. [102]	4 × 4 pin array + 4 air pockets	pneumatic actuators	pressure, curvature, softness, friction, vibration	20	$30 \times 30 \times 12$
Koo et al. [104]	4 × 5 cell array	dielectric elastomer actuators	pressure, curvature	.	$22 \times 20 \times 14^{\ddagger}$
Frediani et al. [105]	soft membrane	dielectric elastomer actuators	softness	15	$27 \times 50 \times 10^{\ddagger}$
Moy et al. [110]	5 × 5 cell array	solenoid 3-way pneumatic valves	pressure, curvature, softness	.	$12 \times 12 \times 30$
Gleeson et al. [115]	rigid tactor	2 servo motors	friction	39	$24 \times 24 \times 41^{\ddagger}$
Solazzi et al. [116]	rigid tactor	Shape Memory Alloys	friction	20	$30 \times 30 \times 25$
Minamizawa et al. [14]	fabric belt	2 DC motors	pressure, friction	35	$50 \times 33 \times 34^{\ddagger}$
Pacchierotti et al. [117]	fabric belt	2 servo motors	pressure, friction	35	$37 \times 18 \times 21$
Bianchi et al. [118]	stretchable fabric	2 DC motors + 1 servo motor	contact, softness	100	$100 \times 60 \times 36$
Tsetserukou et al. [112]	rigid tactor	2 DC motors	contact, pressure, friction	13.5	$26.1 \times 32 \times 38.5$
Leonardis et al. [113], [114]	rigid tactor	3 servo motors	contact, pressure, friction	22	$20 \times 30 \times 39$
Girard et al. [119]	rigid tactor	2 DC motors	friction	22	$20.4 \times 35 \times 34.1$
Schorr and Okamura [120]	rigid tactor	3 DC motors	contact, pressure, friction	32	$21.5 \times 48.8 \times 40.2$
Pabon et al. [121]	3 motors per finger, 5 fingers	Eccentric Rotating Mass (ERM) motors	vibration	.	as a work glove
Sanfilippo et al. [122]	1 motor per finger pad, 5 fingers	Eccentric Rotating Mass (ERM) motors	vibration	$20^{\ddagger}$	as a work glove
Foottit et al. [123]	1 motor per finger pad, 5 fingers	Eccentric Rotating Mass (ERM) motors	vibration	.	as a work glove

No superscript in the last two columns indicates quantities directly measured or found in the cited papers, while superscript ‡ indicates quantities estimated from graphics included in the cited papers. Symbol . indicates that we were not able to retrieve the data in any of the aforementioned ways.

tendons. A more portable and improved design solution of the same concept was then developed in [83], [84] and named *Active Thimble*. A voice-coil actuator was introduced for simulating fast contact transition, and the overall system mobility was reduced to 3-DoF: two degrees of freedom for the orientation and one linear degree of freedom to control the contact force at the fingertip. Gabardi et al. [85] further improved the *Active Thimble* by replacing sheathed tendon actuation with DC motors mounted directly on the joints (see Fig. 2a). Moreover, they increased the portability and wearability of the system by reducing the overall weight and dimensions. The total weight of this device is now only 30 g for $66 \times 35 \times 38$ mm dimensions.

Prattichizzo et al. [5] presented a wearable 3-DoF fingertip device for interaction with virtual and remote environments. It consists of two platforms: one is located on the back of the finger, supporting three small DC motors, and the other is in contact with the volar surface of the fingertip. The motors shorten and lengthen three cables to move the platform toward the user's fingertip and re-angle it to simulate contacts with arbitrarily oriented surfaces. The direction and amount of the force reflected to the user is changed by properly controlling the cable lengths. Three force-sensing resistors near the platform vertices measure the fingertip contact force for closed-loop control. Pacchierotti et al. [86] presented an improved version of the same device that achieves higher accuracy by using motors with encoders and a single force sensor. It consists again of two platforms connected by three wires (see Fig. 2b). Three small electrical motors, equipped with position encoders, control the length of the wires, moving the mobile platform toward the fingertip. One force sensor is placed at the platform's center, in contact with the finger pulp. More recently, Kim et al. [87] integrated this device with four IMU sensors to track its position in 3-dimensional space. They included IMUs on the mobile platform, over the DC motors, on the dorsal side of the palm, and on the palmar side of the proximal phalanx.

However, although these two platform-equipped devices have been successfully employed in various scenarios [88], [89], [90], [91], they are not able to make and break contact with fingertip, which is known to be important in tactile interaction [92], [93]. In this respect, Chinello et al. [94] presented a 3RRS wearable fingertip device. It is composed of two parallel platforms: the upper body is fixed on the back of the finger, housing three small servo motors, and the mobile end-effector is in contact with the volar surface of the fingertip (see Fig. 2c). The two platforms are connected by three articulated legs, actuated by the motors, in order to make and break contact with the skin, move the mobile platform toward the user's fingertip, and re-angle it to simulate contacts with arbitrarily-oriented surfaces. The device was also successfully used to render contact forces in virtual reality applications [95].

Pin-Arrays. Already in 1993, Shimizu et al. [96] investigated the haptic recognition of familiar objects by the early blind, the late blind, and the sighted with two-dimensional and three-dimensional stimuli produced by an array of pins. The authors considered two different arrangements of the tactors. One consisted of 1,827 pins arranged with 3-mm interspacing. The other consisted of 3,927 pins with 2-mm interspacing. Each pin, made of resin, was curved at the top. The diameter of the pins was 2.75 mm for the 3-mm arrangement, and 1.75 mm for the 2-mm arrangement. In 1995, Howe et al. [97] developed a pin-array display aimed at rectifying the deficit of cutaneous feedback in surgical robotics. 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 validated the system by carrying out an experiment of remote palpation. Although these kinds of displays are very flexible and quite effective, they usually employ a large number of actuators that require bulky control and actuation modules.

In constrast, Kim et al. [98] achieved a lightweight and wearable design for a haptic display composed of an 8×4 pin array, with a spatial resolution of 1.5 mm and an overall dimension of $17 \times 34 \times 32$ mm. The authors placed three devices on a glove, being able to provide the human user with cutaneous stimuli to the thumb, index, and middle fingers. Sarakoglou et al. [99] also proposed a compact 4×4 tactor array, actuated remotely through a flexible tendon transmission. The center-to-center pin spacing is 2 mm, the diameter of each pin is 1.5 mm, and the maximum displacement is 2 mm. The total weight of the device is 275 g, of which 10 g are loaded on the actuated finger. Similarly, the device presented in [100], [101] is composed of a 4×4 pin array. The pin array is embedded in a finger clip mechanism that enables the device to be easily worn on the fingertip. The weight of this device is 300 g, of which 30 g are loaded on the actuated finger. Caldwell et al. [102] presented a device able to combine normal indentation and shear stimuli, with the objective of stimulating a wide range of mechanoreceptors, with localized stimuli from DC to 400 Hz. They used a 4×4 pin array to provide information about shape and edges. The spatial separation of the pins was 1.75 mm, while the overall dimensions of the array was 15×15 mm. Pins had a diameter of 1.75 mm at tip. To replicate friction and drag sensations, Caldwell et al. [103] used pneumatic Muscle Actuators (pMA). A pneumatic actuator was mounted on each lateral face of the device, between the pin-array module and an outer aluminum containment shell. The overall dimensions of the combined haptic device was $30 \times 30 \times 12$ mm. All these implementations managed to achieve a compact design, but they still require quite a bulky external drive unit for the actuation and control systems. Koo et al. [104] addressed the wearability challenge of such devices by using dielectric elastomer actuators, that can provide cutaneus stimuli without any electromechanical transmission. Their device is composed of a 4×5 array of stimulating cells. The total active area for the device is 11×14 mm, and the centers of tactile stimulating elements are 3 mm apart. Each element is 2 mm in diameter, the initial height is 0.1 mm, and the maximum displacement is 0.45 mm. The entire device is flexible and lightweight like a bandage. Similarly, Frediani et al. [105] described a wearable wireless fingertip display, able to mechanically stimulate the fingertip. The device was also based on dielectric elastomer actuators. The actuators were placed in contact with the finger pulp, inside a plastic case, which also hosted a compact high-voltage circuitry. A custom wireless control unit was fixed on the forearm and connected to the display via low-voltage leads.

Pneumatic Systems. Similarly to pin arrays, another popular set of wearable systems providing stimuli via normal indentations are pneumatic jets and balloon-based systems. The group of James C. Bliss was one of the first to use air jets for sensory substitution of visual cues for the visually-impaired. One of their first devices consisted of a 12×12 array of air jets placed in contact with the index fingertip. The contour of each letter was displayed to the finger using the air provided by the jets [106], [107], [108]. Kim et al. [109] presented a wearable air-jet display to provide click-like sensations in an augmented reality environment. The display is composed of a 5×5 jet array in contact with the finger pad and of 5 additional air jets placed on each side of the fingertip. Each jet has a diameter of 2.4 mm. Moy et al. [110] tried to achieve a compact design for a fingertip device using a balloon-based end-effector, developing a one-piece pneumatically-actuated tactile display molded from silicone rubber. The tactile display consists of a 5×5 array of elements. Elements are placed 2.5 mm apart from each other and have a diameter of 1 mm. The contact area is 12×12 mm. 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. To a similar end, Gwillian et al. [111] described an adjustable aperture wearable air-jet pneumatic lump display that directs a thin stream of pressurized air through an aperture onto the finger pad. Increasing the air pressure increases the normal force provided at the fingertip, while increasing the air-jet aperture increases the contact area. The display is designed to produce the sensation of a lump with minimal hardware requirements.

5.1.2 Lateral Skin Stretch and Relative Tangential Motion

Lateral skin stretch is a feedback modality in which a shear force is applied to the skin. It exploits the high sensitivity of human skin to tangential stretch and can provide the user with directional information. Skin stretch and tangential motion stimuli can then be combined to provide the illusion of slip. Caress, friction, indentation, push-button, proprioception, and large-radius surface curvature display, as described in Section 3.1, fall under this category.

In 2005, Provancher et al. [124], [125] designed a skin stretch display featuring a roller that translates along the finger and makes and breaks contact with the user's fingertip. The roller is suspended beneath the user's fingertip, and it is either free to rotate or not, portraying rolling and sliding contacts, respectively. The actuation system is driven via two sheathed push–pull wires.

Gleeson et al. [115] introduced a 2-DoF fingertip device that laterally stretches the skin of the fingertip using a 7 mm hemispherical tactor. Its two RC servo motors and compliant flexure stage can move the tactor along any path in the plane of the finger pad. The device is capable of rendering 1 mm of displacement at arbitrary orientations within a plane, with a rate of 5 mm/s. The device has been also used to guide a human user navigating an unknown space [126]. Similarly, Solazzi et al. [116] presented a 2-DoF skin-stretch device actuated by Shape Memory Alloy actuators.

Minamizawa et al. [14] developed a wearable fingertip device able to render the weight of virtual objects by providing, at the same time, cutaneous stimuli tangential and normal to the finger pulp. It consists of two DC motors that move a belt that is in contact with the user's fingertip (see Fig. 3a). When the motors spin in opposite directions, the belt presses into the user's fingertip, and when the motors spin in the same direction, the belt applies a tangential force to the skin. It weighs only 35 g for $50 \times 33 \times 34$ mm dimensions. This device was also used in [127] to display remote tactile experiences: an instrumented glove registers the interaction forces in the remote environment, and three wearable fingertip devices feed those forces back to the human user. A similar device, composed of two servo motors and a belt, was also used by Pacchierotti et al. [117] for multi-finger manipulation of virtual objects and by Hussain et al. [128] for the control of a robotic sixth finger, but in this case the device was not placed on the fingertip as in [14], [127], but instead in contact with the proximal finger phalanx. This configuration allowed improved markerless optical tracking of the fingertips, and avoided preventing use of the fingertips to interact with real objects. Bianchi et al. [118], [129] adopted a similar design for their fabric-based wearable display. Two DC motors move two rollers attached to an elastic fabric in contact with the fingertip, varying its stiffness. A lifting mechanism can independently regulate the pressure exerted by the fabric on the fingertip.

In addition to soft end-effectors, Tsetserukou et al. [112] presented a 2-DoF wearable fingertip device featuring a rigid tactor in contact with the fingertip. It is composed of two DC motors driving a five-bar linkage mechanism mounted at the sides of the fingertip (see Fig. 3b). Similarly to [14], when motors rotate in the same direction, the linkage slides tangentially on the finger pad. On the other hand, when motors rotate in the same direction, the linkage moves towards or away from the fingertip. Leonardis et al. [113], [114] presented a 3RSR wearable skin stretch device for the fingertip. It moves a rigid tactor in contact with the skin, providing skin stretch and making/breaking contact sensations. An asymmetrical 3RSR configuration allows compact dimensions with minimum encumbrance of the hand workspace and minimum inter-finger interference (see Fig. 3c). This device has also been used for upper limb rehabilitation of patients affected by cerebral palsy [130]. Similarly, Girard et al. [119] developed a wearable haptic device able to simulate 2-DoF shear forces at the fingertip. It is composed of a parallelogram structure actuated by two DC motors that move a tactor in contact with the fingertip. It weighs only 22 g for a total dimension of $20 \times 34 \times 35$ mm. The tactor's maximum displacement is 2 mm in both directions. More recently, Schorr and Okamura [120] presented a wearable device able to make and break contact in addition to rendering shear and normal skin deformation to the finger pad. The device is composed of a delta parallel mechanism, which has three translational DoF, enabling both normal, lateral (ulnar and radial) and longitudinal (distal and proximal) skin deformation. It weighs 32 g for $21.5 \times 48.8 \times 40.2$ dimensions. It has an operational workspace of $10 \times 10 \times 10$ mm, and it can apply maximum normal and lateral forces of 2 N and 7.5 N, respectively.

5.1.3 Vibration

In addition to the above-mentioned types of cutaneous feedback, there is also a growing interest in vibrotactile stimuli. Vibration/texture, push-button, and caress display, as described in Section 3.1, fall under this category. The small and lightweight form factor of vibrotactile actuators have enabled researchers to develop highly-wearable interfaces using such technology.

One of the first example of vibrotactile motors used to build wearable haptic devices has been presented by Cheng et al. [131] in 1997. The authors used a 5DT[2] sensing glove (Fifth Dimension Technologies, South Africa), that provided the hand pose, together with a Red Baron tracker (Logitech, Switzerland), that provided the position of the wrist. Two vibrotactile motors per fingertip were used to provide cutaneous feedback about the interaction with virtual objects. Later, Pabon et al. [121] developed a low-cost vibrotactile data-glove composed of two goniometric sensors and three vibrotactile motors per finger. Kurita et al. [132] used vibrotactile stimuli to improve tactile sensitivity. Results showed that applying white noise vibrations to the side of the fingertip improved two-point discrimination, texture discrimination, and grasping force optimization. Romano et al. [133] presented a vibrotactile glove focusing on providing tactile cues associated with slip between the glove and a contact surface. Relative motion is sensed using optical mouse sensors embedded in the glove's surface, and this information is conveyed to the wearer via vibrotactile motors placed inside the glove against the wearer's finger pad. Krishna et al. [134] used a similar vibrotactile glove to deliver facial expressions to visually-impaired people. Three vibrotactile motors per fingertip provide cutaneous information about human emotions. More recently, Muramatsu et al. [135], Galambos and Baranyi [136], Sanfilippo et al. [122], and Foottit et al. [123] presented vibrotactile gloves with one vibrotactile motor per finger pad. The glove presented by Muramatsu et al. also embeds one bend sensor per finger to detect the grasping pose, and the glove presented by Foottit et al. uses IMU and optical bend sensors to track the hand orientation and grasping pose, respectively. Vibrotactile feedback at the fingertips has been also used by Bial et al. [137] for outdoor navigation and by Murray et al. [138] for telemanipulation.

5.2 Whole Hand

In addition to fingertip devices, researchers have also focused on the design and development of wearable haptic interfaces providing cutaneous and kinesthetic stimuli to

TABLE 3
Wearable Haptic Devices for the Whole Hand Considered in Section 5.2

Device	End-effector	Actuation technology	Type of provided stimuli	Weight at the hand (g)	Dimensions (mm)
Leonardis et al. [150]	1 contact point per finger phalanx, 5 fingers	2 DC motors	kinesthetic	950	40 × 100 × 200
Tanaka et al. [153]	pneumatic actuators for the palm, four fingers, and four finger pads	4 bellows actuators + 2 air jet nozzles	kinesthetic, pressure	232	.
Bouzit et al. [154]	contact at the finger pad, 4 fingers	RMII-ND custom pneumatic actuators	kinesthetic	80	.
Sarakoglou et al. [160]	2 contact points per finger, 4 fingers	7 DC motors	kinesthetic	250	.
In et al. [141], [142]	1 tendon per finger , 2 fingers	1 DC motor	kinesthetic	80	as a work glove
Arata et al. [168]	1 tendon per finger, 4 fingers	1 DC motor	kinesthetic	320	.
Nycz et al. [169]	1 tendon per finger, 4 fingers	4 DC motor	kinesthetic	113	.
Polygerinos et al. [170]	1 hydraulic actuator per finger, 5 fingers	5 soft fiber-reinforced actuators	kinesthetic	285	20 × 10 × 200‡
Allotta et al. [171]	2 contact points per finger, 4 fingers	4 servo motors	kinesthetic	330	60 × 90 × 200‡
Ma and Ben-Tzvi [174], [175]	contact at the finger pad, 2 fingers	2 DC motors	kinesthetic	180	40 × 90 × 200‡
Agarwal et al. [176]	3 contact points per finger, 1 finger	series elastic actuators	kinesthetic	80	.
Choi et al. [178]	1 contact point per finger, 3 fingers (+ the thumb)	3 DC motors	kinesthetic	55	38 × 38 × 200
Kim et al. [177]	contact at the finger pad, 1 finger	1 servo motor + 1 linear resonant actuator	contact, kinesthetic, vibration	80	25 × 60 × 150
Fu et al. [165]	2 contact points per finger, 2 fingers	8 DC motor	kinesthetic	.	.
Lambercy et al. [180]	contact at the finger pad, 1 finger	1 servomotor	kinesthetic	126	.
Khurshid et al. [143], [144]	2 contact points per finger, 2 fingers	1 DC motor + 1 voice coil	contact, pressure, kinesthetic, vibration	205	.
Stergiopoulos et al. [185]	2 contact points per finger, 2 fingers	1 DC motor + 1 voice coil	contact, pressure, kinesthetic, vibration	.	.
Lelieveld et al. [186]	3 contact points per finger, 1 finger	4 DC motors	kinesthetic	60	.
Chiri et al. [188], [189]	2 contact points per finger, 1 fingers	1 DC motor	kinesthetic	115	.
Cempini et al. [192]	2 contact points per finger, 2 fingers	4 DC motors	kinesthetic	438	.
Iqbal et al. [145]	1 contact points per finger, 4 fingers	4 DC motors	kinesthetic	460	.
Gollner et al. [201]	32 contact points distributed on the hand	32 shaftless coin vibrating motors	vibration	35‡	as a work glove
Martinez et al. [202]	10 contact points distributed on the hand	10 shaftless coin vibrating motors	vibration	20‡	as a work glove

No superscript in the last two columns indicates quantities directly measured or found in the cited papers, while superscript ‡ indicates quantities estimated from graphics included in the cited papers. Symbol . indicates that we were not able to retrieve the data in any of the aforementioned ways.

the whole hand. Heo et al. [139] presented in 2012 a review on hand exoskeleton technologies for rehabiliation. A non-published report on the state-of-the-art of hand exoskeletons has been also prepared by the University of Bologna [140]. In this section we report on hand exoskeletons that directly addressed challenges related to the wearability of the system. Similarly to Section 5.1, we divide this section in two section, categorizing the devices according to the haptic stimuli they can provide. Table 3 summarizes the features of the devices reviewed in this section.

5.2.1 Kinesthetic Stimuli

Already in 1992, Bergamasco [146] introduced guidelines for providing haptic feedback to the hand by analyzing the contact forces arising during exploratory and manipulative procedures. A few years later, he presented the kinematic scheme of a wearable finger exoskeleton that consisted of four links connected by revolute joints, one corresponding to each joint of the finger [147]. For each joint of the exoskeleton, the flexion-extension direction of the finger was actuated, and all joints integrated rotation sensors, including adduction-abduction movements at the metacarpophalangeal joint. Later on, Bergamasco's PERCRO laboratory proposed several revised versions of this first concept, considering multi-finger designs and improving the overall wearability of the system [148], [149], [150]. In 2002, researchers at the Keio University presented a wearable multi-finger non-isomorphic device actuated by passive clutches [151]. Each finger had 4 degrees of freedom. In the same year, Springer and Ferrier [152] presented a 1-finger exoskeleton device using a four-link serial planar linkage to transmit kinesthetic force from the palm to the fingertip; and Tanaka et al. [153] presented a haptic glove able to provide kinesthetic feedback to four fingers using pneumatic balloon actuators and cutaneous feedback to two finger pads using air jet nozzles. Pneumatic actuators were also used by Bouzit et al. [154] for the well-known Rutgers Master II, which can provide kinesthetic force up to 16 N to the thumb, index, middle, and ring fingers. It uses pneumatic actuators arranged in a direct-drive configuration in the palm. Moreover, the structure also serves as a position measuring exoskeleton by integrating non-contact Hall-effect and infrared sensors. Unlike other hand exoskeletons, the end-effector of the Rutgers Master II is placed on the intermediate phalanx of the fingers, leaving the fingertips free to interact with the environment (similarly to [117] and [155]). Pneumatic actuators were later used in the wearable hand exoskeletons presented in [156], [157], [158], [159], which resulted in more compact and lightweight designs. Hand exoskeletons able to provide kinesthetic feedback have also often been used in rehabilitation applications for hand-related injuries. For example, Sarakoglou et al. [160] proposed a wearable hand exoskeleton exerciser for the rehabilitation of hand-related injuries. It enables the execution of finger therapy regimes, and it can be used as a motion analysis and lost finger mobility diagnosis tool. The exoskeleton provides 1-DoF kinesthetic feedback to the thumb and 2-DoF kinesthetic feedback to the index, middle, and ring fingers. Similarly, Wege and Hommel [161] developed a wearable hand exoskeleton for rehabilitation able to provide kinesthetic feedback to four degrees of freedom of the finger. The exoskeleton moves the fingers by a construction of levers, which are connected through Bowden cables to the motors. Several research groups have indeed used force reflecting hand exoskeletons for rehabilitation purposes [77], [139], [150], [161], [162], [163], [164], [165], [166]. However, of course, wearability is often not the main design goal of these systems.

An extremely wearable version of such hand interfaces has been presented by In et al. [141], [142], which proposed a jointless hand exoskeleton weighting only 80 g (see Fig. 4a). As discussed in Section 4, reducing the weight and form factor of haptic interfaces is indeed important toward a good wearability of the system. The exoskeleton of In et al. is composed of tubes and wires that run along the finger. Pulling the wires toward the palm provides the wearer with kinesthetic feedback along one direction. The challenges of adaptation of this jointless exoskeleton to different hand and finger sizes is discussed in [167]. Another lightweight hand exoskeleton has been presented by Arata et al. [168]. The mechanism is driven through large deformations of a compliant mechanism body, and it weighs 320 g. It is designed to distribute 1-DoF actuated linear motion into three rotational motions of the finger joints, which translate into natural finger flexion/extension. The portability of this exoskeleton has been significantly improved by Nycz et al. [169] using a remote actuation system. A push-pull Bowden cable is used to transmit actuator forces from a backpack to the hand. This remote actuation approach reduced the hand exoskeleton weight by over 50 percent without adverse effects to functionality.

More recently, Polygerinos et al. [170] developed a five-fingers soft robotic glove actuated by hydraulic multi-segment soft actuators. The actuators are designed to replicate finger and thumb motions suitable for typical grasping movements. Moreover, the actuators are placed on the dorsal side of the hand, leaving the palm free to interact with the environment. The exoskeleton weights 285 g and features 1 active DoF per finger. Allotta et al. [171] and Conti et al. [172], [173] developed a compact four-fingers hand exoskeleton weighting 330 g. Each finger module has 1-DoF and it is composed of a parallel kinematic chain. The end-effector is placed at the fingertip, and the device is grounded on the palm and on the intermediate phalanx. Ma and Ben-Tzvi [174], [175] of the George Washington University made the wearability of the system the main requirement of their two-finger exoskeleton. Each finger consists of three parts: a three-link exoskeleton, an actuator unit, and two actuation cables. The DoF of the metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) joints of each finger are coupled together with one actuator module. The total weight of the two-finger prototype is 180 g. Agarwal et al. [176] presented a wearable hand exoskeleton with series elastic actuation capable of bidirectional and independent joint torque control at the finger joints. It weighs 80 g. The design of the exoskeleton also allows the replacement of the stiffness elements without having to remove the cables, making it easy to adjust for different users. Kim et al. [177] developed a wearable hand exoskeleton able to provide 1-DoF kinesthetic feedback to each finger and vibrotactile stimuli at the fingertip. The actuators are placed on the back of the palm, and the weight of a one-finger prototype is 100 g. Choi et al. [178] presented a wearable interface able to render forces between the thumb and three fingers to simulate objects held in precision grasps. Using brake-based locking sliders, the system can withstand 100 N of force between each finger and the thumb. Time-of-flight sensors provide the position of the fingers and an IMU provides orientation tracking. The total weight of the device is 55 g, including a 350 mAh battery that enables the device to be used for around 5 hours and 1,500 grasps. Finally, Achibet et al. [179] recently presented a passive wearable exoskeleton providing kinesthetic feedback to four fingers. It is composed of independent finger modules made of a bendable metal strip, anchored to a plate on the back of the hand and ending at the fingertip. Each strip offers a range of motion to the fingertip of 7.3 cm. The full range can be reached with a force of 2.5 N. Near the fingertip, the metal strip can also house a vibrotactile motor for the rendering of textures.

In addition to weight and form factor, the adaptability of the system to different limb sizes is indeed another main design challenge for wearable haptic systems (see Section 4). In this respect, Fu et al. [165] developed a compact hand exoskeleton able to actuate the MCP, PIP, and DIP joints of each finger. It is composed of three main parts: an adaptive dorsal metacarpal base, a Bowden cable driven actuator, and up to five adaptive dorsal finger exoskeletons. Each finger module has a 2-DoF adaptation system to adjust to different finger sizes. A similar adaptive approach has been also devised for the dorsal metacarpal base. Finally, each joint is equipped with force sensors. Brokaw et al. [164] presented a passive linkage-based device able to provide extension moments to the finger joints to compensate for finger

(a) Uchiyama et al. [182] (b) Kim et al. [183] (c) Mazzoni and Bryan-Kinns [184]

Fig. 5. Three representative wearable haptic devices providing vibrotactile stimuli to the hand.

flexor hypertonia. It is designed to follow the normal kinematic trajectory of the hand during pinch-pad grasping. The finger attachment points can be extended to adjust to different finger lengths, while the thumb attachment can be rotated to match the current user's thumb orientation. Lambercy et al. [180] developed a palm-grounded thumb exoskeleton able to provide forces up to 10 N at the fingertip while weighing less than 150 g. To adapt the exoskeleton to hands of different sizes, the lateral position and orientation of the actuators can be adjusted to ensure proper alignment with the MCP joint. Moreover, the links can be shifted to match the thumb length. More recently, Khurshid et al. [143], [144] developed a wearable device able to provide kinesthetic grip force feedback, along with independently-controllable fingertip contact, pressure, and vibrotactile stimuli. The device is worn on the user's thumb and index fingers, and it allows to control the grip aperture of a PR2 robotic hand (see Fig. 4b). 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, and it contains a lockable sliding linkage to easily adjust the distance between the MCP joint and the side of the thumb piece. The second link is fixed and secured to the index finger. A DC motor actuates the revolute joint, providing kinesthetic feedback to the hand, while one voice-coil actuator per finger provides cutaneous stimuli at the fingertip. Bianchi et al. [181] presented a scaling procedure to automatically adapt the rehabilitation hand exoskeleton of [171], [172], [173] to different patients.

Another relevant design challenge for wearability is ensuring kinematic coupling between the wearer and the exoskeleton joints, impairing as little as possible the motion of the wearer (see again Section 4). For instance, Stergiopoulos et al. [185] developed a two-finger exoskeleton for virtual reality grasping simulation. It allows full finger flexion and extension and provides kinesthetic feedback in both directions. It has 3-DoF at the index finger and 4-DoF at the thumb. Lelieveld et al. [186] proposed two lightweight wearable 4-DoF exoskeletons for the index finger. The first design is a statically balanced haptic interface composed of a rolling-link mechanism and four constant torque springs for active kinesthetic feedback. The second design considers a rolling-link mechanism with a mechanical tape brake for passive kinesthetic feedback. Yang et al. [187] have recently presented a jointless tendon-driven hand exoskeleton which focuses on correctly replicating natural finger motion during grasping. They used two staggered tendons per finger, able to couple the movement of the PIP and DIP as well as the MCP and PIP during finger flexion. Chiri et al. [188], [189] focused on the development of an ergonomic hand exoskeleton featuring full kinematic coupling with the wearer joints, called HANDEXOS. The PIP and DIP joints are implemented with revolute DoF, aligned along the PIP and DIP axes, and they are equipped with an idle pulley for the actuation cable routing. For the MCP joint, the authors considered a self-aligning architecture consisting of a parallel chain made of two revolute and one linear DoF. It weigths 115 g. Later, the BioRobotics Institute proposed many revised versions of this first concept, improving the overall wearability and comfort of the system, also considering rehabilitation applications [77], [190], [191], [192], [193]. Similarly, Iqbal et al. [194] of the Italian Institute of Technology (IIT) developed a Revolute-Revolute-Revolute (RRR) wearable mechanism able to provide high forces (up to 45N) at the proximal phalanx of the thumb and index fingers. Following this, the IIT proposed several revised versions of this first concept, considering multi-finger designs, improving the overall wearability and performance of the system, and addressing rehabilitation applications [145], [195], [196], [197], [198], [199]. For example, the latest hand exoskeleton presented by Iqbal et al. [145] in 2015 weights 460 g, provides 4 DoF per finger (1 active), and can provide up to 8 N at the fingertip (see Fig. 4c). Recently, Sarac et al. [200] presented an underactuated hand exoskeleton with one actuator per finger and a linkage kinematics capable of automatically adapting to user hand size.

5.2.2 Vibration

Due to the small form factor and low mass of vibrotactile actuators, exoskeletons providing only vibrotactile feedback can more easily achieve high wearability levels compared to systems that provide kinesthetic feedback. One of the first examples of vibrotactile gloves has been developed by Uchiyama et al. [182] for providing directions and spatial representation to wheelchair users who have severe visual impairment. The vibration signals are provided through a 3-by-3 array of vibrotactile actuators placed on the back of the hand (see Fig. 5a). One year later, Kim et al. [183] used a similar approach to increase the immersiveness of multimedia experiences such as movies and computer games. They developed a glove housing twenty vibrotactile actuators and devised a mapping algorithm between tactile sensations and multimedia content (see Fig. 5b). Sziebig et al. [203] developed a vibrotactile glove for virtual reality applications composed of six vibrotactile actuators, five on the fingertips and one on the palm. Hayes [204] provided vibrotactile feedback on the hand for haptic-enabled music performances. She integrated two vibrotactile motors on the palm to recreate the vibrations produced by an acoustic instrument. The fingertips are left free to interact with the environment. Karime et al. [205] presented a vibrotactile glove for wrist rehabilitation of post-stroke patients. The glove houses a triple axis accelerometer on the wrist to register tilt angles, and two

(a) Reactive Grip Motion Controller by Tactical Haptics.

(b) Tactai Touch™ system by Tactai.

(c) VR Touch system by GoTouchVR.

Fig. 6. Gaming is one of the most promising application for wearable haptic technologies. For example, (a) the "Reactive Grip" motion controller provides skin stretch and relative tangential motion to the hand to recreate the compelling sensation of holding in-game objects; (b) the "Tactai Touch™" fingertip device is able to provide pressure, texture, and the sensation of making and breaking contact with virtual objects; and (c) the "VR Touch" fingertip device is able to provide pressure and the sensation of making and breaking contact with virtual objects.

vibrotactile actuators on the back of the hand to indicate requested movements. Gollner et al. [201] presented a vibrotactile system to support deafblind people's communication. The glove is made of stretchy fabric equipped with 35 fabric pressure sensors on the palm and 32 shaftless coin vibrating motors on the back. The control unit is integrated in a case mounted on the forearm. More recently, Martinez et al. [202] presented a vibrotactile glove for the identification of virtual 3D objects without visual feedback. They arranged twelve vibrotactile actuators on the palm and fingers, and they controlled them through a microcontroller on the wrist.

Systems similar to the ones reported in this section, featuring different arrangements of vibrotactile actuators across the hand, have shown promising results in various applications, such as robot-assisted surgery [206], guidance of visually-impaired people [207], virtual reality [208], [209], [210], rehabilitation [211], [212], [213], and enhanced cinematic experiences [184] (see Fig. 5c).

6 PERSPECTIVES

The wearability of haptic interfaces have significantly broadened the spectrum of possible applications of haptic technologies. Wearable haptic systems have in fact enabled the use of haptic devices in everyday life. They naturally fit the human body without constraining it, and they can function without requiring any additional voluntary action. In this way, users can seamlessly perceive and interact with the surrounding environment in a natural yet private way. The variety of new opportunities wearable haptics can bring in social interaction, health-care, virtual reality, remote assistance, and robotics are exciting. Wearable haptic technologies have the potential to transform the way humans physically interact with the world.

The primary advantage of wearable haptic devices is their reduced form factor compared to grounded devices, a feature that opens the possibility of easily engaging in multi-contact interactions. With wearable haptics, multi-contact haptic feedback does not require more cumbersome and complex systems, but rather multiple instances of similar designs—this seems particularly promising for grasping and rehabilitation applications. Robotic hands will be able to provide information about the forces exerted at each individual fingertip, enabling a finer control of telemanipulation. Similarly, rehabilitation exoskeletons will be able to provide clinicians with information about forces exerted by the patient at each fingertip. Together with the multi-contact revolution, recent advancements in actuation and power technologies enable researchers to make wearable haptic devices wireless and have low power requirements. In fact, many of the wearable devices for the fingertip reviewed in Section 5.1, can run on a standard lithium-ion battery and communicate wirelessly with the external computer unit. This feature seems particularly promising for consumer applications, such as gaming and immersive environments, and assistive technologies, such as guidance for the visually-impaired.

In our opinion, gaming applications represent a fantastic market for wearable haptic technologies. The gaming industry achieved USD 92bn of revenues in 2015 and it is estimated to reach USD 119bn by 2019, with mobile gaming accounting for almost 50 percent of the revenues [214]. Haptic technologies entered the gaming theater back in 1997, when Sony introduced its DualShock controller for PlayStation and Nintendo its Rumble Pak for the Nintendo 64. Both devices were able to provide a compelling vibrotactile feedback on particular events, such as a race car hitting the retaining wall or a plane crashing on the ground. The DualShock used two vibrotactile motors embedded in its handles, while the Nintendo 64's Rumble Pak used a single motor. Wearable haptics can take the immersiveness of such systems to the next level: a haptic vest can replicate the feeling of being hit by bullets in First Person Shooters (FPS) games, vibrotactile bracelets can reproduce the vibrations of the steering wheel of a race car driven in rough terrain, and fingertip devices can relay the feeling of touching in-game objects in action role-playing games (ARPG) and massively multi-player role-playing games (MMRPG). This opportunity is already being exploited by a few start-up companies. Immerz (USA) raised USD 183,449 on Kickstarter for their "KOR-FX" gaming vest. It converts audio signals coming from the game into vibrotactile haptic stimuli that allow the wearer to feel in-game events such as explosions and punches. A similar experience is promised by the "Feedback jacket" by Haptika (PK), the full-body suit "Teslasuit" by Tesla Studios (UK), the "3RD Space Vest" by TN Games (USA), the "SUBPAC M2" by StudioFeed (USA), and the "Hardlight Suit" by NullSpace VR (USA).

In addition to vibrotactile systems, the hand-held "Reactive grip" controller by Tactical Haptics (USA) provides relative tangential motion and skin stretch to the hand (see Fig. 6a). When the sliding tactor plates move in the same direction, the controller conveys a force cue in the corresponding direction along the length of the handle. When the sliding plate tactors move in opposite directions, the controller provides the user with a torque cue [215]. Microsoft (USA) has also presented two hand-held controllers for virtual reality interaction: the NormalTouch and TextureTouch [216]. The first one renders object surfaces using a 3-DoF moving platform in contact with the fingertip, while the second one uses a 4×4 pin array. Such interfaces have the potential of making the next generation of haptically-enhanced game controllers.

More recently, a few start-up companies have taken up the challenge of designing wearable haptic devices for the fingertips, mainly targeting virtual reality and gaming applications. Tactai (USA) is working on a fingertip wearable haptic device able to render pressure, texture, and the sensation of making and breaking contact with virtual objects [217], [218]. It can apply up to 6 N to the fingertip, and it weighs 29 g for $75 \times 55 \times 30$ mm dimensions (see Fig. 6b). GoTouchVR (France) developed a 1-DoF wearable device equipped with a mobile platform able to apply pressure and make/break contact with the fingertip. It can exert up to 1.5 N on the skin, it weighs 40 g for $50 \times 12 \times 30$ mm dimensions, it is wireless, and the battery guarantees up to 2 hours of playtime (see Fig. 6c). WEART (Italy) is developing a wearable device composed of a static upper body and a mobile end-effector. The upper body is located on the nail side of the finger, while the mobile end-effector is in contact with the finger pulp. The device is able to render pressure, texture, and the sensation of making and breaking contact with virtual objects. It uses a servo motor to move the platform and a voice coil motor to provide vibrotactile stimuli. The device can apply up to 8 N to the fingertip, and it weighs 25 g for $50 \times 145 \times 135$ mm dimensions. Finally, we gladly acknowledge a strong connection between these companies and academic research. For example, Tactical Haptics CEO William R. Provancher is an Adjunct Associate Professor at the University of Utah, Tactai CSO Katherine J. Kuchenbecker is an Associate Professor at the University of Pennsylvania, and WEART co-founder Domenico Prattichizzo is Full Professor at the University of Siena (and, for full disclosure, last author of this paper). Many of the devices reviewed in Section 5 come from their research labs.

The development of wearable haptic systems from gaming applications goes together with the recent development and commercialization of wearable and unobtrusive virtual reality headsets, such as the Oculus Rift and the HTC Vive. In this respect, there are already some promising examples of applications integrating virtual reality headsets with wearable haptic systems [85], [119], [219], and we expect to see many more of them in the next years. Tactical Haptics, Tactai, and GoTouchVR have already been showing demonstrations of their wearable haptics systems featuring immersive environments displayed through these virtual reality headsets [218], [220], [221].

Robotic teleoperation and telepresence are other promising fields for wearable haptics technologies. Being able to reproduce haptic stimuli in different parts of our body, simultaneously and seamlessly, can significantly improve the performance, applicability, and illusion of telepresence of teleoperation systems. We believe that the low cost of wearable devices can take teleoperation and telepresence applications to the consumer market. For example, tactile gloves could improve the experience of online shopping. Think of being able to feel, from home, the fabric of a new piece of clothing you are about to buy on Ebay, the softness of a pillow you are getting shipped from Amazon, or being able to gently squeeze a vegetable on Ocado to check if it is ripe. Another robotic application we think wearable haptics can positively impact is telecommuting. In 2015, 37 percent of U.S. workers have worked remotely, 7 percent more than in 2007 and 28 percent more than in 1995 [222]. While telecommuting is popular for office workers, it is of course more problematic when dealing with manual workers. However, technological advancements in the field of robotics, including the wearability of haptic interfaces, can allow a broader range of workers to access the benefits of remote working.

We would also like to mention the significant impact that wearable haptics technologies can have in assistive applications and, in general, in the delivery of private and effective notifications. While smartphones and smartwatches already deliver notifications through vibrotactile stimuli, the wearability of more complex haptic devices can improve the range of stimuli we are able to perceive. Systems providing wearable haptic guidance can guide firefighters in environments with reduced visibility, help the visually-impaired to walk around in their cities, and warn pedestrians and drivers about imminent dangers. We find skin stretch devices particularly promising for this purpose. By exploiting the high sensitivity of the human skin to tangential stretch, a single tactor can provide effective directional and torsional information with very small movements. For example, we could safely provide drivers with directional information by using a simple skin stretch haptic band fastened to their leg or arm.

Finally, developing wearable haptic devices has significantly pushed the research forward on cutaneous technologies. In fact, as mentioned in Section 2, cutaneous feedback provides an effective way to simplify the design of haptic interfaces, as it enables more compact designs. However, cutaneous stimuli are useful in many other applications, and we therefore expect research on wearable haptics to benefit other fields. For example, the cutaneous technology used by the wearable fingertip devices of the University of Siena [5], [20], initially employed in applications of immersive multi-contact interaction [90], [91], have also been used for non-wearable applications, such as robot-assisted surgery [223] and needle insertion [19].

Moreover, we have also witnessed advancements in the fields of tracking and force sensing for wearable haptics. Indeed, interaction with a virtual environment requires a system to track the position and, depending on the task, even the orientation of the wearable devices or the part of the human body where the feedback is provided. The most common solutions are optical tracking systems with infrared cameras and reflective markers mounted on the devices. The advantages are good accuracy, refresh rate (typically 120 Hz or higher) and wearability, since markers are small and light, while the main drawback is related to occlusion issues. An alternative solution is using IMU units mounted on the devices, and eventually integrate them with an optical tracking system to improve the precision over long sessions. The highest level of wearability can be achieved by vision-based markerless systems, capable of directly identifying the pose of the devices or of the human body using no extra components. It is also important to sense the force applied by the wearable devices on the human body. One promising wearable solution is fingernail sensors, capable of estimating fingertip forces by means of photoplethysmography [224] or photoelasticity [225]. A more common solution is to equip the tactor with force sensitive resistors: FSR are cheap, flexible, light, and compact, but they can detect normal force only. Recently, Leonardis et al. [114] presented a fingertip device with a light and compact 3-DoF optical force sensor embedded in the tactor.

To summarize, we see wearable haptics as having a strong role in applying and developing research in cutaneous haptics, as well as in bringing current technologies to a wider commercial market in the very near future. This article has surveyed the current state of the art in both sectors, and provided a review of cutaneous stimuli that have been exploited or could be exploited by future work. We hope to support the notion that the "wearables" technology trend will continue to play a strong role in pushing haptics forward throughout the coming decade.

ACKNOWLEDGMENTS

This research has received funding from the European Union Seventh Framework Programme FP7/2007-2013 under grant n°601165 of the project "WEARHAP-WEARable HAPtics for humans and robots".

REFERENCES

[1] P. Kremer et al., "Multimodal telepresent control of DLR's Rollin'Justin," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2009, pp. 1601–1602.

[2] M. Mehrtash, N. Tsuda, and M. Khamesee, "Bilateral macro–micro teleoperation using magnetic levitation," *IEEE/ASME Trans. Mechatronics*, vol. 16, no. 3, pp. 459–469, Jun. 2011.

[3] J. Vertut, *Teleoperation and Robotics: Applications and Technology*, vol. 3. Berlin, Germany: Springer, 2013.

[4] R. W. Picard and J. Healey, "Affective wearables," *Pers. Technol.*, vol. 1, no. 4, pp. 231–240, 1997.

[5] D. Prattichizzo, F. Chinello, C. Pacchierotti, and M. Malvezzi, "Towards wearability in fingertip haptics: A 3-DoF wearable device for cutaneous force feedback," *IEEE Trans. Haptics*, vol. 6, no. 4, pp. 506–516, Oct.–Dec. 2013.

[6] S. J. Biggs and M. A. Srinivasan, "Haptic interfaces," in *Handbook of Virtual Environments*. Mahwah, NJ, USA: Lawrence Erlbaum, 2002, pp. 93–116.

[7] M. Bergamasco et al., "An arm exoskeleton system for teleoperation and virtual environments applications," in *Proc. IEEE Int. Conf. Robot. Autom.*, 1994, pp. 1449–1454.

[8] C. Pacchierotti, *Cutaneous Haptic Feedback in Robotic Teleoperation*. Berlin, Germany: Springer, 2015.

[9] B. Parviz, S. Lee, and S. Thrun, "Project glass," 2012. [Online]. Available: https://plus.google.com/111626127367496192147/posts/

[10] F. Chinello, M. Malvezzi, C. Pacchierotti, and D. Prattichizzo, "A three DoFs wearable tactile display for exploration and manipulation of virtual objects," in *Proc. IEEE Haptics Symp.*, 2012, pp. 71–76.

[11] D. Prattichizzo, C. Pacchierotti, and G. Rosati, "Cutaneous force feedback as a sensory subtraction technique in haptics," *IEEE Trans. Haptics*, vol. 5, no. 4, pp. 289–300, Oct.–Dec. 2012.

[12] B. B. Edin and N. Johansson, "Skin strain patterns provide kinaesthetic information to the human central nervous system," *J. Physiology*, vol. 487, no. 1, pp. 243–251, 1995.

[13] R. S. Johansson and Å. B. Vallbo, "Tactile sensibility in the human hand: relative and absolute densities of four types of mechanoreceptive units in glabrous skin," *J. Physiology*, vol. 286, no. 1, pp. 283–300, 1979.

[14] K. Minamizawa, S. Fukamachi, H. Kajimoto, N. Kawakami, and S. Tachi, "Gravity grabber: Wearable haptic display to present virtual mass sensation," in *Proc. ACM SIGGRAPH Emerging Technol.*, 2007, Art. no. 8.

[15] K. Kuchenbecker, D. Ferguson, M. Kutzer, M. Moses, and A. Okamura, "The touch thimble: Providing fingertip contact feedback during point-force haptic interaction," in *Proc. Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst.*, 2008, pp. 239–246.

[16] C. Pacchierotti, D. Prattichizzo, and K. J. Kuchenbecker, "Displaying sensed tactile cues with a fingertip haptic device," *IEEE Trans. Haptics*, vol. 8, no. 4, pp. 384–396, Oct.–Dec. 2015.

[17] S. B. Schorr, Z. F. Quek, R. Y. Romano, I. Nisky, W. R. Provancher, and A. M. Okamura, "Sensory substitution via cutaneous skin stretch feedback," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2013, pp. 2341–2346.

[18] Z. F. Quek, S. B. Schorr, I. Nisky, A. M. Okamura, and W. R. Provancher, "Sensory augmentation of stiffness using fingerpad skin stretch," in *Proc. IEEE World Haptics Conf.*, 2013, pp. 467–472.

[19] C. Pacchierotti, A. Tirmizi, G. Bianchini, and D. Prattichizzo, "Enhancing the performance of passive teleoperation systems via cutaneous feedback," *IEEE Trans. Haptics*, vol. 8, no. 4, pp. 397–409, Oct.–Dec. 2015.

[20] C. Pacchierotti, L. Meli, F. Chinello, M. Malvezzi, and D. Prattichizzo, "Cutaneous haptic feedback to ensure the stability of robotic teleoperation systems," *Int. J. Robot. Res.*, vol. 34, no. 14, pp. 1773–1787, 2015.

[21] C. Pacchierotti et al., "Steering and control of miniaturized untethered soft magnetic grippers with haptic assistance," *IEEE Trans. Autom. Sci. Eng.*, 2017.

[22] M. Wijntjes, A. Sato, V. Hayward, and A. Kappers, "Local surface orientation dominates haptic curvature discrimination," *IEEE Trans. Haptics*, vol. 2, no. 2, pp. 94–102, Apr.–Jun. 2009.

[23] R. Johansson and G. Westling, "Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects," *Exp. Brain Res.*, vol. 56, no. 3, pp. 550–564, 1984.

[24] E. R. Serina, E. Mockensturm, C. D. Mote Jr., and D. Rempel, "A structural model of the forced compression of the fingertip pulp," *J. Biomechanics*, vol. 31, pp. 639–646, 1998.

[25] D. T. V. Pawluk and R. Howe, "Dynamic contact of the human fingerpad against a flat surface," *J. Biomechanical Eng.*, vol. 121, pp. 605–611, 1999.

[26] M. W. A. Wijntjes, A. Sato, V. Hayward, and A. M. L. Kappers, "Local surface orientation dominates haptic curvature discrimination," *IEEE Trans. Haptics*, vol. 2, no. 2, pp. 94–102, Apr.–Jun. 2009.

[27] T. Yoshioka, J. C. Craig, G. C. Beck, and S. S. Hsiao, "Perceptual constancy of texture roughness in the tactile system," *J. Neuroscience*, vol. 31, no. 48, pp. 17603–17611, 2011.

[28] M. Wiertlewski, C. Hudin, and V. Hayward, "On the 1/f noise and non-integer harmonic decay of the interaction of a finger sliding on flat and sinusoidal surfaces," in *Proc. IEEE World Haptics Conf.*, 2011, pp. 25–30.

[29] X. Libouton, O. Barbier, Y. Berger, L. Plaghki, and J.-L. Thonnard, "Tactile roughness discrimination of the finger pad relies primarily on vibration sensitive afferents not necessarily located in the hand," *Behavioural Brain Res.*, vol. 229, no. 1, pp. 273–279, 2012.

[30] B. Delhaye, V. Hayward, P. Lefèvre, and J.-L. Thonnard, "Texture-induced vibrations in the forearm during tactile exploration," *Frontiers Behavioral Neuroscience*, vol. 6, no. 37, pp. 1–10, 2012.

[31] T. Amemiya and H. Gomi, "Distinct pseudo-attraction force sensation by a thumb-sized vibrator that oscillates asymmetrically," in *Proc. Int. Conf. Human Haptic Sens. Touch Enabled Comput. Appl.*, Jun. 2014, pp. 88–95.

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

[33] G. Ambrosi, A. Bicchi, D. De Rossi, and E. P. Scilingo, "The role of the contact area spread rate in haptic discrimination of softness," *IEEE Trans. Robot. Autom.*, vol. 16, no. 5, pp. 496–504, Oct. 2000.

[34] R. Ackerley, E. Eriksson, and J. Wessberg, "Ultra-late EEG potential evoked by preferential activation of unmyelinated tactile afferents in human hairy skin," *Neuroscience Lett.*, vol. 535, pp. 62–66, 2013.

[35] H. Olausson et al., "Functional role of unmyelinated tactile afferents in human hairy skin: Sympathetic response and perceptual localization," *Exp. Brain Res.*, vol. 184, no. 1, pp. 135–140, 2008.

[36] R. Ackerley, I. Carlsson, H. Wester, H. Olausson, and H. B. Wasling, "Touch perceptions across skin sites: Differences between sensitivity, direction discrimination and pleasantness," *Frontiers Behavioral Neuroscience*, vol. 8, 2014, Art. no. 54.

[37] N. D. Sylvester and W. R. Provancher, "Effects of longitudinal skin stretch on the perception of friction," in *Proc. IEEE World Haptics Conf.*, 2007, pp. 373–378.

[38] M. J. Adams et al., "Finger pad friction and its role in grip and touch," *J. Roy. Soc. Interface*, vol. 10, no. 80, 2013, Art. no. 20120467.

[39] S. Derler and G.-M. Rotaru, "Stick-slip phenomena in the friction of human skin," *Wear*, vol. 301, pp. 324–329, 2013.

[40] Q. Wang and V. Hayward, "In vivo biomechanics of the fingerpad skin under local tangential traction," *J. Biomechanics*, vol. 40, no. 4, pp. 851–860, 2007.

[41] V. Hayward and M. Cruz-Hernandez , "Tactile display device using distributed lateral skin stretch," in *Proc. Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst.*, 2000, vol. 69, Art. no. 2.

[42] V. Hayward, A. V. Terekhov, S. C. Wong, P. Geborek, F. Bengtsson, and H. Jörntell, "Spatio-temporal skin strain distributions evoke low variability spike responses in cuneate neurons," *J. Roy. Soc. Interface*, vol. 11, no. 93, 2014, Art. no. 20131015.

[43] O. Al Atassi , S. Fani, A. Terekhov, V. Hayward, M. Ernst, and A. Bicchi, "A change in the fingertip contact area induces an illusory displacement of the finger," in *Proc. Int. Conf. Human Haptic Sens. Touch Enabled Comput. Appl.*, 2014, Art. no. 72.

[44] B. B. Edin and N. Johansson, "Skin strain patterns provide kinaesthetic information to the human central nervous system," *J. Physiology*, vol. 487, pp. 243–251, 1995.

[45] G. M. Goodwin, D. I. McCloskey, and P. B. Matthews, "Proprioceptive illusions induced by muscle vibration: Contribution by muscle spindles to perception?" *Science*, vol. 175, no. 4028, pp. 1382–1384, 1972.

[46] P. Cordo, V. S. Gurfinkel, L. Bevan, and G. K. Kerr, "Proprioceptive consequences of tendon vibration during movement," *J. Neurophysiology*, vol. 74, no. 4, pp. 1675–1688, 1995.

[47] G. Robles-De-La-Torre and V. Hayward, "Force can overcome object geometry in the perception of shape through active touch," *Nature*, vol. 412, no. 6845, pp. 445–448, 2001.

[48] V. Hayward and O. R. Astley, "Performance measures for haptic interfaces," in *Robotics Research*. London, U.K.: Springer-Verlag, 1996, pp. 195–206.

[49] Y. Tsumaki, H. Naruse, D. N. Nenchev, and M. Uchiyama, "Design of a compact 6-DOF haptic interface," in *Proc. IEEE Int. Conf. Robot. Autom.*, 1998, vol. 3, pp. 2580–2585.

[50] T. H. Massie and J. K. Salisbury, "The PHANTOM haptic interface: A device for probing virtual objects," in *Proc. ASME Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst.*, 1994, vol. 55, no. 1, pp. 295–300.

[51] G. Millet, S. Haliyo, S. Regnier, and V. Hayward, "The ultimate haptic device: First step," in *Proc. IEEE World Haptics Conf.*, 2009, pp. 273–278.

[52] D. C. Ruspini, K. Kolarov, and O. Khatib, "The haptic display of complex graphical environments," in *Proc. Annu. Conf. Comput. Graph. Interactive Techn.*, 1997, pp. 345–352.

[53] S. Grange, F. Conti, P. Rouiller, P. Helmer, and C. Baur, "Overview of the Delta haptic device," in *Proc. Int. Conf. Human Haptic Sens. Touch Enabled Comput. Appl.*, 2001, Art. no. 164.

[54] N. Gurari and G. Baud-Bovy, "Customization, control, and characterization of a commercial haptic device for high-fidelity rendering of weak forces," *J. Neuroscience Methods*, vol. 235, pp. 169–180, 2014.

[55] J. J. Gil, Á. Rubio, and J. Savall, "Decreasing the apparent inertia of an impedance haptic device by using force feedforward," *IEEE Trans. Control Syst. Technol.*, vol. 17, no. 4, pp. 833–838, Jul. 2009.

[56] D. F. Collins, K. M. Refshauge, G. Todd, and S. C. Gandevia, "Cutaneous receptors contribute to kinesthesia at the index finger, elbow, and knee," *J. Neurophysiology*, vol. 94, no. 3, pp. 1699–1706, 2005.

[57] K. Shikata, Y. Makino, and H. Shinoda, "Inducing elbow joint flexion by shear deformation of arm skin," in *Proc. IEEE World Haptics Conf.*, 2015.

[58] P. Cordo, V. S. Gurfinkel, L. Bevan, and G. K. Kerr, "Proprioceptive consequences of tendon vibration during movement," *J. Neurophysiology*, vol. 74, no. 4, pp. 1675–1688, 1995.

[59] M. Konyo, H. Yamada, S. Okamoto, and S. Tadokoro, "Alternative display of friction represented by tactile stimulation without tangential force," in *Proc. Int. Conf. Human Haptic Sens. Touch Enabled Comput. Appl.*, 2008, pp. 619–629.

[60] B. B. Edin, "Cutaneous afferents provide information about knee joint movements in humans," *J. Physiology*, vol. 531, no. 1, pp. 289–297, 2001.

[61] M. Baumann, K. E. MacLean, T. W. Hazelton, and A. McKay, "Emulating human attention-getting practices with wearable haptics," in *Proc. IEEE Haptics Symp.*, 2010, pp. 149–156.

[62] K. Bark, J. Wheeler, P. Shull, J. Savall, and M. Cutkosky, "Rotational skin stretch feedback: A wearable haptic display for motion," *IEEE Trans. Haptics*, vol. 3, no. 3, pp. 166–176, Jul.–Sep. 2010.

[63] M. Bianchi et al., "Design and preliminary affective characterization of a novel fabric-based tactile display," in *Proc. IEEE Haptics Symp.*, 2014, pp. 591–596.

[64] H. Z. Tan, R. Gray, J. J. Young, and R. Traylor, "A haptic back display for attentional and directional cueing," *Haptics-e*, vol. 3, no. 1, pp. 1–20, 2003.

[65] S. Ertan, C. Lee, A. Willets, H. Z. Tan, and A. Pentland, "A wearable haptic navigation guidance system," in *Proc. Int. Symp. Wearable Comput.*, 1998, pp. 164–165.

[66] J. Cha, M. Eid, L. Rahal, and A. E. Saddik, "HugMe: An interpersonal haptic communication system," in *Proc. IEEE Int. Workshop Haptic Audio Visual Environ. Games*, 2008, pp. 99–102.

[67] J. K. S. Teh, A. D. Cheok, Y. Choi, C. L. Fernando, R. L. Peiris, and O. N. N. Fernando, "Huggy pajama: A parent and child hugging communication system," in *Proc. Int. Conf. Interaction Des. Children*, 2009, pp. 290–291.

[68] F. Arafsha, K. M. Alam, and A. El Saddik, "EmoJacket: Consumer centric wearable affective jacket to enhance emotional immersion," in *Proc. Int. Conf. Innovations Inf. Technol.*, 2012, pp. 350–355.

[69] E. Gunther and S. O'Modhrain, "Cutaneous grooves: Composing for the sense of touch," *J. New Music Res.*, vol. 32, no. 4, pp. 369–381, 2003.

[70] M. Giordano et al., "Design and implementation of a whole-body haptic suit for "ilinx", a multisensory art installation," in *Proc. 12th Int. Conf. Sound Music Comput.*, 2015, pp. 169–175.

[71] O. Spakov, J. Rantala, and P. Isokoski, "Sequential and simultaneous tactile stimulation with multiple actuators on head, neck and back for gaze cuing," in *Proc. IEEE World Haptics Conf.*, 2015, pp. 333–338.

[72] T. McDaniel, S. Krishna, V. Balasubramanian, D. Colbry, and S. Panchanathan, "Using a haptic belt to convey non-verbal communication cues during social interactions to individuals who are blind," in *Proc. IEEE Int. W. Haptic Audio Visual Environ. Games*, 2008, pp. 13–18.

[73] N. Edwards et al., "A pragmatic approach to the design and implementation of a vibrotactile belt and its applications," in *Proc. IEEE Int. W. Haptic Audio Visual Environ. Games*, 2009, pp. 13–18.

[74] V. Buchmann, M. Billinghurst, and A. Cockburn, "Directional interfaces for wearable augmented reality," in *Proc. ACM SIGCHI New Zealand Chapter's Int. Conf. Human-Comput. Interaction: Des. Centered HCI*, 2008, pp. 47–54.

[75] D. Tsetserukou, "HaptiHug: A novel haptic display for communication of hug over a distance," in *Proc. Int. Conf. Haptics: Generating Perceiving Tangible Sensations*, 2010, pp. 340–347.

[76] V. Zatsiorsky and B. Prilutsky, *Biomechanics of Skeletal Muscles*. Champaign, IL, USA: Human Kinetics, 2012.

[77] A. Chiri, N. Vitiello, F. Giovacchini, S. Roccella, F. Vecchi, and M. C. Carrozza, "Mechatronic design and characterization of the index finger module of a hand exoskeleton for post-stroke rehabilitation," *IEEE/ASME Trans. Mechatronics*, vol. 17, no. 5, pp. 884–894, Oct. 2012.

[78] F. Gemperle, C. Kasabach, J. Stivoric, M. Bauer, and R. Martin, "Design for wearability," in *Proc. Int. Symp. Wearable Comput.*, 1998, pp. 116–122.

[79] B. Buchholz, T. J. Armstrong, and S. A. Goldstein, "Anthropometric data for describing the kinematics of the human hand," *Ergonomics*, vol. 35, no. 3, pp. 261–273, 1992.

[80] C. Wagner, "The pianist's hand: Anthropometry and biomechanics," *Ergonomics*, vol. 31, no. 1, pp. 97–131, 1988.

[81] A. Frisoli, M. Solazzi, F. Salsedo, and M. Bergamasco, "A fingertip haptic display for improving curvature discrimination," *Presence: Teleoperators Virtual Environ.*, vol. 17, no. 6, pp. 550–561, 2008.

[82] F. Salsedo, M. Bergamasco, A. Frisoli, and G. Cini, "Portable haptic interface," U.S. Patent WO2 006 054 163 A3, 2005.

[83] M. Solazzi, A. Frisoli, and M. Bergamasco, "Design of a novel finger haptic interface for contact and orientation display," in *Proc. IEEE Haptics Symp.*, 2010, pp. 129–132.

[84] M. Solazzi, A. Frisoli, and M. Bergamasco, "Design of a cutaneous fingertip display for improving haptic exploration of virtual objects," in *Proc. IEEE Int. Symp. Robots Human Interactive Commun.*, 2010, pp. 1–6.

[85] M. Gabardi, M. Solazzi, D. Leonardis, and A. Frisoli, "A new wearable fingertip haptic interface for the rendering of virtual shapes and surface features," in *Proc. IEEE Haptics Symp.*, 2016, pp. 140–146.

[86] C. Pacchierotti, A. Tirmizi, and D. Prattichizzo, "Improving transparency in teleoperation by means of cutaneous tactile force feedback," *ACM Trans. Appl. Perception*, vol. 11, no. 1, 2014, Art. no. 4.

[87] M. Kim, I. Jang, Y. Lee, Y. Lee, and D. Lee, "Wearable 3-DOF cutaneous haptic device with integrated IMU-based finger tracking," in *Proc. Int. Conf. Ubiquitous Robots Ambient Intell.*, 2016, pp. 649–649.

[88] D. Prattichizzo, C. Pacchierotti, S. Cenci, K. Minamizawa, and G. Rosati, "Using a fingertip tactile device to substitute kinesthetic feedback in haptic interaction," in *Proc. Int. Conf. Haptics: Generating Perceiving Tangible Sensations*, 2010, pp. 125–130.

[89] C. Pacchierotti, F. Chinello, and D. Prattichizzo, "Cutaneous device for teleoperated needle insertion," in *Proc. IEEE RAS EMBS Int. Conf. Biomed. Robot. Biomechatronics*, 2012, pp. 32–37.

[90] L. Meli, S. Scheggi, C. Pacchierotti, and D. Prattichizzo, "Wearable haptics and hand tracking via an RGB-D camera for immersive tactile experiences," in *Proc. ACM Special Interest Group Comput. Graph. Interactive Techn. Conf. Posters*, 2014, Art. no. 56.

[91] S. Scheggi, L. Meli, C. Pacchierotti, and D. Prattichizzo, "Touch the virtual reality: Using the Leap Motion controller for hand tracking and wearable tactile devices for immersive haptic rendering," in *Proc. ACM Special Interest Group Comput. Graph. Interactive Techn. Conf. Posters*, 2015, Art. no. 31.

[92] B. B. Edin, L. Ascari, L. Beccai, S. Roccella, J.-J. Cabibihan, and M. Carrozza, "Bio-inspired sensorization of a biomechatronic robot hand for the grasp-and-lift task," *Brain Res. Bulletin*, vol. 75, no. 6, pp. 785–795, 2008.

[93] G. Westling and R. S. Johansson, "Responses in glabrous skin mechanoreceptors during precision grip in humans," *Exp. Brain Res.*, vol. 66, no. 1, pp. 128–140, 1987.

[94] F. Chinello, M. Malvezzi, C. Pacchierotti, and D. Prattichizzo, "Design and development of a 3RRS wearable fingertip cutaneous device," in *Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechatronics*, 2015, pp. 293–298.

[95] A. G. Perez et al., "Optimization-based wearable tactile rendering," *IEEE Trans. Haptics*, 2017.

[96] Y. Shimizu, S. Saida, and H. Shimura, "Tactile pattern recognition by graphic display: Importance of 3-D information for haptic perception of familiar objects," *Perception Psychophysics*, vol. 53, no. 1, pp. 43–48, 1993.

[97] R. D. Howe, W. J. Peine, D. A. Kantarinis, and J. S. Son, "Remote palpation technology," *IEEE Eng. Med. Biol. Mag.*, vol. 14, no. 3, pp. 318–323, May/Jun. 1995.

[98] S.-C. Kim et al., "Small and lightweight tactile display (SaLT) and its application," in *Proc. 3rd Joint EuroHaptics Conf. Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst.*, 2009, pp. 69–74.

[99] I. Sarakoglou, N. Tsagarakis, and D. G. Caldwell, "A portable fingertip tactile feedback array-transmission system reliability and modelling," in *Proc. 1st Joint Eurohaptics Conf. Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst.*, 2005, pp. 547–548.

[100] I. Sarakoglou, N. G. Tsagarakis, and D. G. Caldwell, "A compact tactile display suitable for integration in VR and teleoperation," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2012, pp. 1018–1024.

[101] I. Sarakoglou, N. Garcia-Hernandez , N. G. Tsagarakis, and D. G. Caldwell, "A high performance tactile feedback display and its integration in teleoperation," *IEEE Trans. Haptics*, vol. 5, no. 3, pp. 252–263, Jul.–Sep. 2012.

[102] D. G. Caldwell, N. Tsagarakis, and C. Giesler, "An integrated tactile/shear feedback array for stimulation of finger mechanoreceptor," in *Proc. IEEE Int. Conf. Robot. Autom.*, 1999, vol. 1, pp. 287–292.

[103] D. G. Caldwell, G. Medrano-Cerda, and M. Goodwin, "Characteristics and adaptive control of pneumatic muscle actuators for a robotic elbow," in *Proc. IEEE Int. Conf. Robot. Autom.*, 1994, pp. 3558–3563.

[104] I. M. Koo, K. Jung, J. C. Koo, J.-D. Nam, Y. K. Lee, and H. R. Choi, "Development of soft-actuator-based wearable tactile display," *IEEE Trans. Robot.*, vol. 24, no. 3, pp. 549–558, Jun. 2008.

[105] G. Frediani, D. Mazzei, D. E. De Rossi, and F. Carpi, "Wearable wireless tactile display for virtual interactions with soft bodies," *Frontiers Bioengineering Biotechnol.*, vol. 2, 2014, Art. no. 31.

[106] J. C. Bliss, J. W. Hill, and B. Wilber, *Characteristics of the Tactile Information Channel*. Washington, DC, USA: National Aeronautics and Space Administration, 1969.

[107] E. G. Johnsen and W. R. Corliss, *Human Factors Applications in Teleoperator Design and Operation*. New York, NY, USA: Wiley-Interscience, 1971.

[108] K. B. Shimoga, "A survey of perceptual feedback issues in dexterous telemanipulation. II. Finger touch feedback," in *Proc. IEEE Virtual Reality Annu. Int. Symp.*, 1993, pp. 271–279.

[109] Y. Kim, S. Kim, T. Ha, I. Oakley, W. Woo, and J. Ryu, "Air-jet button effects in AR," in *Proc. 16th Int. Conf. Advances Artif. Reality Tele-Existence*, 2006, pp. 384–391.

[110] G. Moy, C. Wagner, and R. S. Fearing, "A compliant tactile display for teletaction," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2000, vol. 4, pp. 3409–3415.

[111] J. C. Gwilliam, A. Degirmenci, M. Bianchi, and A. M. Okamura, "Design and control of an air-jet lump display," in *Proc. IEEE Haptics Symp.*, 2012, pp. 45–49.

[112] D. Tsetserukou, S. Hosokawa, and K. Terashima, "LinkTouch: A wearable haptic device with five-bar linkage mechanism for presentation of two-DOF force feedback at the fingerpad," in *Proc. IEEE Haptics Symp.*, 2014, pp. 307–312.

[113] D. Leonardis, M. Solazzi, I. Bortone, and A. Frisoli, "A wearable fingertip haptic device with 3 DoF asymmetric 3-RSR kinematics," in *Proc. IEEE World Haptics Conf.*, 2015, pp. 388–393.

[114] D. Leonardis, M. Solazzi, I. Bortone, and A. Frisoli, "A 3-RSR haptic wearable device for rendering fingertip contact forces," *IEEE Trans. Haptics*, 2016.

[115] B. Gleeson, S. Horschel, and W. R. Provancher, "Design of a fingertip-mounted tactile display with tangential skin displacement feedback," *IEEE Trans. Haptics*, vol. 3, no. 4, pp. 297–301, Oct.–Dec. 2010.

[116] M. Solazzi, W. R. Provancher, A. Frisoli, and M. Bergamasco, "Design of a SMA actuated 2-DoF tactile device for displaying tangential skin displacement," in *Proc. IEEE World Haptics Conf.*, 2011, pp. 31–36.

[117] C. Pacchierotti, G. Salvietti, I. Hussain, L. Meli, and D. Prattichizzo, "The hRing: A wearable haptic device to avoid occlusions in hand tracking," in *Proc. IEEE Haptics Symp.*, 2016, pp. 134–139.

[118] M. Bianchi, E. Battaglia, M. Poggiani, S. Ciotti, and A. Bicchi, "A wearable fabric-based display for haptic multi-cue delivery," in *Proc. IEEE Haptics Symp.*, 2016, pp. 277–283.

[119] A. Girard, M. Marchal, F. Gosselin, A. Chabrier, F. Louveau, and A. Lécuyer, "HapTip: Displaying haptic shear forces at the fingertips for multi-finger interaction in virtual environments," *Frontiers ICT*, vol. 3, 2016, Art. no. 6.

[120] S. B. Schorr and A. Okamura, "Three-dimensional skin deformation as force substitution: Wearable device design and performance during haptic exploration of virtual environments," *IEEE Trans. Haptics*, 2017.

[121] S. Pabon et al., "A data-glove with vibro-tactile stimulators for virtual social interaction and rehabilitation," in *Proc. Annu. Int. Workshop Presence*, 2007.

[122] F. Sanfilippo, L. I. Hatledal, and K. Pettersen, "A fully–immersive hapto–audio–visual framework for remote touch," in *Proc. IEEE Int. Conf. Innovations Inf. Technol.*, 2015.

[123] J. Foottit, D. Brown, S. Marks, and A. Connor, "Development of a wearable haptic game interface," *EAI Endorsed Trans. Creative Technol.*, vol. 16, no. 6, Apr. 2016, Art. no. e5.

[124] W. Provancher, M. Cutkosky, K. Kuchenbecker, and G. Niemeyer, "Contact location display for haptic perception of curvature and object motion," *Int. J. Robot. Res.*, vol. 24, no. 9, pp. 691–702, 2005.

[125] W. R. Provancher, K. J. Kuchenbecker, G. Niemeyer, and M. R. Cutkosky, *Perception of Curvature and Object Motion Via Contact Location Feedback*. Berlin, Germany: Springer, 2005, pp. 456–465.

[126] R. L. Koslover, B. T. Gleeson, J. T. De Bever, and W. R. Provancher, "Mobile navigation using haptic, audio, and visual direction cues with a handheld test platform," *IEEE Trans. Haptics*, vol. 5, no. 1, pp. 33–38, Jan.–Mar. 2012.

[127] D. Prattichizzo, F. Chinello, C. Pacchierotti, and K. Minamizawa, "RemoTouch: A system for remote touch experience," in *Proc. IEEE Int. Symp. Robots Human Interactive Commun.*, 2010, pp. 676–679.

[128] I. Hussain, G. Salvietti, L. Meli, C. Pacchierotti, and D. Prattichizzo, "Using the robotic sixth finger and vibrotactile feedback for grasp compensation in chronic stroke patients," in *Proc. IEEE/RAS-EMBS Int. Conf. Rehabil. Robot.*, 2015, pp. 67–72.

[129] M. Bianchi, “A fabric-based approach for wearable haptics,” *Electronics*, vol. 5, no. 3, 2016, Art. no. 44.

[130] I. Bortone et al., “Serious game and wearable haptic devices for neuro motor rehabilitation of children with cerebral palsy,” in *Converging Clinical and Engineering Research on Neurorehabilitation II*. Cham, Switzerland: Springer, 2017, pp. 443–447.

[131] L.-T. Cheng, R. Kazman, and J. Robinson, “Vibrotactile feedback in delicate virtual reality operations,” in *Proc. ACM Int. Conf. Multimedia*, 1997, pp. 243–251.

[132] Y. Kurita, M. Shinohara, and J. Ueda, “Wearable sensorimotor enhancer for fingertip based on stochastic resonance effect,” *IEEE Trans. Human-Mach. Syst.*, vol. 43, no. 3, pp. 333–337, May 2013.

[133] J. M. Romano, S. R. Gray, N. T. Jacobs, and K. J. Kuchenbecke, “Toward tactilely transparent gloves: Collocated slip sensing and vibrotactile actuation,” in *Proc. 3rd Joint EuroHaptics Conf. Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst.*, 2009, pp. 279–284.

[134] S. Krishna, S. Bala, T. McDaniel, S. McGuire, and S. Panchanathan, “VibroGlove: An assistive technology aid for conveying facial expressions,” in *Proc. Int. Conf. Human Factors Comput. Syst.*, 2010, pp. 3637–3642.

[135] Y. Muramatsu, M. Niitsuma, and T. Thomessen, “Perception of tactile sensation using vibrotactile glove interface,” in *Proc. IEEE Int. Conf. Cognitive Infocommunications*, 2012, pp. 621–626.

[136] P. Galambos and P. Baranyi, “Vibrotactile force feedback for telemanipulation: Concept and applications,” in *Proc. IEEE Int. Conf. Cognitive Infocommunications*, 2011, pp. 1–6.

[137] D. Bial, D. Kern, F. Alt, and A. Schmidt, “Enhancing outdoor navigation systems through vibrotactile feedback,” in *Proc. Int. Conf. Human Factors Comput. Syst.*, 2011, pp. 1273–1278.

[138] A. M. Murray, R. L. Klatzky, and P. K. Khosla, “Psychophysical characterization and testbed validation of a wearable vibrotactile glove for telemanipulation,” *Presence: Teleoperators Virtual Environ.*, vol. 12, no. 2, pp. 156–182, 2003.

[139] P. Heo, G. M. Gu, S.-J. Lee, K. Rhee, and J. Kim, “Current hand exoskeleton technologies for rehabilitation and assistive engineering,” *Int. J. Precision Eng. Manuf.*, vol. 13, no. 5, pp. 807–824, 2012.

[140] M. M. Foumashi, M. Troncossi, and V. P. Castelli, “State-of-the-art of hand exoskeleton systems,” Internal Report Università di Bologna–DIEM. 2011. [Online]. Available: http://amsacta.unibo.it/3198/1/Mozaffari-et-al_2011.pdf

[141] H. In, K.-J. Cho, K. Kim, and B. Lee, “Jointless structure and under-actuation mechanism for compact hand exoskeleton,” in *Proc. IEEE Int. Conf. Rehabil. Robot.*, 2011, pp. 1–6.

[142] H. In, B. B. Kang, M. Sin, and K.-J. Cho, “Exo-Glove: Soft wearable robot for the hand with soft tendon routing system,” *IEEE Robot. Autom. Mag.*, vol. 22, no. 1, pp. 97–105, Mar. 2015.

[143] R. M. Pierce, E. A. Fedalei, and K. J. Kuchenbecker, “A wearable device for controlling a robot gripper with fingertip contact, pressure, vibrotactile, and grip force feedback,” in *Proc. IEEE Haptics Symp.*, 2014, pp. 19–25.

[144] R. M. Khurshid, N. Fitter, E. Fedalei, and K. Kuchenbecker, “Effects of grip-force, contact, and acceleration feedback on a teleoperated pick-and-place task,” *IEEE Trans. Haptics*, vol. 10, no. 1, pp. 40–53, Jan.–Mar. 2017.

[145] J. Iqbal, N. Tsagarakis, and D. Caldwell, “Four-fingered lightweight exoskeleton robotic device accommodating different hand sizes,” *Electron. Lett.*, vol. 51, no. 12, pp. 888–890, 2015.

[146] M. Bergamasco, “Design of hand force feedback systems for glove-like advanced interfaces,” in *Proc. IEEE Int. Workshop Robot Human Commun.*, 1992, pp. 286–293.

[147] M. Bergamasco–, “Haptic interfaces: The study of force and tactile feedback systems,” in *Proc. IEEE Int. Workshop Robot Human Commun.*, 1995, pp. 15–20.

[148] C. A. Avizzano, F. Bargagli, A. Frisoli, and M. Bergamasco, “The hand force feedback: Analysis and control of a haptic device for the human-hand,” in *Proc. IEEE Int. Conf. Syst. Man Cybern.*, 2000, vol. 2, pp. 989–994.

[149] M. Fontana, A. Dettori, F. Salsedo, and M. Bergamasco, “Mechanical design of a novel hand exoskeleton for accurate force displaying,” in *Proc. IEEE Int. Conf. Robot. Autom.*, 2009, pp. 1704–1709.

[150] D. Leonardis et al., “An EMG-controlled robotic hand exoskeleton for bilateral rehabilitation,” *IEEE Trans. Haptics*, vol. 8, no. 2, pp. 140–151, Apr.–Jun. 2015.

[151] T. Koyama, I. Yamano, K. Takemura, and T. Maeno, “Multi-fingered exoskeleton haptic device using passive force feedback for dexterous teleoperation,” in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2002, vol. 3, pp. 2905–2910.

[152] S. L. Springer and N. J. Ferrier, “Design and control of a force-reflecting haptic interface for teleoperational grasping,” *J. Mech. Des.*, vol. 124, no. 2, pp. 277–283, 2002.

[153] Y. Tanaka, H. Yamauchi, and K. Amemiya, “Wearable haptic display for immersive virtual environment,” in *Proc. JFPS Int. Symp. Fluid Power*, 2002, pp. 309–314.

[154] M. Bouzit, G. Burdea, G. Popescu, and R. Boian, “The Rutgers Master II-new design force-feedback glove,” *IEEE/ASME Trans. Mechatronics*, vol. 7, no. 2, pp. 256–263, Jun. 2002.

[155] P. Heo and J. Kim, “Power-assistive finger exoskeleton with a palmar opening at the fingerpad,” *IEEE Trans. Biomed. Eng.*, vol. 61, no. 11, pp. 2688–2697, Nov. 2014.

[156] K. Tadano, M. Akai, K. Kadota, and K. Kawashima, “Development of grip amplified glove using bi-articular mechanism with pneumatic artificial rubber muscle,” in *Proc. IEEE Int. Conf. Robot. Autom.*, 2010, pp. 2363–2368.

[157] H. Du, W. Xiong, Z. Wang, and L. Chen, “Design of a new type of pneumatic force feedback data glove,” in *Proc. Int. Conf. Fluid Power Mechatronics*, 2011, pp. 292–296.

[158] W. Surendra, A. Tjahyono, and K. C. Aw, “Portable and wearable five-fingered hand assistive device,” in *Proc. Int. Conf. Mechatronics Mach. Vis. Practice*, 2012, pp. 431–435.

[159] I. Koo, B. B. Kang, and K.-J. Cho, “Development of hand exoskeleton using pneumatic artificial muscle combined with linkage,” *J. Korean Soc. Precision Eng.*, vol. 30, no. 11, pp. 1217–1224, 2013.

[160] I. Sarakoglou, N. G. Tsagarakis, and D. G. Caldwell, “Occupational and physical therapy using a hand exoskeleton based exerciser,” in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2004, vol. 3, pp. 2973–2978.

[161] A. Wege and G. Hommel, “Development and control of a hand exoskeleton for rehabilitation of hand injuries,” in *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, 2005, pp. 3046–3051.

[162] S. B. Godfrey, R. J. Holley, and P. S. Lum, “Clinical effects of using HEXORR (hand exoskeleton rehabilitation robot) for movement therapy in stroke rehabilitation,” *Amer. J. Phys. Med. Rehabil.*, vol. 92, no. 11, pp. 947–958, 2013.

[163] M. Mulas, M. Folgheraiter, and G. Gini, “An EMG-controlled exoskeleton for hand rehabilitation,” in *Proc. Int. Conf. Rehabil. Robot.*, 2005, pp. 371–374.

[164] E. B. Brokaw, I. Black, R. J. Holley, and P. S. Lum, “Hand spring operated movement enhancer (HandSOME): A portable, passive hand exoskeleton for stroke rehabilitation,” *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 19, no. 4, pp. 391–399, Aug. 2011.

[165] Y. Fu, Q. Zhang, F. Zhang, and Z. Gan, “Design and development of a hand rehabilitation robot for patient-cooperative therapy following stroke,” in *Proc. Int. Conf. Mechatronics Autom.*, 2011, pp. 112–117.

[166] J. Lee and J. Bae, “Design of a hand exoskeleton for biomechanical analysis of the stroke hand,” in *Proc. IEEE Int. Conf. Rehabil. Robot.*, 2015, pp. 484–489.

[167] B. B. Kang, H. In, and K. Cho, “Force transmission in joint-less tendon driven wearable robotic hand,” in *Proc. Int. Conf. Control Autom. Syst.*, 2012, pp. 1853–1858.

[168] J. Arata, K. Ohmoto, R. Gassert, O. Lambercy, H. Fujimoto, and I. Wada, “A new hand exoskeleton device for rehabilitation using a three-layered sliding spring mechanism,” in *Proc. IEEE Int. Conf. Robot. Autom.*, 2013, pp. 3902–3907.

[169] C. J. Nycz, T. Bützer, O. Lambercy, J. Arata, G. S. Fischer, and R. Gassert, “Design and characterization of a lightweight and fully portable remote actuation system for use with a hand exoskeleton,” *IEEE Robot. Autom. Lett.*, vol. 1, no. 2, pp. 976–983, Jul. 2016.

[170] P. Polygerinos, Z. Wang, K. C. Galloway, R. J. Wood, and C. J. Walsh, “Soft robotic glove for combined assistance and at-home rehabilitation,” *Robot. Auton. Syst.*, vol. 73, pp. 135–143, 2015.

[171] B. Allotta, R. Conti, L. Governi, E. Meli, A. Ridolfi, and Y. Volpe, “Development and experimental testing of a portable hand exoskeleton,” in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2015, pp. 5339–5344.

[172] R. Conti, B. Allotta, E. Meli, and A. Ridolfi, “Development, design and validation of an assistive device for hand disabilities based on an innovative mechanism,” *Robotica*, pp. 1–15, 2015.

[173] R. Conti, E. Meli, and A. Ridolfi, "A novel kinematic architecture for portable hand exoskeletons," *Mechatronics*, vol. 35, pp. 192–207, 2016.

[174] Z. Ma and P. Ben-Tzvi, "RML glove—An exoskeleton glove mechanism with haptics feedback," *IEEE/ASME Trans. Mechatronics*, vol. 20, no. 2, pp. 641–652, Apr. 2015.

[175] Z. Ma and P. Ben-Tzvi , "Design and optimization of a five-finger haptic glove mechanism," *J. Mechanisms Robot.*, vol. 7, no. 4, 2015, Art. no. 041008.

[176] P. Agarwal, J. Fox, Y. Yun, M. K. O'Malley, and A. D. Deshpande, "An index finger exoskeleton with series elastic actuation for rehabilitation: Design, control and performance characterization," *Int. J. Robot. Res.*, vol. 34, no. 14, pp. 1747–1772, 2015.

[177] H. Kim, M. Kim, and W. Lee, "HapThimble: A wearable haptic device towards usable virtual touch screen," in *Proc. CHI Conf. Human Factors Comput. Syst.*, 2016, pp. 3694–3705.

[178] I. Choi, E. W. Hawkes, D. L. Christensen, C. J. Ploch, and S. Follmer, "Wolverine: A wearable haptic interface for grasping in virtual reality," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2016, pp. 986–993.

[179] M. Achibet et al., "FlexiFingers: Multi-finger interaction in VR combining passive haptics and pseudo-haptics," in *Proc. IEEE Symp. 3D User Interfaces*, 2017, pp. 103–106.

[180] O. Lambercy, D. Schröder, S. Zwicker, and R. Gassert, "Design of a thumb exoskeleton for hand rehabilitation," in *Proc. Int. Convention Rehabil. Eng. Assistive Technol.*, 2013, Art. no. 41.

[181] M. Bianchi, F. Fanelli, L. Giordani, A. Ridolfi, F. Vannetti, and B. Allotta, "An automatic scaling procedure for a wearable and portable hand exoskeleton," in *Proc. IEEE Int. Forum Res. Technol. Soc. Ind. Leveraging Better Tomorrow*, 2016, pp. 1–5.

[182] H. Uchiyama, M. A. Covington, and W. D. Potter, "Vibrotactile glove guidance for semi-autonomous wheelchair operations," in *Proc. Annu. Southeast Regional Conf.*, 2008, pp. 336–339.

[183] Y. Kim, J. Cha, I. Oakley, and J. Ryu, "Exploring tactile movies: An initial tactile glove design and concept evaluation," *IEEE MultiMedia*, 2009.

[184] A. Mazzoni and N. Bryan-Kinns, "Mood glove: A haptic wearable prototype system to enhance mood music in film," *Entertainment Comput.*, vol. 17, pp. 9–17, 2016.

[185] P. Stergiopoulos, P. Fuchs, and C. Laurgeau, "Design of a 2-finger hand exoskeleton for VR grasping simulation," *Proc. Int. Conf. Human Haptic Sens. Touch Enabled Comput. Appl.*, 2003, pp. 80–93.

[186] M. J. Lelieveld, T. Maeno, and T. Tomiyama, "Design and development of two concepts for a 4 DOF portable haptic interface with active and passive multi-point force feedback for the index finger," in *Proc. ASME Int. Des. Eng. Tech. Conf. Comput. Inf. Eng. Conf.*, 2006, pp. 547–556.

[187] J. Yang, H. Xie, and J. Shi, "A novel motion-coupling design for a jointless tendon-driven finger exoskeleton for rehabilitation," *Mechanism Mach. Theory*, vol. 99, pp. 83–102, 2016.

[188] A. Chiri et al., "HANDEXOS: Towards an exoskeleton device for the rehabilitation of the hand," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2009, pp. 1106–1111.

[189] A. Chiri et al., "On the design of ergonomic wearable robotic devices for motion assistance and rehabilitation," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, 2012, pp. 6124–6127.

[190] T. Lenzi et al., "The neuro-robotics paradigm: NEURARM, NEUROExos, HANDEXOS," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, 2009, pp. 2430–2433.

[191] M. Cempini et al., "Kinematics and design of a portable and wearable exoskeleton for hand rehabilitation," in *Proc. IEEE Int. Conf. Rehabil. Robot.*, 2013, pp. 1–6.

[192] M. Cempini, M. Cortese, and N. Vitiello, "A powered finger–thumb wearable hand exoskeleton with self-aligning joint axes," *IEEE/ASME Trans. Mechatronics*, vol. 20, no. 2, pp. 705–716, Apr. 2015.

[193] S. R. Soekadar, M. Witkowski, N. Vitiello, and N. Birbaumer, "An EEG/EOG-based hybrid brain-neural computer interaction (BNCI) system to control an exoskeleton for the paralyzed hand," *Biomed. Eng./Biomedizinische Technik*, vol. 60, no. 3, pp. 199–205, 2015.

[194] J. Iqbal, N. Tsagarakis, A. E. Fiorilla, and D. Caldwell, "Design requirements of a hand exoskeleton robotic device," in *Proc. IASTED Int. Conf. Robot. Appl.*, 2009, vol. 664, no. 81, pp. 44–51.

[195] J. Iqbal, N. G. Tsagarakis, A. E. Fiorilla, and D. G. Caldwell, "A portable rehabilitation device for the hand," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, 2010, pp. 3694–3697.

[196] J. Iqbal, N. G. Tsagarakis, and D. G. Caldwell, "A multi-DOF robotic exoskeleton interface for hand motion assistance," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, 2011, pp. 1575–1578.

[197] J. Iqbal, N. Tsagarakis, and D. Caldwell, "Design of a wearable direct-driven optimized hand exoskeleton device," in *Proc. Int. Conf. Advances Comput.-Human Interactions*, 2011, pp. 23–28.

[198] J. Iqbal, H. Khan, N. G. Tsagarakis, and D. G. Caldwell, "A novel exoskeleton robotic system for hand rehabilitation–conceptualization to prototyping," *Biocybernetics Biomed. Eng.*, vol. 34, no. 2, pp. 79–89, 2014.

[199] J. Iqbal, N. Tsagarakis, and D. Caldwell, "Human hand compatible underactuated exoskeleton robotic system," *Electron. Lett.*, vol. 50, no. 7, pp. 494–496, 2014.

[200] M. Sarac, M. Solazzi, D. Leonardis, E. Sotgiu, M. Bergamasco, and A. Frisoli, "Design of an underactuated hand exoskeleton with joint estimation," in *Advances in Italian Mechanism Science*. Berlin, Germany: Springer, 2017, pp. 97–105.

[201] U. Gollner, T. Bieling, and G. Joost, "Mobile Lorm glove: Introducing a communication device for deaf-blind people," in *Proc. Int. Conf. Tangible Embedded Embodied Interaction*, 2012, pp. 127–130.

[202] J. Martínez, A. García, M. Oliver, J. Molina Masso, and P. González, "Identifying 3D geometric shapes with a vibrotactile glove," *IEEE Comput. Graph. Appl.*, vol. 36, no. 1, pp. 42–51, Jan./Feb. 2016.

[203] G. Sziebig, B. Solvang, C. Kiss, and P. Korondi, "Vibro-tactile feedback for VR systems," in *Proc. 2nd Conf. Human Syst. Interactions*, 2009, pp. 406–410.

[204] L. Hayes, "Vibrotactile feedback-assisted performance," in *Proc. Int. Conf. New Interfaces Musical Expression*, 2011, pp. 72–75.

[205] A. Karime, H. Al-Osman , W. Gueaieb, and A. El Saddik, "E-glove: An electronic glove with vibro-tactile feedback for wrist rehabilitation of post-stroke patients," in *Proc. IEEE Int. Conf. Multimedia Expo*, 2011, pp. 1–6.

[206] A. Hein and M. Brell, "conTACT—A vibrotactile display for computer aided surgery," in *Proc. 2nd Joint EuroHaptics Conf. Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst.*, 2007, pp. 531–536.

[207] J. S. Zelek, S. Bromley, D. Asmar, and D. Thompson, "A haptic glove as a tactile-vision sensory substitution for wayfinding," *J. Visual Impairment Blindness*, vol. 97, no. 10, pp. 1–24, 2003.

[208] L. I. Lugo-Villeda, A. Frisoli, S. Pabon, M. A. Padilla, E. Sotgiu, and M. Bergamasco, "Light-exoskeleton and data-glove integration for enhancing virtual reality applications," in *Proc. Int. Conf. Adv. Robot.*, 2009, pp. 1–6.

[209] E. Giannopoulos, A. Pomes, and M. Slater, "Touching the void: Exploring virtual objects through a vibrotactile glove," *Int. J. Virtual Reality*, vol. 11, pp. 19–24, 2012.

[210] J. Foottit, D. Brown, S. Marks, and A. M. Connor, "An intuitive tangible game controller," in *Proc. Conf. Interactive Entertainment*, 2014, pp. 1–7.

[211] F. Delbressine et al., "Motivating arm-hand use for stroke patients by serious games," in *Proc. Int. Conf. IEEE Eng. Med. Biol. Soc.*, 2012, pp. 3564–3567.

[212] C.-Y. Lin, C.-M. Tsai, P.-C. Shih, and H.-C. Wu, "Development of a novel haptic glove for improving finger dexterity in poststroke rehabilitation," *Technol. Health Care*, vol. 24, no. s1, pp. S97–S103, 2015.

[213] T. Estes, D. Backus, and T. Starner, "A wearable vibration glove for improving hand sensation in persons with spinal cord injury using passive haptic rehabilitation," in *Proc. Int. Conf. Pervasive Comput. Technol. Healthcare*, 2015, pp. 37–44.

[214] Newzoo, "Global games market report Q1," 2016. [Online]. Available: https://newzoo.com/insights/articles/global-games-market-reaches-99–6-billion-2016-mobile-generating-37/

[215] W. Provancher, "Creating greater VR immersion by emulating force feedback with ungrounded tactile feedback," *IQT Quart.*, vol. 6, no. 2, pp. 18–21, 2014.

[216] H. Benko, C. Holz, M. Sinclair, and E. Ofek, "NormalTouch and TextureTouch: High-fidelity 3D haptic shape rendering on handheld virtual reality controllers," in *Proc. Annu. Symp. User Interface Softw. Technol.*, 2016, pp. 717–728.

[217] C. Grant, "On eve of VR launches, hands-on with a new haptic ideal," 2016. [Online]. Available: https://web.archive.org/web/20160325214035/http://www.polygon.com/virtual-reality/2016/3/25/11306368/tactai-haptics-vr-virtual-reality-touch

[218] J. Gaudiosi, "Tactai gets in touch with Ericsson for AR and VR 'dynamic tactile wave' tech," 2017. [Online]. Available: https://uploadvr.com/tactai-touch-ericsson/

[219] A. Sand, I. Rakkolainen, P. Isokoski, J. Kangas, R. Raisamo, and K. Palovuori, "Head-mounted display with mid-air tactile feedback," in *Proc. 21st ACM Symp. Virtual Reality Softw. Technol.*, 2015, pp. 51–58.

[220] B. Lang, "Hands-on: Tactical haptics' vive demo is further proof that VR needs more than rumble," 2015. [Online]. Available: https://web.archive.org/web/20160312220656/http://www.roadtovr.com/tactical-haptics-htc-vive-demo-virtual-reality-feedback-rumble/

[221] K. Bye, "Tricking the brain is the only way to achieve a total haptics solution," 2017. [Online]. Available: https://web-beta.archive.org/web/20170121102102/http://www.roadtovr.com/tricking-brain-way-achieve-total-haptics-solution

[222] Gallup, "Gallup social series: Work and education," 2015. [Online]. Available: http://www.gallup.com/poll/184649/telecommuting-work-climbs.aspx

[223] C. Pacchierotti, D. Prattichizzo, and K. J. Kuchenbecker, "Cutaneous feedback of fingertip deformation and vibration for palpation in robotic surgery," *IEEE Trans. Biomed. Eng.*, vol. 63, no. 2, pp. 278–287, Feb. 2016.

[224] S. A. Mascaro and H. H. Asada, "Measurement of finger posture and three-axis fingertip touch force using fingernail sensors," *IEEE Trans. Robot. Autom.*, vol. 20, no. 1, pp. 26–35, Feb. 2004.

[225] Y. Tanaka, A. Sano, M. Ito, and H. Fujimoto, "A novel tactile device considering nail function for changing capability of tactile perception," in *Proc. Int. Conf. Human Haptic Sens. Touch Enabled Comput. Appl.*, 2008, pp. 543–548.

Claudio Pacchierotti (S'12-M'15) received the BS, MS, and PhD degrees from the University of Siena, Italy, in 2009, 2011, and 2014, respectively. He spent the first seven months of 2014 visiting the Penn Haptics Group, University of Pennsylvania, Philadelphia, which is part of the General Robotics, Automation, Sensing, and Perception (GRASP) Laboratory. He also visited the Department of Innovation in Mechanics and Management, University of Padua and the Institute for Biomedical Technology and Technical Medicine (MIRA), University of Twente, in 2013 and 2014, respectively. He received the 2014 EuroHaptics Best PhD Thesis Award for the best doctoral thesis in the field of haptics, and the 2015 Meritorious Service Award for his work as a reviewer for the *IEEE Transactions on Haptics*. He was a postdoctoral researcher in the Department of Advanced Robotics, Italian Institute of Technology, Genova, Italy, in 2015 and 2016, respectively. He is currently a CR2 researcher in the CNRS at Irisa and Inria Rennes Bretagne Atlantique, Rennes, France. His research deals with robotics and haptics, focusing on cutaneous force feedback techniques, wearable devices, and haptics for robotic surgery. He is a member of the IEEE.

Stephen Sinclair received the PhD degree in music technology from McGill University, Montreal, QC, Canada, in 2012. He pursued a postdoctoral fellowship with the Université Pierre et Marie Curie (Paris VI), Paris, France, in the Institut des Systèmes Intelligents et de Robotique. He is currently a research engineer at Inria Chile, Santiago de Chile. His research interests include haptic display, sensory integration, human-machine interaction, audio and signal processing, numerical simulation, and robotics. He is a member of the IEEE.

Massimiliano Solazzi received the PhD degree in innovative technologies from Scuola Superiore Sant'Anna, in 2010. He is an assistant professor in applied mechanics with the Scuola Superiore Sant'Anna, Pisa, Italy. He carries out his research at the PERCRO Laboratory-TeCIP. His research interests concerns: the design of robotic interfaces for virtual reality, teleoperation and rehabilitations, and the psychophysical validation of HMI. He is a member of the IEEE.

Antonio Frisoli received the MSc degree in mechanical engineering, in 1998, and the PhD degree (with Hons.) in industrial and information engineering from Scuola Superiore Sant'Anna, Italy, in 2002. He is an associate professor of mechanical engineering with Scuola Superiore Sant'Anna, where he is currently head of the HRI area at PERCRO Laboratory-TeCIP and former chair of the IEEE Technical Committee on Haptics. His research interests concern the design and control of haptic devices and robotic systems, rehabilitation robotics, advanced HRI, and kinematics. He is a member of the IEEE.

Vincent Hayward (F'08) received the Dr-Ing degree from the University of Paris XI, Paris, France, in 1981. He was a postdoctoral fellow and then as a visiting assistant professor with Purdue University, in 1982, and joined CNRS, Paris, France, as Charge de Recherches, in 1983. In 1987, he joined the Department of Electrical and Computer Engineering, McGill University, Montreal, QC, Canada, as an assistant, associate and then full professor in 2006. He was the director of the McGill Center for Intelligent Machines from 2001 to 2004 and held the "Chaire internationale d'haptique" with the Université Pierre et Marie Curie (UPMC), Paris, France, from 2008 to 2010. He is currently a professor (on leave) with UPMC. Since January 2017, he has been sharing his time between a professorship of tactile perception and technology in the School of Advanced Studies, University of London, supported by a Leverhulme Trust Fellowship and serving as the chief scientific officer of Actronika SAS in Paris. His current research interests include haptic device design, haptic perception, and robotics. He is a fellow of the IEEE.

Domenico Prattichizzo (F'16) received the PhD degree in robotics and automation from the University of Pisa, in 1995. Since 2002, he has been an associate professor of robotics with the University of Siena and since 2009, he has been a scientific consultant at Istituto Italiano di Tecnologia. In 1994, he was a visiting scientist in the MIT AI Lab. Since 2014, he has been an associate editor of the *Frontiers on Robotics and AI*. From 2007 to 2013, he was associate editor in chief of the *IEEE Transactions on Haptics*. From 2003 to 2007, he was associate editor of the *IEEE Transactions on Robotics* and the *IEEE Transactions on Control Systems Technologies*. He has been chair of the Italian Chapter of the IEEE RAS (2006-2010), and was awarded with the IEEE 2009 Chapter of the Year Award. His reseach interests include haptics, grasping, visual servoing, mobile robotics, and geometric control. He is currently the coordinator of the IP collaborative project "WEARable HAPtics for Humans and Robots" (WEARHAP). He is a fellow of the IEEE.