

Smart Tactile Gloves for Haptic Interaction, Communication, and Rehabilitation

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Wearable human machine interfaces (HMI) such as smart gloves have attracted considerable interest in recent years. The quality of the interactive experience with the real and virtual world using wearable HMI technologies depends on the intuitive two-way haptic interfaces they offer and the real-time touch-based information they send and receive. Herein, various smart glove solutions and their application in interaction, rehabilitation, virtual (VR) and augmented reality (AR), and augmentative and alternative communication (AAC) tasks are reviewed. While the early variants of such systems were based on commercial touch sensors and displays integrated (e.g., stitched) on wearables, electronic skin (e-skin)-type technologies with multifunctional capabilities are being explored nowadays for rich user experience and comfort. In this regard, instead of using separate touch sensors and actuators, miniaturized integrated devices providing both touch sensing and vibrotactile actuation have also been reported recently. Such advances, the associated challenges, and the advantages they offer for users to enjoy the full characteristic benefits of VR/ARs for interaction, immersion, and imagination are discussed. Finally, the huge potential the smart-glove-type solutions hold for advances in various application areas such as robotics, health care, sensorial augmentation for nondisabled and tactile Internet is also discussed.

as 5G/6G communication,^[12] the Internet of things (IoT),^[13] tactile Internet,^[14] machine learning,^[15] and neural computing,^[16] one can only see bright prospects for smart wearable technologies such as intelligent human machine interfaces (HMIs).^[17] The HMI is at the center of efficient collaboration between humans and the rapidly advancing digitalized world.^[18,19] Although human interaction with the real or virtual world takes place through the five basic sensory modalities, the majority of HMI technologies rely on vision, audio, and touch-sensing modalities. The latter is the major modality when it comes to physical interaction.^[2,20,21] However, sensory feedback alone is not enough as the two-way tactile communication from the contact point to the controlling unit (e.g., the brain in the case of humans)^[10,22] is important for any effective interaction. To achieve two-way tactile communication, an interface that has the capability of sensing a stimulus and receiving feedback is desired. For example, with interactive VR/AR systems, the user can


1. Introduction

Smart wearable technologies are rapidly revolutionizing our interactive experience with the real and virtual world through a variety of virtual and augmented reality (VR/AR) systems^[1,2] as well as underpinning advances in several technological areas touching life, such as healthcare technologies,^[3,4] assistive technologies,^[5–7] smart homes,^[8] and robotics.^[9–11] With the remarkable progress in related underpinning technologies such

send information via touch sensors and receive signals via different modalities, including visual, auditory, haptic, vestibular, and olfactory stimuli. VR tools that use computer-based interactive simulations to enable users to engage in environments that appear and feel similar to the real world are considered to be considerably useful for rehabilitation.^[23,24] Likewise, the AR systems can infuse interactive virtual elements into the physical environment and thus supplement the real world.^[23]

The quality of the user experience with these systems depends on the intuitive interface offered by these systems, and their ability to provide easy-to-understand information. However, most VR/AR systems primarily provide visual and auditory feedback, which does not provide verisimilar immersive experiences. This is particularly unsuitable for people with impaired senses, such as the deaf and blind.^[25] Conventionally, the HMI has involved gadgets such as keyboards, joysticks, mice, screens, and Braille. However, the majority of these gadgets have one of more drawbacks, such as being bulky and nonintuitive, having low precision for monitoring human motions or transmitting complex commands, and having no capability to generate a feedback signal based on tactile sensing. As the requirement for richer, more versatile, and seamless interactions rises, researchers have explored several wearable options with sensors based on various sensing mechanisms such as capacitive,^[9,26–29]

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piezoresistive,^[30,31] piezoelectric,^[32] optical,^[2] and triboelectric.^[33] Through these sensors, various physical parameters necessary for the perception of external stimuli (e.g., pressure, temperature, strain, shear force, vibration)^[34] are measured and used for the delivery of information or to control a machine. Advances in fields such as material sciences has further led to the realization of novel wearable and implantable devices^[35] with flexible, stretchable form factors and features such as disposability or degradability.^[35,36] These devices can conformally attach to the human body to accurately detect stimuli such as slight motion, pressure, or physiological signals.^[37,38] These advances in sensing mechanisms have created more opportunities for the realization of smart and user-friendly glove-based HMIs, and some of the aforementioned sensors are already being explored to realize HMIs in different forms such as touchpads, arm/wrist bands, vests, and gloves.^[39] The glove-based HMI tools are becoming popular because the hands are involved in most of the manipulation tasks and gestures.^[39] The glove-based devices have also found application in rehabilitation, augmentative and alternative communication (AAC),^[40] and interactive VR/AR systems.

With technological advances leading to faster interactive devices, there is a need to explore how they could also improve the overall user experience, and to suit a variety of users, such as deafblind people who have impaired vision and hearing modalities. Such aspects are considered in this article with multidisciplinary inputs spanning across fields such as material science, engineering, human–computer interaction, and robotics. This Review focuses mainly on tactile smart gloves utilizing tactile sensing and feedback; for kinesthetic force feedback gloves we refer the reader to Caeiro-Rodríguez et al.^[39] We have discussed the existing wearable smart tactile gloves for VR/AR interaction, AAC, and rehabilitation and present the e-skin as an alternative interface for better user experience and more. This discussion is motivated by the recent advances in e-skin,^[41] haptics,^[41,42] and the IoT,^[43] which have brought huge benefits in several applications, including conformable wearable systems, interactive holograms,^[2] robotics, and health monitoring. Due to limited sensory modality, the designing and development of devices for interaction among deafblind people presents a worst-case scenario. Therefore, we envisage that any HMI developed to be usable by deafblind people could also be applied in the majority of other interactions where a human–human or HMI is used by sighted and hearing people.

The rest of the article is organized as follows. Touch sensing in humans is discussed in Section 2 as it often serves as the inspiration for the design of artificial tactile skins. In fact, the design requirements for smart gloves follows the discussion on the human tactile system. Various technologies for wearable tactile gloves are presented in Section 3 to provide the reader an overview of current state-of-the-art devices and their limitations. Many of the smart gloves reported so far use independent sensing and actuation devices, which often leads to integration complexity due to limited space. The recent technological solutions reported to address such challenges are discussed in Section 4. These include the technology advances showing tactile sensors and actuators as single devices and their integration in smart gloves for a rich interactive experience. Such advances also offer new opportunities, which are discussed in Section 5 along with current and potential future challenges. The key outcomes are

summarized in Section 6, where future directions are also discussed. The comprehensive discussion presented in this article is expected to benefit researchers and practitioners aiming to develop intuitive smart tactile gloves for various applications.

2. Human Tactile Sensing and Requirements for Designing Smart Gloves

The skin is the largest organ of the human body and the primary tactile interface that plays a vital role in human interaction with the external world.^[44] It is also a means of communicating visual and audio information using the densely packed mechanoreceptors distributed all over the body. To develop an effective interactive tactile communication interface, it is important to understand the psychophysics of the human skin, as well as the communication methods used by deafblind people—who present a worst-case scenario for development of intuitive haptic interfaces. This section summarizes the important human skin characteristics that have inspired many works related to tactile sensing and perception, and includes a summary of the communication methods used by deafblind people.

2.1. Tactile Sensing and Perception Mechanism

Knowledge of the psychophysics of the human tactile system is essential to realize an effective tactile communication interface that provides realistic feelings. The human tactile system is well developed, with the skin at the center of it. The human sense of touch is grouped into cutaneous and kinesthetic sense based on the site of the sensory input.^[34] The cutaneous sense has different kinds of sensory receptors, such as mechanoreceptors (respond to mechanical stimulation), thermoreceptors (respond to thermal stimulation), and nociceptors (respond to the sensation of pain). The cutaneous sense receives sensory input from the receptors (cold, warm, pain receptors and mechanoreceptors) embedded in the skin, while the kinesthetic sense receives sensory input from the receptors within muscles, tendons, and joints. The human skin is densely packed with different types of mechanoreceptors, which are part of the several sensory receptors that translate tactile stimuli to the brain in the form of electric nerve impulses.^[45–47] These electric nerve impulses are information encoded as action potentials (time between voltage spikes),^[48] which are then interpreted in the brain.^[47] **Table 1** summarizes the various characteristics of the mechanoreceptors of the human skin. Mechanoreceptors are particularly concerned with the interpretation of mechanical stimuli such as force, vibration, and movement at the surface of the skin.^[46,47] They are classified into two types: 1) slow-adapting receptors (SA-I and SA-II), which respond to static and quasi-static stimuli—meaning that they produce a sustained signal in response to a sustained stimulus—and 2) fast-adapting receptors (FA-I and FA-II), which respond to dynamic stimuli such as vibrations.^[38,44,49] **Figure 1** shows these receptors and the mechanism of the human tactile perception. This starts from the time a stimulus is presented to the skin, followed by the stimuli being encoded by the relevant mechanoreceptor as an action potential. This action potential is sent to the synapses via the nerve fibers, and the information is then processed further by the synapses and sent to the brain,

Table 1. Characteristics of the various mechanoreceptors of the human skin.

	FA I Meissner	SA I Merkel	FA II Pacianian	SA II Ruffini
Field diameter ^{a)} [mm]	3–4	3–4	>20	>10
Mean receptive area ^{a)}	12.6 mm ²	11 mm ²	101 mm ²	59 mm ²
Spatial acuity ^{b)}	poor 3–4 mm	0.5 mm	10+	7+
Frequency range	8–200 Hz	DC–200 Hz	50 – 1000 Hz	DC–200 Hz
Most excited frequency range ^{a)}	8–64 Hz	2–32 Hz	>64 Hz	<8 Hz
Indentation threshold ^{b)}	6 μm	30 μm	0.08 μm	300 μm
Response properties ^{c)}	Responsive to dynamic skin deformations at relatively low frequency (≈5–50 Hz)	Responsive to dynamic skin deformations at low frequency (≈<5 Hz)	Extremely responsive to high-frequency vibration (≈40–400 Hz)	Low responsiveness to dynamic force; responsive to static force
Density and location ^{a),c)}	70–140 cm ⁻² in dermal papillae of the fingertip	70–140 cm ⁻² in fingertip epidermis	20 cm ⁻² in dermal and subcutaneous tissue, distributed throughout the hand	50 cm ⁻² in dermal and subcutaneous tissue, distributed throughout the hand

^{a)}Adapted from ref. [47]; ^{b)}Adapted from ref. [34]; ^{c)}Adapted from ref. [167].

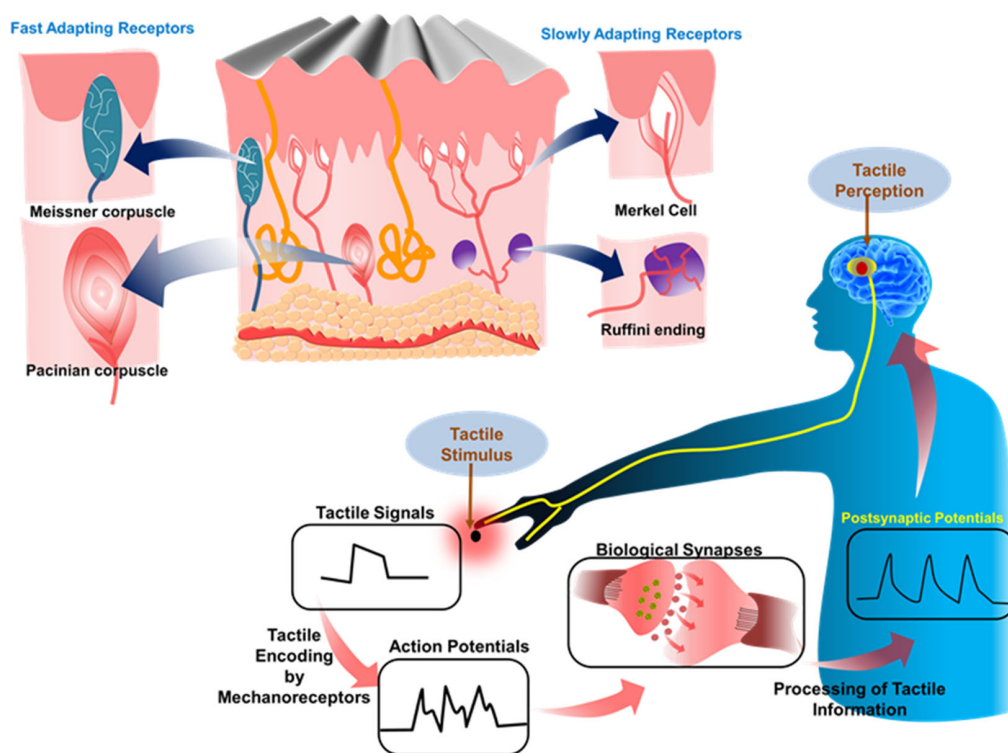


Figure 1. The human skin structure and the flow of tactile information. Adapted with permission.^[159] Copyright 2020, Wiley.

which interprets it. The efficiency of the human tactile sensation is enhanced by its specialized layered structure. The dermis and epidermis of the skin have specialized microridges between the dermis and epidermis junction that help to amplify the tactile stimuli.^[50] As a result of the rich properties and functionalities of the human tactile system, it can be a means of communication for auditory and visual information, or both, as in the case of deafblind people.

The thermal properties of the human skin are another key feature to understand while trying to develop biomimetic devices such as smart gloves for various interactions, including VR/AR. The poor thermal conductivity of the human skin (thermal conductivity of $0.37 \text{ W m}^{-1} \text{ K}^{-1}$ and poor thermal diffusivity of $10^{-7} \text{ m}^2 \text{ s}^{-1}$) enables it to sustain the temperature of the human body.^[51] However, the human skin reliably senses external temperature through its highly responsive thermoreceptors.^[51] Just

as with the mechanoreceptors, these thermoreceptors enable bidirectional thermal interactions of the skin with the environment.

The various characteristics of the receptors (mechanoreceptors and thermoreceptors) as discussed in this section endow the skin with specific perceivable thresholds for different parts of the body to different stimuli, as discussed in the following section.

2.2. Tactile Perception Threshold

In this section, the different thresholds for human tactile perception to different stimulations, such as pressure, vibration, and temperature, as well as spatial characteristics of the skin are presented. Although there are different mechanoreceptors in the skin, its tactile reception results from a combination of receptors in a particular skin area. As a result, the skin responds to different thresholds of tactile stimulus and this depends on several factors, such as location, contact area, type, and duration of the stimulus, age, gender, and even hormone levels.^[46,52,53] The perceived intensity of stimulation is also determined by the depth and the rate of skin indentation. In terms of age, the difference in vibrotactile detection for a glabrous finger is less pronounced at lower ($\approx 5\text{--}10\text{ Hz}$) than at higher frequencies ($\approx 300\text{ Hz}$).^[47,53,54] Generally, for vibrotactile applications, the target is to stimulate the FA-II, which is extremely responsive to frequency vibration of $\approx 40\text{--}400\text{ Hz}$.

In terms of pressure, the sensitivity of a specific part of the body to pressure is inversely proportional to the applied pressure, and the perception threshold depends on the part being considered.^[34,47,55] The human detectable indent corresponding to different areas of the palm is around $\approx 10\text{--}50\ \mu\text{m}$,^[56] and the pressure exerted by a tactile device should be above $\approx 60\text{ mN cm}^{-2}$ to adequately stimulate the finger mechanoreceptor.^[57] A 5 mN force is sufficient to excite 90% of the SA-I and FA-I mechanoreceptors^[56] and a force of 87 mN mm^{-2} could be applied with a Von Frey hair with a diameter of $\approx 0.27\text{ mm}$.^[34] For tangential forces, more sensitivity is observed at the forearm in comparison with the normal forces, whereas at the finger pad sensitivity to tangential forces is lower than to normal force.^[58] Based on this, some guidelines have been reported as a consideration for the development of tactile displays. This includes 1) that tangential stimulation should be a superior choice when an actuator is limited primarily in terms of peak displacement and 2) that normal stimulation should be a superior choice on the finger pad (and tangential on hairy skin) when an actuator is limited primarily in terms of peak force.^[58,59]

Considering surface exploration, $0.85\ \mu\text{m}$ has been reported as the minimum perceivable height of a static raised feature on a smooth surface and small dots $\approx 40\ \mu\text{m}$ in diameter and $8\ \mu\text{m}$ in height can be detected $\approx 75\%$ of the time with active scanning.^[47] The human skin is sensitive to spatial differences at the frequency bands of $\approx 1\text{--}3$ and $18\text{--}32\text{ Hz}$ (this corresponds to the frequency range of FA-I and SA-I receptors), and spatial acuities gradually decrease as the frequency of vibration increases over $\approx 50\text{ Hz}$.^[60] However, it is known that vibration perception varies with age^[61] and vibration is perceived differently at different frequencies. The effects of vibration frequency, pulse-width duty

cycle, number of contactors, on differential thresholds, examined at five different areas of the hand, show a variation with the frequency and number of active contactors with highest sensitivity observed at $\approx 120\text{ Hz}$.^[62] The vibration range of $\approx 20\text{--}1000\text{ Hz}$ is perceivable with maximum sensitivity around $\approx 250\text{ Hz}$, which corresponds to the frequency range of FA-II receptors.^[63] For vibrotactile perception of the human finger, the sensitivity is shown to increase as the frequency increases, with the exception of very high frequencies.^[60] Based on the perception capabilities of the human hand, a summary of the requirements of a tactile display is given in **Table 2**.

For the hand to effectively read an array of haptic actuators, it is important to consider spatial resolution as this will aid effective discrimination of individual stimulation. A spatial resolution of $\approx 1\text{ mm}$ is recommended for the fingertips and $\approx 5\text{ mm}$ for less sensitive areas such as the palm and shoulders.^[34] However, the significant loss of receptors with age affects tactile sensitivity and the ability to discriminate vibrotactile patterns.^[64,65] The experiments show that older adults (60 years and above) are able to reliably identify only a simple one-element vibrotactile pattern, whereas younger subjects can master even three to four elements.^[65,66] It is therefore important to pay attention to this age-related tactile threshold in the design of tactile aids, particularly for deafblind people as a majority of them are older people. Tactile aids for deafblind people often involve rapid tactile processing of information, such as reading of Braille. Experienced adult Braille readers can read at the rate of ≈ 104 words per minute.^[67] This means that they are meant to scan $\approx 100\text{--}300$ separate Braille cells with one fingertip in $\approx 60\text{ s}$. Braille cells are composed of one to six raised dots, which are about $\approx 1.5\text{ mm}$ diameter at the base, and are separated by 2.3 mm from each other, and by 4.1 mm from the nearest dots in adjacent cells.^[68]

Thermoreceptors in the different parts of the human body vary in density and sensitivity, and are made up of cold and warm receptors, which operate at different temperature ranges and at different depths. Cold receptors are relatively more in number, respond faster (typically in the range of $10\text{--}20\text{ ms}^{-1}$), and are located closer to the surface of the skin ($\approx 0.15\text{--}0.17\text{ mm}$), in

Table 2. Requirements of a tactile display based on the perception of the human hand.

Spatial resolution	$\approx 1\text{ mm}$ (fingertips), $\approx 5\text{ mm}$ (other less sensitive areas)
Perceivable skin indentation	≈ 10 to $\approx 50\ \mu\text{m}^{\text{a}}$
Minimum perceivable height of raised features	$\approx 0.85\ \mu\text{m}^{\text{b}}$
Perceivable diameter of a raised feature	$\approx 40\ \mu\text{m}$ (for a $\approx 8\ \mu\text{m}$ feature height) ^b
Frequency requirements	Frequency bandwidth: $0\text{--}1000\text{ Hz}^{\text{c}}$ Temporal resolution: 1 ms
Displacement requirements	Max. displacement (per actuator): 0.3 cm Static displacement resolution: 0.02 cm Dynamic displacement resolution: $10^{-5\text{c}}$
Force Requirements	Dynamic range: $0\text{--}10\text{ N}^{\text{c}}$; resolution: 0.01 N

^a)Adapted from ref. [56]; ^b)Adapted from ref. [59]; ^c)Adapted from ref. [47].

comparison to the warm receptors, which are located at a depth of $\approx 0.3\text{--}0.6$ mm, with the speed of their afferent fibers ranging from ≈ 1 to 2 m s^{-1} . Considering sensitivity, the fingertips, for instance, are less sensitive to temperature in comparison to the lips. The human skin has a thermal neutral zone ($30\text{--}36^\circ\text{C}$), within which it experiences no thermal sensation. The cold receptors are triggered below ($<30^\circ\text{C}$) this thermal neutral zone, and the warm receptors are triggered above it ($36\text{--}50^\circ\text{C}$).^[51,69] However, when the temperature of the human skin exceeds 45°C or falls below 15°C , it activates the nociceptors, which induce the sensation of pain.^[49] Thus, wearable thermal haptics for AR should operate in the temperature range from 15 to 45°C . Furthermore, it is paramount not to change the core temperatures of the human body below 33°C and above 41°C , which can lead to loss of consciousness and is detrimental to the human body.^[50] Other factors such as the location of the stimulation, the magnitude, and the rate of change of thermal activation should be considered while designing thermal haptics and sensors for AR.^[51] These fundamental understandings of the thermal interaction between thermoreceptors and external objects will provide a framework for designing thermal haptics and sensors to stimulate and receive information from the human skin.

More details on the emerging thermal technologies and design strategies for haptic-enabled AR can be found in Parida et al.^[51]

The perception thresholds presented in this section would be a key starting point for anyone who would like to design a smart tactile glove capable of recreating human-like sensation, particularly for VR/AR applications.

2.3. Gesture and Touch-Based Approaches for Deafblind People

As mentioned in the Introduction, human interaction is mainly through vision, audio, and touch, but this does not work for deafblind people as they have both impaired vision and hearing modalities^[70]; therefore, they rely on touch sensing. This means it is challenging for them to interact with systems with conventional tactile interfaces such as keyboards. Deafblind people use various tactile and nontactile methods of communication in different circumstances, or at different times of their life. These communication methods include nonverbal (used mainly by people born [congenital] deaf and blind), block alphabets, moon, object, and symbol-based approach, lip reading (e.g., Tadoma), imitation, observation, and Braille. Popularly, the methods used by deafblind people involve either gesture or touch and specifically the common tactile approaches are 1) deafblind manual alphabets^[71] (touch-based) and 2) Braille.

The deafblind manual alphabet is “an alphabet-based method of spelling out words onto a deafblind person’s hand,” in which letters are denoted either by a touch or by movement on the palm, or by a sign with the fingers.^[71] Different deafblind manual alphabets and fingerspelling are used in different countries and/or regions, and are classified into 1) one-handed (uses fingerspelling/gesture-based approach) and 2) two-handed alphabets^[72] (uses touch). The one-handed manual alphabets are touch-based, and the letters are spelt by either opening or closing one or more fingers with the hand held vertically as a gesture. The listener feels the movement by putting their hand over the top of the speaker’s fingers and the back of their hand to feel

orientation of the fingers. A typical example of this is the American deafblind manual alphabet (A-DMA). The two-handed manual alphabet approach is touch-based and in this case, the letters are spelt onto the palm and/or fingers with the other hand (of the speaker). So, the palm of the listener is used as a paper with the speaker using a finger to write on it. The popular alphabets, shown in **Figure 2**, include the British deafblind manual alphabet (B-DMA), used in the UK (Figure 2a,b),^[73] the LORM alphabet used in Austria, parts of Germany, and Poland (Figure 2c),^[74] and the Malossi alphabet (Figure 2d) used in Italy.^[75]

Braille is another touch-based approach used by deafblind people for communication. It is a tactile system of reading and writing founded by Louis Braille and used mainly by the blind community and a minority of deafblind people.^[76] Letters and numbers are represented by raised dots arranged in six-dot Braille cells, as shown in Figure 2e. It is read by moving a finger over a line of Braille cells and shapes outlined by the raised dots are used to mentally determine the alphabet.^[72,77] The Braille-based tactile communication method used by deafblind people in Japan, called Finger Braille, involves the index, middle, and ring fingers of both the left and right hand to represent the six dots of the Braille cell.^[78] To communicate, the sender physically touches these fingers on the recipient’s hand to pass across information (Figure 2f). Finger Braille is simple, easier to learn and use, when compared to the standard Braille reading. So, fabrication of a tactile interface that uses this kind of method would also mean that deafblind people can easily use it for communication.

2.4. Key Requirements of Smart Tactile Gloves

Smart gloves could be used for augmentative and alternative communication and the key requirements for their realization are summarized in **Table 3**. These are qualitative features presented as a guide for researchers interested in this area.

3. Technologies for Wearable Smart Tactile Gloves

This section presents the recent progress in wearable smart gloves, including smart gloves for VR/AR interaction, rehabilitation, as well as AAC. Smart gloves have been used as an interactive HMI for many applications, including, gaming, VR/AR, AAC, and rehabilitation. These are often gloves worn on the hand with integrated sensors (e.g., touch, pressure, flex)^[79] for sensing the pressure, bending, and orientation of the hand. This serves as an input to the machine or system that the user of the glove interacts with. Conventional HMIs such as touchpads, keyboards, and joysticks are gradually being replaced by more intuitive and effective approaches such as voice, vision, or wearable smart gloves. Although the vision and voice-based HMIs have numerous advantages, the issues of privacy and low control accuracy have limited their widespread implementation.^[80]

Considering that the hand plays a vital role in our daily interaction, it has become a very good means of interacting with machines in applications such as manufacturing, training, entertainment, and health care. Following this, researchers have

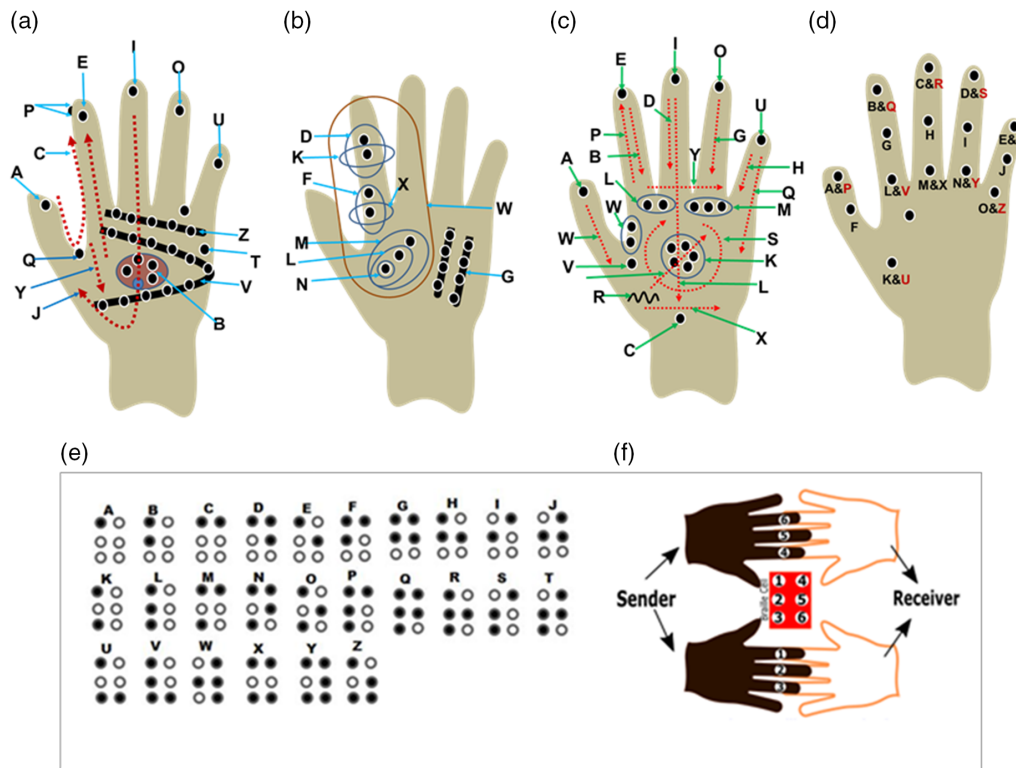


Figure 2. Mapping of tactile points for the communication methods used by deafblind people. a,b) British deafblind manual alphabet. c) Tactile points for the Lorm alphabet method of communication. d) Tactile points for the Malossi alphabet. e) Six-dot Braille cells showing the corresponding English alphabets. f) Physical touching by a deafblind sender on the recipient's hand to pass across information using a finger Braille communication approach.

Table 3. Key requirements of smart gloves.

Feature	Description
Tracking of hand motion	To efficiently track hand motion, a high degree of freedom (DoF) and large motion range are required—up to 23 DoFs: 4 DoFs for each finger (2 for the first joint and 1 for each of the remaining joints) and 3 DoFs for hand rotation.
Haptic feedback	Tactile feedback helps to enhance user experience and for two-way communication during interaction. Considering the thresholds discussed in Section 2.2 and Table 2, haptic feedback could be provided as mechanical vibration, heat, ^[168] surface shape changing and friction modulation, and popularly achieved using vibration motors, linear resonant actuators, voice coils, solenoids, piezoelectric actuators, thermoresistive heaters, Peltier devices, etc.
Wearability	A smart glove should be comfortable to wear, easy to put on to give the user some level of freedom to carry out other functions with the hand.
Size	Gloves could be made with varying sizes or made to be adaptable.
Weight	Because smart gloves are worn on the hand, they should be lightweight, typically varying from ≈50 to ≈300 g.
Power supply	Power supply is key and low power will be a huge advantage. Self-powered gloves should be considered.
Wireless communication	To remotely control machines, wireless communication (e.g., Bluetooth or Wi-Fi based) is preferred.

developed various glove-based HMIs for these applications. These gloves utilize different types of sensors to measure the bending angle, pressure, and/or different orientations of the hand and/or fingers during interaction.^[79] **Figure 3a** summarizes the existing smart gloves, starting from a manual interaction example, where users interact without any device, including the manual measurement of the finger angle using goniometers as used in hand rehabilitation. Figure 1a also shows the three main categories of smart gloves: 1) gesture-based smart gloves (G-SGs); 2) touch-based smart gloves (T-SGs); and 3) gesture

and touch-based smart gloves (GT-SGs). The majority of these gloves either utilize off-the-shelf sensors and rigid actuators for obtaining the contact feature or providing feedback during interaction. For example, a G-SG utilizes either an inertial measurement unit (IMU), strain sensor, or a combination of the two, positioned on different fingers to detect the orientation of the hand and fingers, which is read by an attached circuit.^[81] Specifically, the detection of motion for the distal, middle, and proximal phalanx of each finger has been the priority for most researchers. In T-SGs, the gloves are integrated with touch/

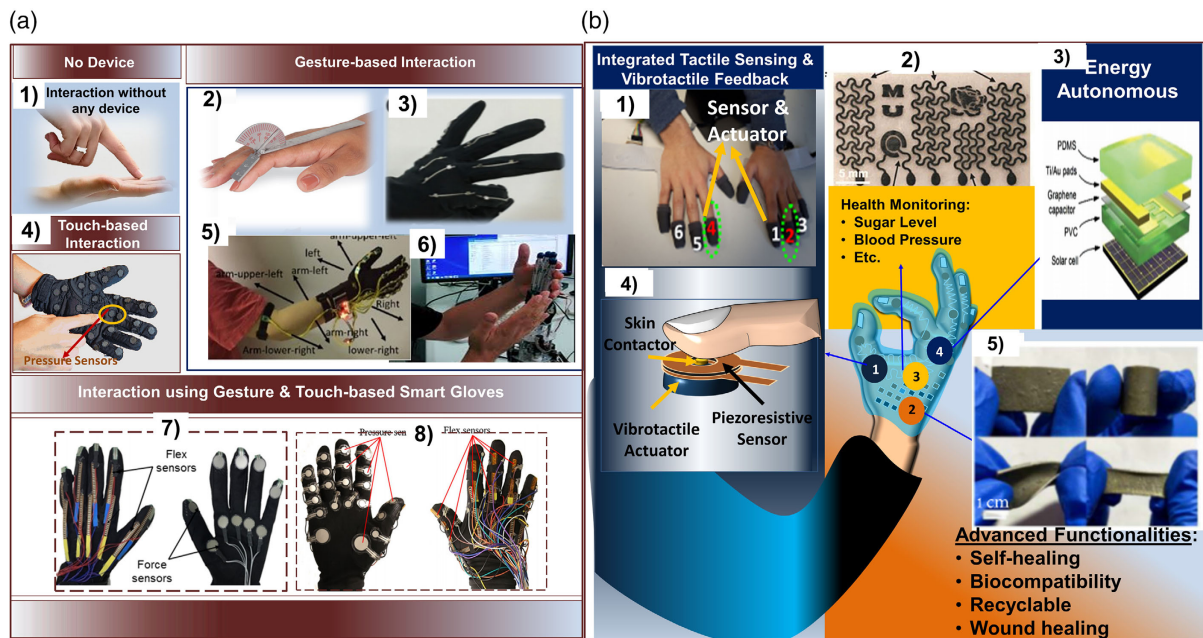


Figure 3. a1) Manual user interaction without any device. a2) Finger angle measurement using a goniometer used by medical practitioners for rehabilitation purposes. This is a manual means of measuring finger angles without any device. Reproduced under the terms of the creative commons (CC-BY 4.0).^[160] Copyright 2021 The Author(s), Published by MDPI. a3) A gesture-based smart glove using a polymer-enhanced highly stretchable conductive fiber strain sensor. Reproduced with permission.^[122] Copyright 2016, Wiley. a4) A touch-based interactive smart glove using the Lorm alphabet method of communication for deafblind people. Reproduced with permission.^[161] Copyright 2012, ACM. a5) IMMU-based data glove for 3D human gesture capturing and recognition. Reproduced with permission.^[81] Copyright 2018, Elsevier. a6) Gesture-based approach using PARLOMA—a novel human–robot interaction system for deafblind remote communication. Reproduced under the terms of the Creative Commons Attribution License (CC-BY 4.0)^[107] Copyright 2015 The Author(s). Licensee InTech. Published by Sage. a7) A wearable hand rehabilitation soft glove combining touch and gesture approach. Reproduced with permission.^[91] Copyright 2021, IEEE. a8) A smart glove utilized for the characterization of the fine hand movement in badminton. Reproduced with permission.^[131] Copyright 2020, Taylor & Francis. b) Reproduced under the terms of the Creative Commons Attribution License (CC BY 4.0).^[6] Copyright 2020, The Author(s), Published by IEEE. b2) Gas-permeable, multifunctional on-skin electronics based on laser-induced porous graphene and sugar-templated elastomer sponges. Reproduced with permission.^[162] Copyright 2018, Wiley. b3) Energy-autonomous e-skin, Reproduced under the terms of Creative Commons Attribution License (CC BY 4.0)^[27] Copyright 2017, The Author(s), Published by Wiley. b4) An assistive smart glove realized with integrated touch sensors and actuators, for communication by deafblind people. Reproduced under the terms of the Creative Commons Attribution License (CC BY 4.0)^[6] Copyright 2020, The Author(s), Published by IEEE. b5) A self-healing and self-powered material for electronic skin application. Reproduced under the terms of the Creative Commons Attribution License (CC-BY)^[164] Copyright 2021 The Author(s), Published by Science and Technology Review Publishing House.

pressure sensors to measure external contact with objects or human touch during interaction. To be able to obtain richer information during interaction, some of the smart gloves measure both the touch and orientation of the hand, and these types of smart gloves can be classified as GT-SGs.^[80] The sensors used in smart gloves include those fabricated using different sensing mechanisms such as piezoresistive, capacitive, and piezoelectric.^[38] The separately integrated components in these gloves do not provide a seamless and intuitive user experience. For example, in smart gloves using IMUs, the precision and accuracy of the hand orientation is dependent on the number and sensitivity of the attached IMUs, and because most of the IMUs utilize the mature micro-electro-mechanical systems (MEMS) technology, they usually offer very good accuracy and repeatability.^[81] However, smart gloves realized purely with IMUs are unable to measure applied forces on the finger or hand, which limits their use. Commercial and custom resistive strain sensors (to measure their bending angle) based on highly stretchable and conformable materials have been used as an alternative.^[82]

The rapid advances in flexible and printed electronics provide timely opportunities to address the aforementioned challenges through development of customizable tactile sensors, actuators, and artificial e-skins. The e-skin-type solutions enabled by flexible electronics, shown in Figure 3b, could advance the glove-based HMIs to provide richer intuitive user experience. These include monolithic integration of both sensing and actuation to realize a seamless interface for both tactile sensing and feedback,^[30] energy autonomy,^[83] which means that these interfaces could even become self-powered^[20,84] and self-healing, biocompatibility, and ability to heal wounds.^[85] Recently, self-powered piezoelectrics an triboelectric sensors and e-skins have also emerge as new options for glove-based HMIs.^[4,20,86] Although the majority of the existing e-skins mainly focus on sensing, integrating actuators on will give them more capabilities such as the ability to provide simultaneous and controllable tactile feedback to the user.^[29,87] With these new salient features, the glove-based HMIs will be able to harness the full potential for interaction and monitoring of health conditions for

elderly people, who form a major part of the deafblind.^[49,88,89] These transformational benefits are also applicable in virtual reality, gaming, etc.

3.1. Gesture Based Smart Gloves

This section focuses on the G-SGs in which the outputs of the integrated sensors or IMUs are used to determine the hand orientations, which are processed using different computation techniques.^[90] Hand gesture is a natural and intuitive human way of interaction, and as a result, gesture-based HMIs have been explored.^[91] These types of smart gloves have been utilized in different applications, including rehabilitation (e.g., stroke rehabilitation), VR/AR, as well as AAC (e.g., communication by deaf-blind people). In general, gesture-based smart gloves are not widely used, and the majority of them utilize vision-based systems,^[92] in which the user's hand is recorded with video and processed using computer algorithms. The vision-based systems restricts the user to a certain space for the camera to adequately capture their gesture, which reduces their wearability and portability. For sophisticated finger movements, vision-based gesture systems may also suffer from issues such as self-occlusion.

Alternatively, gesture-based HMIs using smart gloves with integrated sensors have been explored for the determination of finger orientation^[93] and recognition of several meaningful human expressions. This technology is currently being explored in several areas of rehabilitation, including its use for patients with stroke, Parkinson disease, cerebral palsy, brain injury, and so on.^[94] VR-based rehabilitation has also been investigated for orthopedic patients following hand surgery,^[4] or ankle accident.^[12] Some of these gloves have also been utilized for other interactive manipulation purposes, including gaming and telemanipulation.^[95] Among them, smart tactile gloves for rehabilitation of patients with stroke are among the most popular. These technologies were developed mainly to remedy the limitations and inaccuracies of the manual approach of practitioners using goniometers and questionnaires to measure joint angles to understand rehabilitation progress, respectively. In general, they utilize different types of sensors^[96–98] or IMUs^[25,99,100] to measure the bending angle, pressure, and/or different orientations of the hand and/or fingers during interaction.

In addition to rehabilitation, gesture-based smart gloves have also been utilized for the purpose of augmentative and alternative communication (AAC), for example, to support deafblind people who use the fingerspelling communication method. In this type of communication, different finger gestures are used to communicate letters, words, or phrases, as a result of their vision and hearing impairment.^[40] The majority of the early devices that support

such gesture-based communication are fingerspelling robotic hands, such as the DEXTER series and the Robotic Alphabet (RALPH),^[101] both used for one-way communication.^[102–105] In this case a robotic hand makes a gesture and users physically touch the hand to read the gestures. The talking glove is another gesture-based device for deafblind people.^[106] It consists of a fingerspelling-to-speech system based on a glove with strain gauges embedded at each finger joint to measure the bending angle. Through an adaptive pattern recognition algorithm, the output of sensors is used to determine the intended letter. Although it enables deafblind people to communicate with one another, it is not wearable or portable. Depth sensors have also been used to recognize hand gestures, which are then remotely used to control a fingerspelling robotic hand. The deafblind user touches the robotic hand to interpret the received gesture.^[107] **Table 4** summarizes the gesture-based robotic fingerspelling hands.

CyberGlove^[108,109] (**Figure 4d1**) is one of the earlier forms of gesture-based smart gloves that utilize tactile sensors. In this case, about 18–22 bend sensors were integrated at different locations in the glove for measuring hand postures. It is proposed to be usable as an interface for VR/AR as well as rehabilitation. A similar approach has also been used to realize a tactile glove for gesture recognition.^[110] Considering the position of the sensors in these gloves, they are more suitable for VR/AR and a game console rather than for measuring accurate joint angles needed for rehabilitation purposes. In this regard, researchers have explored more suitable tactile gloves such as the one with knitted piezoresistive sensors to track flexion, extension, and movement of the metacarpophalangeal (MCP) joint of the thumb.^[111] The glove helps to monitor the daily activities of patients.

The pneumatic principle has also been used to realize smart gloves for rehabilitation purposes (**Figure 4e**); for example, instead of using sensors on each of the fingers, a soft pneumatic actuator is attached on each finger to control and estimate the bending.^[112] The designed hand rehabilitation glove is tested by measuring its output force and actual wearing experience. The output force can reach up to $\approx 2.5\text{--}3\text{ N}$ when the pressure is $\approx 200\text{ kPa}$. The PneuGlove is another rehabilitation glove for stroke patients.^[113] A soft robotic glove for supporting individuals with functional grasp pathologies has also been explored and reported to improve grasping capability after use. Through the use of a soft material and fluid pressurization, this glove is able to flex, bend, and twist during its use, enabling the user's hand to easily practice grasping operations.^[114] Unlike some of the previously described gloves, these are quite compliant and flexible. Smart gloves utilizing a Hall effect sensor and infrared/photodiodes have been used to measure adduction–abduction motion of the proximal joint of

Table 4. Gesture-based robotic fingerspelling hands.

Device	Tactile sensor used	Tactile feedback actuator used	Type of communication	Year	Ref.
Mechanical hand	None	None	One-way	1978	[103]
Dexter and Dexter II	None	None	One-way	1987	[104]
Gallaudet Fingerspelling hand	None	None	One-way	1993	[105]
Robotic Alphabet (RALPH)	None	None	One-way	1994	[101]
The talking glove	None	None (uses LCD for feedback to deafblind (DB) person)	Two-way	1988	[106]

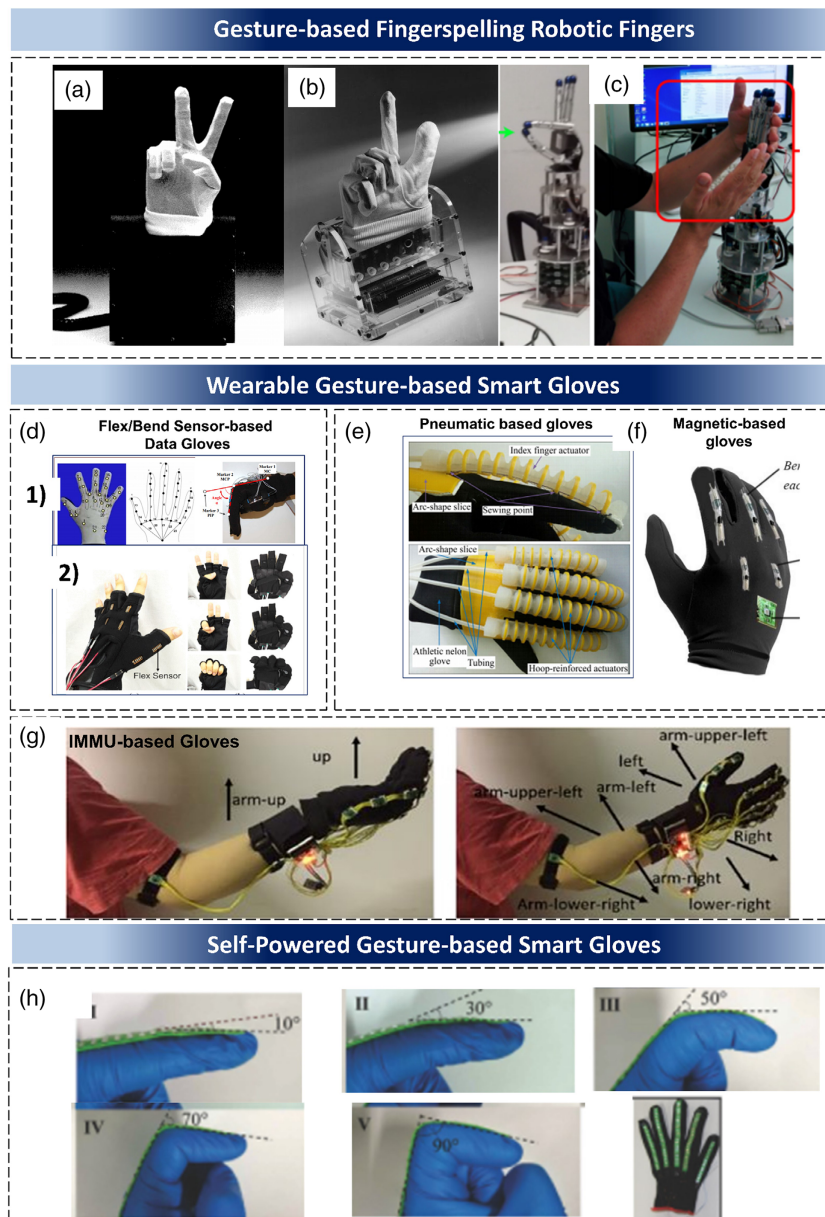


Figure 4. a) An early version of a gesture-based mechanical robotic fingerspelling hand for deafblind people; deafblind people touch the hand to read the associated gestures. Reproduced under the terms of the Creative Commons Attribution License (CC-BY 4.0)^[165] Copyright 1994 The Author(s), Published by Rehabilitation Research and Development Service of the Veterans Health Administration Office of Research and Development. b) RALPH: a fourth-generation fingerspelling hand; it has no sensors and to read gestures deafblind people touch the hand to understand it. Reproduced under the terms of the Creative Commons Attribution License Rehabilitation R&D Center^[101] Copyright 1994 The Author(s), Published by Stanford Rehabilitation R&D Center. c) PARLOMA—a human–robot interaction system for deafblind remote communication. This enables the remote control of a robotic hand to create different gestures, Reproduced under the terms of the Creative Commons Attribution License (CC-BY 4.0)^[107] Copyright The Author(s), Published by Sage. d) A new hand-measurement method to simplify calibration in cyberglove-based virtual rehabilitation. Reproduced with permission.^[109] Copyright 2010, IEEE. d2) A fully fabric-based bidirectional soft robotic glove for assistance and rehabilitation of the hand impaired. Reproduced with permission.^[166] Copyright 2017, IEEE. e) Wearable hand rehabilitation glove with soft a hoop-reinforced pneumatic actuator; the glove enables people with hand injuries to practice grasping. Reproduced under the terms of the Creative Commons Attribution License (CC-BY 4.0)^[107] Copyright The Author(s), Published by Central South University Press and Springer-Verlag GmbH Germany. f) A smart glove with gesture recognition ability for the hearing and speech impaired, The glove maps the orientation of the hand and fingers with the help of bend sensors, Hall effect sensors, and an accelerometer. Reproduced with permission.^[98] Copyright 2014, IEEE. g) 3D human gesture capturing and recognition by the IMMU-based data glove; the glove hand gesture is based on inertial and magnetic measurement units (IMMUs), which are made up of three-axis gyroscopes, three-axis accelerometers, and three-axis magnetometers. Reproduced with permission.^[81] Copyright 2018, Elsevier. h) A self-powered, stretchable, and flexible triboelectric nanogenerator for monitoring finger gestures. Reproduced with permission.^[120] Copyright 2018, Wiley.

Table 5. Wearable gesture-based smart gloves.

Glove name	Active element (sensor used)	Actuator used	Performance	Evaluated application	Ref.
5DT Data Glove (commercial)	Fiber-optic sensor	None	Recognition accuracy of 97.4%, 12 static gestures	Rehabilitation, object grasping, and manipulation	[169]
Talking glove	Five strain gauges	None	N/A	Communication by deafblind people	
IMU sensor-based electronic goniometric (iSEG) glove	16 nine-axes IMUs	None	85.24% accuracy for sensors	Rehabilitation	[170]
IMMU glove	18 IMMUs	None	Accuracy of 89.59% for 10 static gestures, accuracy of 82.5% in recognizing 16 dynamic gestures	Defined static gestures	[81]
reduced graphene oxide (RGO) glove	Ten RGO-coated fibers	None	98.5% recognition of 10 static and 98.3% for 9 dynamic gestures	Chinese sign language	[171]
Cyberglove (commercial)	18 Sensors	None	90% recognition of American sign language words	Word recognition using American sign language	[172]
Robost data glove	14 fluid-based sensors	None	88.5% for 15 gestures	Random gestures involving flexion–extension and abduction–adduction movements	[173]

the fingers and also been explored for assistive purposes (Figure 4f).^[97,98] Hand orientations have also been measured using accelerometer-based smart tactile gloves.^[25,99,100] In this case, accelerometers are attached to the fingers to measure their orientation. Some of them also combine an accelerometer and other sensors to improve tracking. A smart glove with nine-axis inertial sensors and force sensitive resistors has been used to track hand movements in real time.^[115] Recently, inertial fusion has also been used to develop data gloves for hand motion measuring.^[116] **Table 5** summarizes various wearable gesture-based smart gloves.

Smart gloves using vision-based hand gesture recognition, with a camera and computer algorithm to recognize the hand gestures, have also been reported.^[81,100,117] Figure 4g shows one such smart glove comprising 18 inertial and magnetic measurement units (IMMUs) made up of three-axis gyroscopes, three-axis accelerometers, and three-axis magnetometers.^[81] The gestures captured by this glove using extreme learning machine (ELM) include 3D motions of the arm, palm, and fingers. Another example is a glove measuring the MCP and proximal interphalangeal (PIP) joint angles of five fingers for dynamic real-time hand gesture recognition using a soft sensor embedded in the data glove.^[118] To meaningfully separate dynamic gestures, a deep learning gesture-spotting algorithm is also used for detection of the start/end of a gesture sequence.^[119]

As interest in self-powered wearable devices, including triboelectric nanogenerators, continues to rise, self-powered noncontact smart gloves capable of a wide range of gestures have also been explored^[120,121] (Figure 4h). The fiber-based smart glove consists of an electrified layer made of wool yarn, polydimethylsiloxane (PDMS)-coated wool yarn, and an effective sensing layer on the palm, where electrodes made of carbon nanotubes (CNT)-coated cotton fabric is sewed. With excellent characteristics such as flexibility, compatibility with human skin, and fewer electrodes, this smart glove provides a good sensing and interactive gesture recognition experience.^[121] A gesture-based smart glove has

also been realized recently using a poly(vinylidene fluoride-co-trifluoroethylene) (P(VDF-TrFE)) polymer nanofiber mat and silver nanowire layer based strain sensors.^[122]

3.2. Touch-Based Smart Tactile Gloves

The touch-based smart gloves discussed in this section are activated by the user during interaction, using the touch sensors on the glove to either send information or obtain contact information about an object. Some of these smart gloves, shown in **Figure 5**, have been utilized for rehabilitation and AAC. Most of these devices are worn like a smart glove on the hand to adequately represent the gestural or touch communication approach as described in Section 2. These types of gloves have been widely used for communication among deafblind people by implementing the manual alphabets, Braille,^[123] (Figure 5a,b), as well as the less popular Morse code.^[124] The Hand-tapper developed in the UK is one of the early examples of the touch-based glove used by deafblind people.^[73] It is based on the British deafblind manual alphabet and contains a Braille keyboard and a vibration feedback. A pattern-decoding glove is another example, which uses force-sensitive resistors (FSRs) at tactile points to accept input from users.^[125] However, both the Hand-tapper and the pattern-decoding glove are not portable and are tethered to a computer. In this regard, the LORM glove (Figure 5c)^[74] is worth noting. It is a wearable fabric glove with fabric pressure sensors for sending messages, and 32 off-the-shelf vibration motors at the back of the glove for receiving. Figure 5d shows the mapping and position of these sensors on the glove. The DB-hand is another two-way wearable device which uses ten off-the-shelf tactile switches as tactile points for sending messages and coin-type vibration motors for haptic feedback.^[75] Another smart glove for Malossi users reported recently uses sensors but has no haptic feedback.^[126] There are not many examples of Braille-based wearable tactile communication interfaces for



Figure 5. a) Refreshable Braille display using triboelectric nanogenerators; it enables Braille users to be able to read different English letters corresponding to the Braille code. Reproduced with permission.^[123] Copyright 2021, Wiley. b) Body Braille: this device is worn on the body and has six cells to represent the different cells of standard Braille. Reproduced with permission.^[127] Copyright 2008, IEEE. c) Mobile Lorm glove: introducing a communication device for deafblind people; it has fabric-based pressure sensors that enable deafblind people to compose and send messages to a remote mobile phone user. Reproduced with permission.^[161] Copyright 2012, ACM. d) Mapping and position of the sensors for a smart glove developed for deafblind people who use Lorm. Reproduced with permission.^[161] Copyright 2012, ACM. e) SmartFingerBraille: this glove contains touch sensors at the tip of the index, middle, and ring finger and vibrotactile actuators at the back of these fingers; the touch sensors are used to compose messages and send to a remote mobile phone user based on the Braille code. Reproduced with permission.^[129] Copyright 2017, IEEE.

deafblind people that are in the form of a smart glove. This could primarily be because Braille communication is mainly through tactile exploration of a surface to read raised dots.^[123] So the majority of the existing communication devices tend to be tactile displays that involve surfaces presented to the user to explore^[123] (Figure 5a), or

wearable on other parts of the body (Figure 5b).^[127,128] In this regard, one example is the SmartfingerBraille^[129] (Figure 5e), which uses FSRs at the tip of the index, middle, and ring finger of both hands and a vibration motor at their back. By tapping the glove on any hard surface, the user can compose and send messages to

Table 6. Touch-based smart gloves.

Device	Tactile sensor used	Actuator used	Type of communication	Year	Ref.
Handtapper	None (uses a standard QWERTY keyboard for input)	14 movable pins	Two-way	1991	[73]
Pattern-decoding glove	14 FSRs	None	One-way	1993	[125]
Lorm glove	Fabric pressure sensors	32 Vibration motors	Two-way	2012	[74]
DB-hand	10 Tactile buttons	10 Vibration motors	Two-way	2008	[75]

another mobile phone user. A mobile communication glove has also been reported with capacitive sensors to represent six dots of Braille on the fingers of one hand.^[130] The touch-based smart gloves and their key features are summarized in **Table 6**.

3.3. Gesture and Touch-Based Smart Gloves

The HMI smart gloves summarized in this section use a combination of both gesture and touch and find application in areas such as telemanipulation, medical/military training, virtual collaborative product design, smart manufacturing, gaming entertainment, and product advertising. Combining both gesture and touch allows richer information and hence this type of

smart glove has been used for training of patients during rehabilitation.^[96] One example, shown in **Figure 6a**, is the pair of sensory and motor gloves, realized using a soft material, for mirror therapy and task-oriented therapy.^[96] The sensory glove contains a force-and-flex sensor and is worn on the nonaffected hand, which contains the force-and-flex sensors to measure the gripping force and bending angle of each finger joint for motion detection. The motor glove, driven by micromotors, is worn on the affected hand to provide an assistive force for training tasks. Also, smart data gloves with integrated flex-and-pressure sensors to measure the kinematics and kinetics during the fore-hand grip and backhand grip in sports have been reported^[131] (**Figure 6b**).

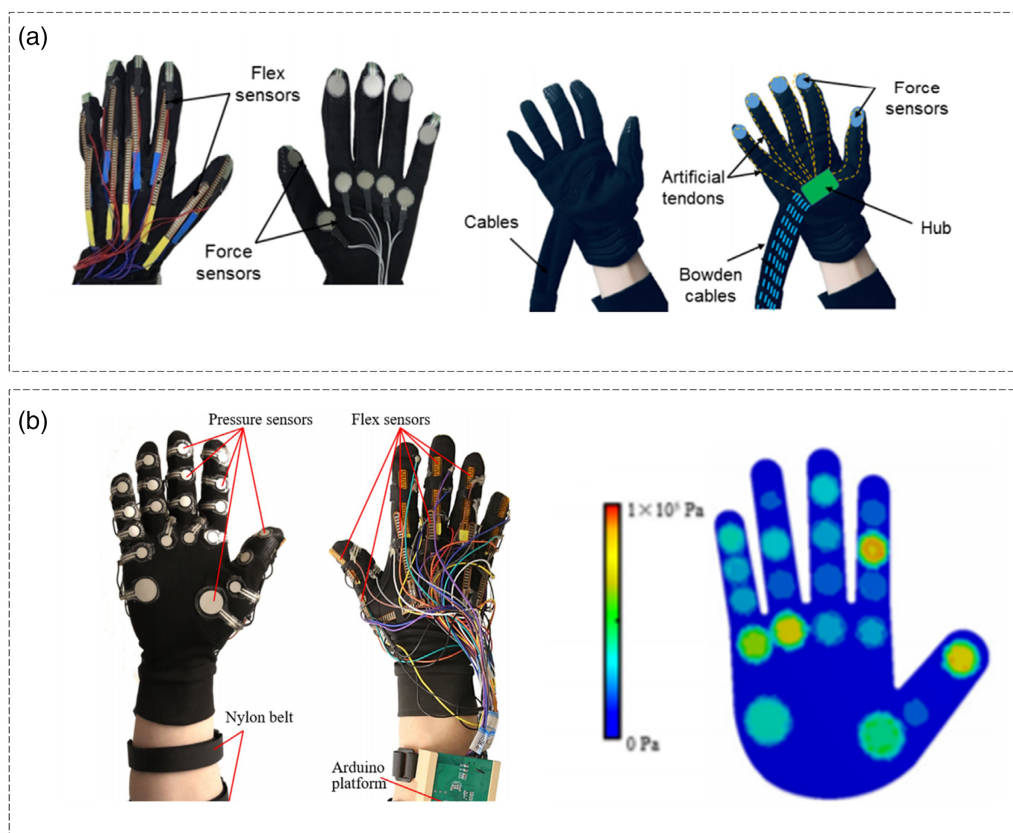


Figure 6. Smart gloves combining gesture and touch. a) A wearable hand rehabilitation system with soft gloves: this glove enables the recognition of touch at some locations in the fingers and palm area and is also capable of measuring finger bending angles for gesture recognition. Reproduced with permission.^[96] Copyright 2021, IEEE. b) This glove uses pressure sensors and flex sensors to characterize fine hand movement. It was tested and utilized for badminton, but could find applications in VR/AR applications as well. Reproduced with permission.^[131] Copyright 2020, Taylor & Francis.

4. Technologies for Integrated Tactile Sensing and Actuation in Smart Gloves

Two-way communication is essential for effective human interaction. In this regard, HMIs with the capability of sending information from a user to a machine and enabling the user to obtain feedback from the machine in a form they will understand are highly desirable. In this section, we discuss the technologies that enable two-way communication with both sensors and actuators in smart gloves. While a sensor is used to obtain information about the contact feature, actuators are used as a means of feedback to the user via haptic sensations such as vibration, skin heat, stretch, and electrical stimulation.

Some VR/AR smart gloves, including those for rehabilitation, with integrated sensors for tactile feedback are shown in **Figure 7a**.^[132–135] They have been used to display different tactile information, including temperature. A VR system that utilized a wearable glove with force sensors and an arm band with a vibration motor has been used to conduct experiments with children affected by cerebral palsy.^[133] Because this system was compliant with different levels of motor skills, it allowed patients to complete the experimental rehabilitation session with performance varying according to the expected motor abilities. A skin-like thermal device for recreating thermal sensation in VR has been reported.^[136] Also reported recently is a real-time thermal display

glove that comprises piezoelectric sensors to sense hand motion and flexible thermoelectric devices for bidirectional thermal stimuli on the skin^[137] (Figure 7b). Another example is the self-powered, painless, and highly sensitive electro-tactile (ET) system for achieving virtual tactile experiences.^[138] Although this is worn in the forearm and not designed in the form of a glove, it could have the potential to improve the use of VR/AR for rehabilitation purposes. A smart glove with triboelectric-based finger-bending sensors, a palm-sliding sensor, and piezoelectric mechanical stimulators has also been reported.^[139] In the field of mobility support for deafblind people, a virtual leading block consisting of a wearable interface for finger Braille has been developed.^[140] The device can inform users of their direction and position through tactile sensation.

Sensors and actuators have also been integrated for bidirectional communication in touch-based smart gloves for use in applications such as AAC. This is effective for deafblind communication, where there is impaired hearing and vision. The examples include a two-way device based on finger Braille with force sensors at the tip of the index, middle, and ring finger to enable sending of messages and a vibration motor each at the back of these fingers of both hands to represent the six Braille dots.^[129]

Most of the different types of smart gloves presented so far either use only sensors with no integrated mechanism for tactile feedback or use separately off-the-shelf sensors and actuators

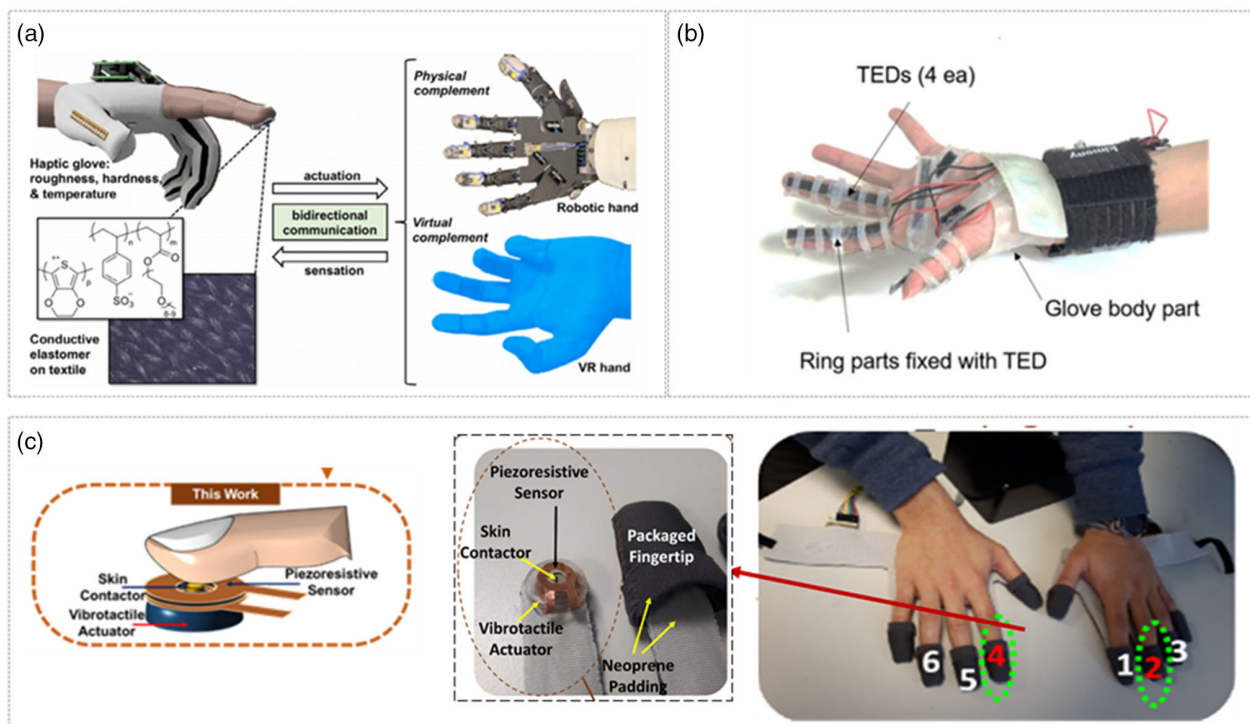


Figure 7. Smart gloves with integrated sensor and actuator. a) Virtual texture generated using an elastomeric conductive block copolymer in a wireless multimodal haptic glove; it is capable of bidirectional communication of information using haptic feedback. Reproduced under the terms of the Attribution 4.0 International of Creative Commons.^[132] Copyright 2020 The Author(s), Published by Wiley. b) A thermal display glove for interacting with VR. This glove enables the recreation of thermal sensation in VR/AR, Reproduced under the terms of the Attribution 4.0 International of Creative Commons.^[137] Copyright 2020, Springer Nature. c) A wearable assistive tactile communication smart glove with sensors and actuators integrated at the index, middle, and ring finger of both hands to enable assistive two-way communication for people who have the knowledge of Braille. Reproduced under the terms of the Attribution 4.0 International of Creative Commons.^[6] Copyright The Author(s), Published by IEEE.

(e.g., T-SGs and GT-SGs). As these commercial off-the-shelf sensors sometimes have incompatible specification, it is challenging to use them for the realization of a soft, flexible, and seamless HMI capable of providing two-way communication and an intuitive user experience. To overcome these limitations, a tactile communication interface that utilizes a custom-made haptic feedback electromagnetic actuator using a flexible coil in tandem with a flexible piezoresistive pressure sensor has been explored (Figure 7c).^[6] This smart glove was realized using custom-fabricated sensors made with flexible PCB in tandem with a vibrotactile actuator realized with a thin 50 μm polyimide sheet. The application of this glove is similar to that shown in a previous study^[129] (Figure 5e), but instead of having sensors at the tip of the fingers and actuators behind the fingers, it has both sensors and actuators integrated at the tip of the fingers.^[6] The evaluation conducted with deafblind people showed that users were able to use this Braille-based communication interface to send messages using the pressure sensors and receive messages via the integrated actuator at a vibration frequency of up to ≈ 200 Hz. To expand its application, a similar approach has also been used to realize a touch-based smart glove^[7] that supports deafblind people who communicate using Morse code.^[124] In this case, with only two fingers, a deafblind person, or a sighted and hearing user, can intuitively communicate or remotely control an object and receive vibrotactile feedback.

The advances in e-skins, including the fabrication of soft sensors and skin-like devices, have enabled the detection of different stimuli, such as touch, pressure, strain, temperature, and slip.^[29,88,141] The e-skin equipped with actuators will have the capability for simultaneous tactile sensing and actuation. Taking advantage of these advances, we have recently demonstrated the possibility of integrating sensors and electromagnetic actuators in one device (Figure 8) using a soft sensor, flexible sensors, and a flexible actuator.^[6,7,30] These integrated devices, called SensAct, can provide simultaneous sensing and vibrotactile feedback at the same tactile point. The structure of such a device is shown in Figure 8a,b. Instead of separately integrated sensors and actuators as common with the aforementioned smart gloves, the integrated sensor and actuator provide the opportunity to realize a single device with a sensor and actuator integrated as one tactile point. For instance, the communication methods used by deafblind people require the use of the same tactile point for sending and receiving of information. So integrating a sensor and actuator as one device and using it as a single element for a tactile point will enable the realization of smart gloves, which effectively represent this kind of communication approach. This kind of integrated technology creates a unique opportunity for assistive tactile communication technologies, rehabilitation, immersive VR/AR, as well as robotics. The use of large-area skin-like vibrotactile actuators for VR/AR, demonstrated recently, shows the possibility of this technology for tactile communication.^[142] Although the reported work demonstrated the possibility for large-area skin-like vibrotactile actuators, it lacks the much-needed sensing capability necessary for an effective two-way tactile communication. Further, the electromagnetic vibrotactile actuator based on rigid coils used in this work poses a challenge in terms of flexibility and conformability. In this regard, the adoption of a skin-like approach for the vibrotactile actuator through the fabrication of the coil on a flexible

substrate (Figure 8c) could offer a better solution, as both sensors and the accompanying actuators will all be soft and flexible (Figure 8d).^[6,30] The demonstrated actuator realized using the flexible coil can provide actuation in the range of ≈ 10 – 200 Hz with a displacement of up to ≈ 191 μm . This much thickness mode movement is good enough to be picked by Ruffini corpuscles in the skin.^[59] So, the integration of vibrotactile feedback in an e-skin in tandem with tactile sensing could allow the e-skin to recreate two-way tactile communication in addition to other advanced capabilities such as self-healing and health monitoring.^[88] Another advantage of this approach is the possibility of using the output of the sensing layer as a feedback to proportionally modulate the level of actuation, which increases the granularity of the information extracted from the e-skin because of an external stimulus.

Several reported e-skins possess only the tactile sensing capability, which can only serve as a one-way communication interface if directly adopted for deafblind communication. An example, shown in Figure 9a, includes a piezoelectric-based stretchable sensor and its application in some of the gesture-based communication (e.g., fingerspelling for deafblind communication) where gestures are used for communication.^[141] Another example of an e-skin, shown in Figure 9b, demonstrates the tactile mapping for object grasping as well as an alternative for some communication smart gloves for deafblind people.^[143] Other skin-like haptic interfaces have also been reported,^[136,144] and adopting such technologies as smart tactile gloves has the potential to advance the wearability and user experience. However, without actuation, this remains a one-way channel and it cannot provide any haptic feedback to the user. Seamless integration of controllable actuation with the existing sensing capabilities in an e-skin in a conformable soft material will bridge this gap and advance the state of the art. This sort of technology is poised to revolutionize human interaction and communication for various applications.

5. Challenges and Opportunities

The reviewed literature shows that the majority of existing smart gloves either use only sensors or integrate them with off-the-shelf actuators in a nonmonolithic way. This approach comes with a significant degree of integration challenges and the tactile interfaces are not always comfortable for use, thus affecting the quality of user experience for applications such as AAC and VR/AR.^[94] This is particularly due to the unavailability of suitable multifunctional (i.e., sensing and actuation) devices for an interactive interface. The e-skin research, which has rapidly advanced over the last decade, has mainly focused on sensing and energy devices and hence lacks bidirectional tactile capability. As a result, there is overdependence on delivering feedback to the user through vision and hearing modalities. One of the engineering solutions to this issue is to develop a tactile interface that has seamlessly integrated tactile-sensing and haptic-feedback capabilities. In this regard, advancing e-skin-type solutions with tightly coupled touch sensors and actuators, just like human skin has receptors embedded in muscles, could bring huge benefits for interactive interfaces for rehabilitation as well many other applications, such as tactile Internet,^[145] holographic displays,^[2] interactive haptic surfaces, soft robotics,^[146] and VR/AR.^[30]

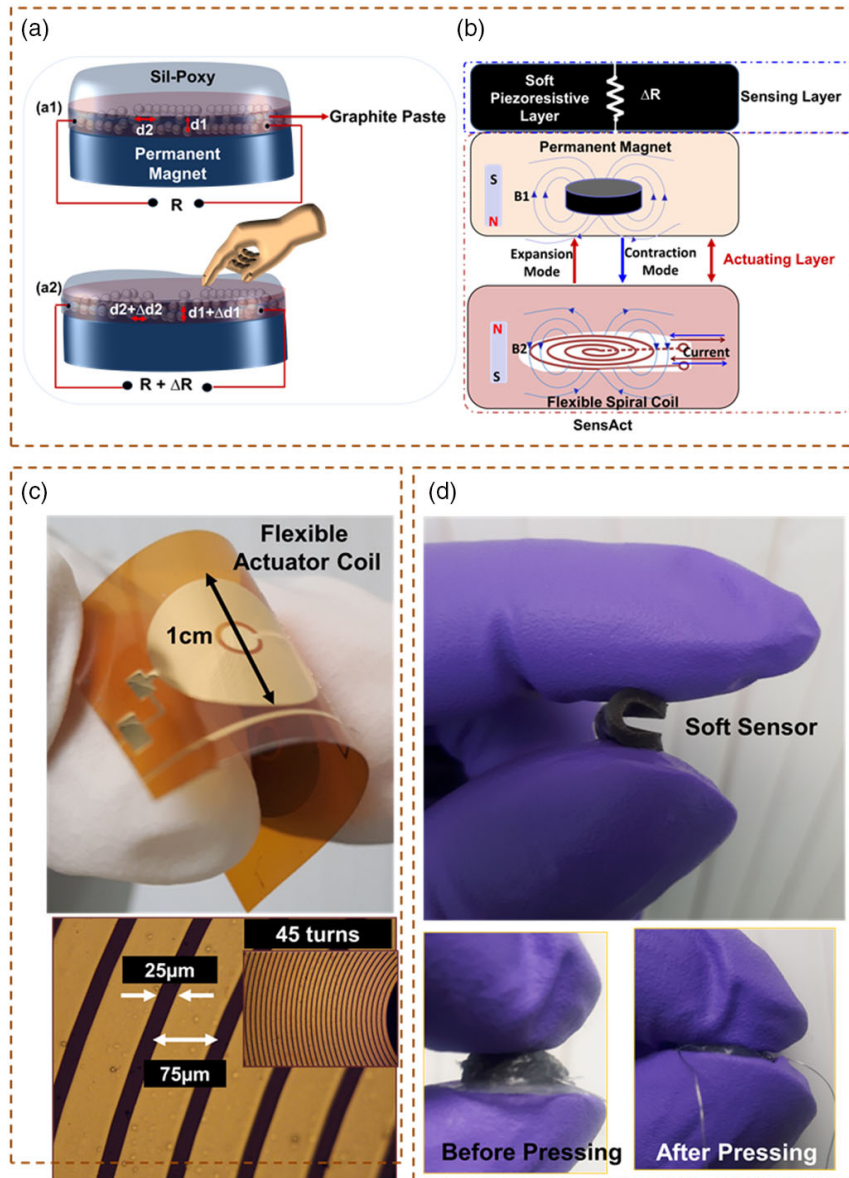


Figure 8. A haptic device with an integrated soft sensor and flexible actuator; this integrated device has a sensor and an actuator integrated together as a single device. a) Schematic of the integrated sensor and actuator device. b) Structure and working principle of the integrated sensor and actuator. c) Fabrication flexible coil for the actuation layer. d) The soft sensing layer. The sensing layer is a piezoresistive pressure sensor and the electromagnetic actuator can operate in two modes (expansion and contraction/squeeze) and two states (vibration and nonvibration). Reproduced under the terms of the Attribution 4.0 International of Creative Commons.^[30] Copyright 2021 The Author(s), Published by Wiley.

Despite the huge progress in the fabrication of soft and flexible sensors in the past decade, full system-level implementation is still a challenge. Realization of an array of actuators capable of providing localized haptic feedback is still in its infancy and issues such as crosstalk and power management are some of the technological hurdles to overcome. Ideally, wearable devices should have multifunctional capabilities, low power usage, and less wiring, to ease the process of donning and doffing. Wireless communication (Table 7) is needed when designing portable and wearable tactile communication devices to reduce the dependence on tethering to a bulky system (e.g., computer). So rather

than approaching sensing and actuation separately, some interesting approaches will be to endow tactile displays with both tactile sensing and feedback, stiffness-control, and wireless-communication capabilities. This will have a huge impact in many different fields and will lead to an e-skin that not only senses external stimuli and provides health benefits, but also is capable of being used for effective and reliable two-way tactile communication. This will help to overcome social isolation and enable deafblind people to independently interact with sighted and hearing people as well as machines in a more natural and intuitive way. Smart objects, robots, and interactive surfaces

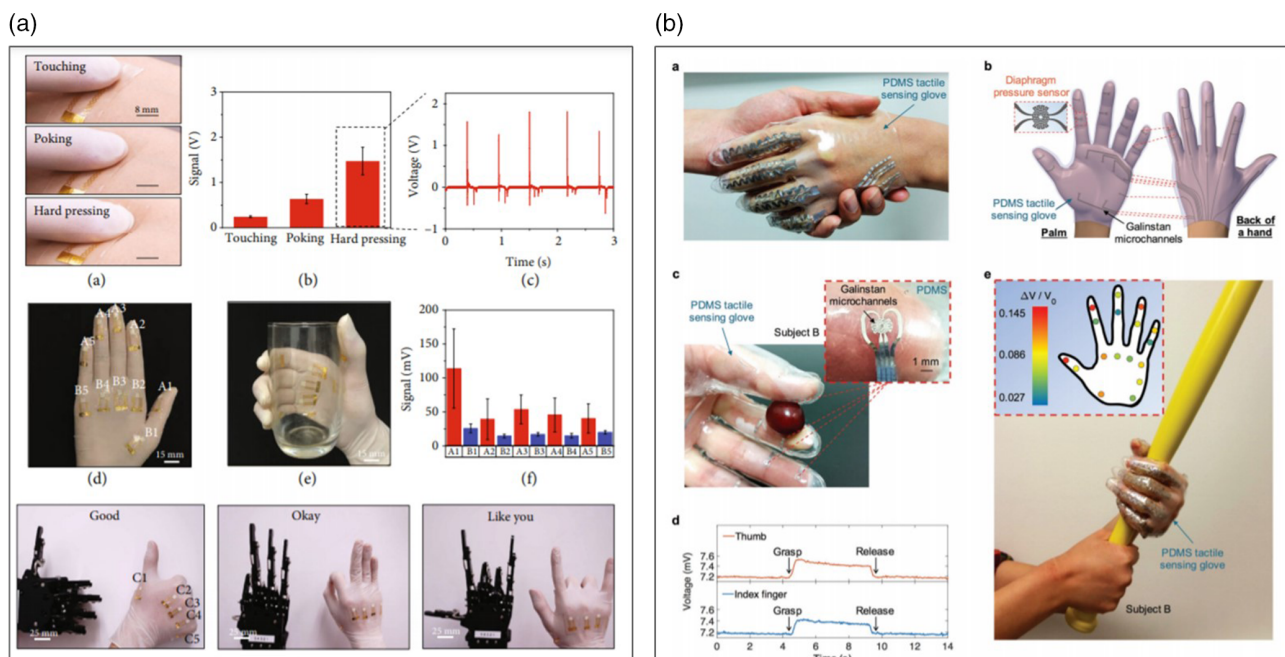


Figure 9. Flexible sensors for advancing tactile communication gloves. a) An electronic skin from high-throughput fabrication of an intrinsically stretchable lead zirconate titanate elastomer. This kind of technology will open the door for skin-like smart gloves. Reproduced under the terms of the Attribution 4.0 International of Creative Commons.^[141] Copyright 2020 The Author(s), Published by American Association for the Advancement of Science. b) Wearable microfluidic diaphragm pressure sensor for health and tactile touch monitoring, suitable for mapping the tactile points when grasping an object and could also open the door for the realization of skin-like touch-based smart gloves as discussed in this work. Reproduced with permission.^[143] Copyright 2017, Wiley.

will also benefit immensely. For example, it has been reported that wearing glove reduces sensitivity of the hand,^[7,147] and so integration of seamlessly integrated multimodal tactile sensing in smart gloves could improve work wear or medical gloves,^[148] increasing the granularity of the information that can be extract by touching objects with gloves.

By donning smart objects using e-skin-type interfaces, it is possible to also realize highly interactive surfaces. This technology could be explored also in many other areas; for example, it could be used for sensorial augmentation of nondisabled as well as human–robot interactions. In the latter, robots could interact with humans by sending information in the form of haptic feedback to users, thus enhancing their sensory awareness. If integrated into work wear, these haptic interfaces could also be used for security and rescue purposes, allowing the exchange of information in dangerous situations. Further, with the advances in the technologies for fabrication of biomimetic e-skins, we also envision the realization of smart skin-like gloves with all the

human-like sensing capabilities, enabling users to use the gloves to explore surfaces and obtain richer information (e.g., softness, temperature, roughness) about the contact feature. Considering the fast-growing IoT, where sensors serve as data sources, enabling the harvesting of information from users, actuators will help to improve the quality of feedback that users receive from IoT devices. Furthermore, with the rapidly growing interest and research on tactile Internet,^[145] the potential of seamlessly integrating sensors and actuators cannot be overemphasized. In general, we envision e-skins with integrated sensing and actuation as an innovative opportunity for advancing HMIs by providing them with the capabilities for richer user interaction experience. Further, considering the rapid advances in the field of 3D/4D printing technology,^[149] it is possible to realize flexible/soft smart structures with intrinsic sensing.^[26] By 3D printing the sensors and electronics, using novel 3D-printing materials,^[9] the issues with device integration, including routing of wires in smart gloves,^[150] could be significantly solved. Also, a recent interesting

Table 7. Wireless communication protocols used in smart gloves.

Parameter	Bluetooth ^[174,175]	ZigBee ^[175,176]	Ultra-wide band (UWB) ^[177]	Wi-Fi ^[178–180]	Recommended for smart gloves
Frequency band	2.4 GHz	868/915 MHz; 2.4 GHz ^[175]	3.1–10.6 GHz	2.4 GHz; 5 GHz ^[178,179]	All
Max signal rate	1 Mb s	250 Kb/s	1 10 Mb s	35 Mb s ^{−1} –1 Gb s ^{−1}	Bluetooth, Zigbee
Nominal range (m)	10–100	10–100	10	1–50	All
Nominal transmitter power	0–10 dBm	(−25) to 0 dBm	−41.3 dBm/MHz	20 dBm (100 mW)	ZigBee, Bluetooth
Channel bandwidth	1 MHz	0.3/0.6 MHz; 2 MHz	500 MHz–7.5 GHz	20–160 MHz	Bluetooth, ZigBee

Table 8. Power consumption of different types of smart gloves with different materials and mechanisms used.

Sensing mechanism (material)	Actuator (material)	Power	Type of smart glove	Wireless comm.	Year [ref.]
Resistive (P(VDF-TrFE) polymer nanofiber mat and silver nanowire layer)	N/A	<10 mW	Gesture-based	N/A	2016 ^[122]
Inertia and magnetic (IMMU)	N/A	≈50–300 mW	Gesture-based	Bluetooth	2018 ^[81]
Optical (infrared diodes and photodiodes)	N/A	≈500 mW	Gesture-based	N/A	[98]
Capacitive (fabric-based)	Vibration Motors	≈100–200 mW	Touch-based	Bluetooth	2012 ^[161]
Resistive (conductive polymer)	Electromagnetic (flexible voice coil-based actuator)	≈150 mW	Touch-based	Bluetooth	2020 ^[6,7]
Piezoelectric [polyvinylidene fluoride (PVDF)]	Thermal (thermoelectric devices)	≈452 mW	Gesture-based	N/A	2020 ^[137]
Resistive (conductive polymer)	Mix-mode: Thermoelectric, Electromagnetic, Electrotactile [Polymer based materials]	>0.2 W	Gesture-based	N/A	2020 ^[132]
Resistive (fabric-based)	N/A	227 mW.	Gesture and Touch-based	Wifi	2021 ^[96]
Triboelectric/electrostatic (fabric coated with carbon nanotubes [CNTs])	N/A	Self-powered ≈1.1288 nW,	Gesture-based	N/A	2018 ^[121]

approach is the use of a deep learning skin sensor for the detection of finger motions.^[151] This approach is able to capture dynamic motions from a distance using a single sensor and a deep neural network, without creating a sensor network. This opens great opportunities for the development of gloveless-type HMIs and reduces the integration challenges.

New signal-processing strategies, for example, using neuro-morphic devices, may also be needed for the aforementioned solutions to efficiently process tactile information in a parallel and low-power manner. Table 8 shows the power consumption for different smart gloves, with many taking up to 200 mW. The research in self-powered sensors^[138,152] and actuators will foster the realization of autonomous systems with fewer wires and increased wearability. For example, the sensing layer of the SensAct-type devices presented in Ozioko et al.^[30] could be replaced with flexible solar cells.^[20] Most commonly, self-powered sensors including pressure sensors have been realized using piezoelectricity^[153] and triboelectrification, in which the charges that occur at the contact surface of two different materials are used to effectively convert frictional contact into electrical signal.^[154] Although the piezoelectric sensors^[155] are capable of reducing the consumption of sensor nodes in IoT, for instance, these types of sensors usually have the disadvantages of low sensitivity and limited variety of sensing materials compared to triboelectric nanogenerators.^[154,156] By combining the dynamic sensing capabilities of the TENG-based pressure sensors with the static pressure-sensing capabilities of capacitive or resistive-based pressure sensors, etc., it is possible to also realize smart gloves (e.g., the touch-based smart gloves) with integrated static and dynamic sensing capabilities. By combining these with haptic feedback, the details extracted from contact with the environment will be further enhanced. This also provides opportunities for researchers working in the field of artificial intelligence for health care^[157] as well as invasive technologies such as neural

bypass, where electrodes are inserted in the brain and thoughts are delivered to the skin.^[19,158] The haptic feedback from the integrated actuators could also be used to deliver the output to deaf-blind users through the skin in a swift, seamless, and efficient manner. Some other obvious challenges in adopting the new technologies discussed herein for the realization of the new generation of smart tactile gloves is that a majority of them are still emerging and hence, mass production, stability, and lifetime of the devices are not yet guaranteed.

6. Conclusion and Discussion

Smart gloves based on different technologies, being utilized in several applications, including VR/AR, rehabilitation, and augmentative and alternative communication, are presented herein. Due to the requirements such as intuitive interfaces, there has been a burgeoning interest in glove-based HMIs as alternatives for conventional HMIs such as keyboards, joysticks, as well as vision and voice-based interaction approaches. This is motivated by the fact that the human hand is regularly used for daily interaction and the conventional HMI approaches are relatively bulky, lack intuitiveness, and may suffer self-occlusion as in the case of vision and voice-based approaches. The article also discussed how the rapid advances in e-skin technology (including the monolithic integration of soft/flexible sensors and actuators) could be adopted for the realization of a seamless and more intuitive HMI. The reviewed smart gloves were divided as gesture-based (e.g., smart gloves for stroke rehabilitation), touch-based (e.g., smart gloves for communication by deafblind people), as well as those with a combination of gesture and touch for a richer interactive experience (e.g., as in rehabilitation and VR/AR systems). In general, these smart gloves utilize either sensors and/or IMMUs to measure contact force and finger/hand orientation.

In some cases (e.g., for the VR/AR gloves), tactile feedback is integrated to provide tactile sensation and represent some physical parameters such as temperature and proprioception.

However, a majority of these gloves utilize separately integrated sensors and/or off-the-shelf actuators for tactile feedback. Sometimes it is difficult to find sensors and actuators with the same size, compatibility, or having the desired characteristics. This is a challenge when it comes to the realization of an HMI that is conformable with the human skin and capable of enabling rich bidirectional user interaction. To this end, a monolithic fabrication of a custom-made and seamlessly integrated sensor and actuator will be advantageous as it will enhance the user experience and enable the gloves to be appropriately tailored to the desired application. Excitingly, the advances in e-skins^[10,38,88] provide great opportunities for the realization of such glove-based HMIs.

As discussed in this Review, an e-Skin as an interactive two-way HMI should have four main important components: 1) tactile sensors, 2) tactile feedback actuators, 3) strain sensors, and 4) other advanced functionalities for health monitoring, etc. Considering the touch-based gloves, for instance, the tactile sensors and the tactile feedback actuators need to be seamlessly integrated as one device from the fabrication stage and the sensor-actuator pair used as a building block for every tactile point on the glove, enabling every tactile point to have the ability of both sensing and tactile feedback. This will lead to the realization of a highly customizable tactile interface with the same tactile point utilized for both sending and receiving of tactile information. In addition to tactile sensing and feedback capabilities, detection of other physical and chemical information from the body will enable precise monitoring of basic health and early diagnosis of a variety of diseases. This means that the same wearable HMI used for interaction could also enable users to monitor their health. This is key for older people and for supporting people who have some sensory impairment (e.g., deafblind people) or health challenges such as heart disease and diabetes.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

haptics, human machine interface, interaction technologies, rehabilitation, smart glove

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