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1 Wearable multi-sensory haptic devices

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10 Abstract

11 Haptic devices enable communication via touch, augmenting visual and auditory displays or by offering alternative channels of
12 communication when vision and hearing are unavailable. Because of the different types of haptic stimuli that are perceivable by users –
13 vibration, skin stretch, pressure and temperature, among others – devices can be designed to communicate complex information by
14 delivering multiple types of haptic stimuli simultaneously. These multi-sensory haptic devices are often designed to be wearable, and
15 have been developed for use in a wide variety of applications including communication, entertainment and rehabilitation. Multi-sensory
16 haptic devices present unique challenges to designers because human perceptual acuity can vary widely depending on the wearable
17 location on the body and/or the heterogeneity in human perceptual performance, particularly when multiple cues are presented
18 simultaneously. Additionally, packaging haptic systems in a wearable form factor presents its own engineering challenges, such as cue
19 masking, device mounting and actuator capabilities, among others. Thus, in this Review we discuss the state-of-the-art and specific
20 obstacles present in the field to produce multi-sensory devices that enhance the human capacity for haptic interaction and information
21 transmission.

22 [H1] Introduction

23 Haptic feedback devices incorporate technologies that deliver kinesthetic (that is, the perception of forces acting on the
24 musculoskeletal system, in coordination with sensation of bodily position and movement (proprioception)) or tactile
25 sensations to a human user, enabling individuals to receive encoded information through the touch sensory channel. This
26 touch feedback has been used to enhance realism in virtual environments,¹ close the action-confirmation loop in user
27 interfaces,² improve the efficacy of training programs³ and augment or substitute for other senses.⁴ When first introduced in
28 the 1960s,^{5,6} haptic devices relied on rigid, grounded mechanisms to produce the forces felt by the user, typically via a
29 handheld probe or through exoskeleton structures. Owing to advances in actuation and sensing technologies and a
30 developing understanding of human haptic perception and the benefits of haptic feedback, the range of applications in which
31 haptic devices have been employed has expanded.

32 Since the 2000s, as component technologies (sensors, actuators, computing and batteries) have miniaturized, there has
33 been a steady shift in personal computing technologies moving from desktop to handheld to wearable form factors. Given
34 the availability of such off-the-shelf technologies, haptic feedback has increasingly been incorporated into consumer devices
35 like wrist-worn fitness trackers and smart watches that provide vibrational notifications, as well as in video game applications,
36 which provide touch sensations via glove interfaces and haptic vests. A recent survey of numerous haptic devices, including
37 grounded, handheld, exoskeleton, finger-worn, and arm-worn devices, along with devices for the torso, head, feet and legs,
38 demonstrates this shift towards wearability as a key driver in device development, with a strong desire to produce devices
39 that can be integrated into every-day life without constraining the user⁷. With this shift in form factor, wearable haptic devices
40 now increasingly focus on providing cutaneous cues directly to the skin, rather than providing kinesthetic force feedback felt
41 through the musculoskeletal system.

42
43 Wearable haptic devices that are focused on delivering cutaneous tactile feedback primarily transmit stimuli such as
44 vibration, shear force, pressure and thermal stimuli to the skin of a user, generating afferent responses from a variety of
45 different sensory receptors in the skin. Many wearable haptic devices use commercially available actuators that are designed
46 to transmit a single type of haptic cue. Some devices combine several actuators to provide haptic cues to multiple locations
47 on the body such as in the case of vibrotactile arrays. Most wearable haptic devices proposed to date have focused on the
48 optimization of haptic cue transmission using a single modality, typically vibration, due to the low cost and low power
49 requirements of vibrotactile actuators. Such systems are well-suited to delivering discrete cues, such as notifications or alerts

50 like those in smart watches and phones. More recently, researchers have begun to develop wearable haptic devices that can
51 convey multi-sensory haptic cues that combine several different types of haptic stimuli – most frequently, vibration combined
52 with skin stretch, squeeze or even thermal stimuli. In this Review, we use the term multi-sensory to refer specifically to haptic
53 interactions and devices involving more than one mechanism of haptic feedback, and the term multi-modal to refer to
54 interactions involving multiple sensory modalities such as touch, hearing and vision. By integrating multiple actuation
55 methods, each generating distinct haptic stimuli within a single device, a wide range of haptic perceptual experiences can be
56 achieved, therefore substantially expanding the potential for wearable haptic devices.

57 As wearable systems continue to evolve, several important considerations have emerged regarding their design,
58 implementation and use to optimize human-machine interaction. A variety of wearable multi-sensory haptic technologies
59 and devices have been developed, each designed to communicate tactile cues in distinct ways. The integration of these body-
60 worn devices into everyday life requires thoughtful design to ensure user satisfaction and widespread acceptance. These
61 wearable technologies are particularly well-suited for specific use cases, such as virtual reality, rehabilitation and remote
62 communication, where sensory feedback enhances the user experience. As the field advances, the direction of research and
63 development should focus on refining these technologies to improve both functionality and comfort. Scientists and engineers
64 have a critical role in shaping this progression, ensuring that future innovations align with both technological potential and
65 the needs of users.

66 In this Review, we survey the state of multi-sensory wearable haptics with a focus on body-worn devices that convey
67 multiple types of cutaneous haptic sensations. Although we highlight numerous examples of wearable haptic devices
68 throughout, readers are directed to other comprehensive surveys to gain a full picture of the state of current devices⁷⁻¹⁰.
69 Here, we instead focus on the engineering aspects for wearable multi-sensory haptic devices by emphasizing design
70 considerations and challenges in human perception. By analysing these questions in the context of the component
71 technologies and by exploring the wide range of applications of wearable haptic devices, we can better understand the future
72 trajectory of the fields and in doing so provide guidelines with which to shape research and development in this rapidly
73 evolving technological space.

74 [H1] Multi-sensory haptic perception

75 In the same way that graphics and audio target a person's sight and hearing to convey information, wearable haptic devices
76 use the skin as their primary communication channel with their human wearer. Thus, understanding the function and
77 interplay of the skin's cutaneous receptors is key to comprehending the mechanics of these devices. Given the engineering
78 focus of this Review, we provide only a high-level overview of cutaneous haptic perception in the following section. For more
79 details on the mechanisms of human haptic perception, the reader is referred to other comprehensive surveys^{11,12}.

80 [H2] Cutaneous haptic perception

81 Receptors in the skin respond to a variety of cutaneous stimuli - not just mechanoreceptors that sense mechanical stimuli
82 applied to the body, but also thermoreceptors that sense temperature, and nociceptors that detect pain.¹³ Mechanoreceptors
83 encode information related to mechanical action on the skin including pressure, stretch and vibration. They are present in
84 varying density across the body¹⁴ and can be categorized according to their receptive fields and rates of adaptation.^{15,16}
85 Rapidly adapting afferents innervate Meissner and Pacinian corpuscles and are associated with detecting changes in sensation
86 (such as making and breaking contact). Their peak sensitivity to skin vibrations occurs around 40 Hz (Meissner corpuscles)
87 and 250 Hz (Pacinian corpuscles). Slow-adapting afferents innervate Merkel disks and Ruffini cylinders and are associated
88 with detecting sustained presence of stimuli within their receptive field (for example, a varying pressure stimulus). Their peak
89 sensitivities to skin vibrations and skin stretch occur at low frequencies on the order of 1 Hz.¹⁷ Thermoreceptors sense
90 changes in temperature in a range between 15 °C and 45 °C, also referred to as the non-dangerous thermal range, whereas
91 pain receptors are activated outside this range.^{18,19} Thermoreceptors can be divided into cold and warm receptors, which
92 respond to decreases and increases in skin temperature, respectively.

93 Nociceptors detect various types of pain stimuli, with different receptor types partially associated with different
94 sensations. Although most haptic devices have focused on providing only mechanical stimulation to mechanoreceptors,
95 nociceptors in the skin are responsive to chemical stimuli, providing additional potential channels for haptic feedback. For
96 example, in wearable devices using flexible microfluidic channels, common (and safe) chemicals could be delivered to the
97 skin to elicit predictable sensations such as tingling (santalol), numbing (lidocaine), stinging (cinnamaldehyde), warming
98 (capsaicin) and cooling (menthol).²⁰

99 When an external mechanical stimulus is applied to the skin, all the cutaneous mechanoreceptor afferents in the area
100 are stimulated, providing tactile information according to their receptive characteristics. Cutaneous receptors respond to

101 different aspects of skin deformation according to their function. The mechanoreceptors, in response to stimuli, generate
102 action potential spikes that are transmitted to the central nervous system. The perception of intensity, shape, motion and
103 texture result from the integration of tactile information across multiple classes of tactile afferents that are activated during
104 most haptic interactions.¹⁷ Together, the afferents encode multiple types of information (such as pressure, vibration, stretch,
105 temperature, and/or pain) that can then be interpreted. This integration process is similar to how the brain combines images
106 registered by both eyes into a coherent view of the environment.

107 [H2] Cue perception challenges

108 Wearable haptic devices pose a number of specific challenges relating to cue delivery and perception. On the mechanical
109 side, devices need to be designed to accommodate the limits of the human user, operating within a narrow range of safe and
110 comfortable stimulation. For multi-sensory devices this problem is even more pronounced, as devices need to deliver multiple
111 simultaneous actuations, often with very different actuation profiles and mechanisms, while still guaranteeing comfortable
112 interaction in a small form factor. Additionally, perceptual issues in multi-sensory devices are complex, as concurrent cues
113 must be delivered in ways that are both individually salient and which do not interfere with each other mechanically or
114 perceptually.

115 [H3] Individual differences in skin mechanical response to stimuli

116 Owing to its compliance, softness and elasticity, the skin deforms on contact to provide a large contact area that enables
117 simultaneous activation of multiple receptors, conveying rich information to the brain. The presence of irregularities on the
118 skin's surface at specific locations such as the fingertips (via fingerprints) concentrates the applied external stimuli toward
119 the mechanoreceptors, increases friction and improves the ability to discriminate textures.²¹⁻²³ One of the main issues in the
120 design and use of wearable multi-sensory haptic devices is in the lack of understanding of skin's mechanical response to
121 stimuli, making it difficult to create haptic devices, stimuli and interactions that are experienced in a consistent way across
122 users. Human perception of tactile stimuli is entirely dependent on the contact mechanics that arise between the device and
123 the skin's surface.²⁴ Haptic actuation indirectly stimulates mechanoreceptors within the various layers of skin²⁵ in concert with
124 the layers of fat, muscle, veins and other tissues. Owing to variability in body and limb size, musculature and body fat,²⁶ as
125 well as the presence of hair, sweat, dust or other variations at the skin's surface, there are unique mechanical interactions
126 between a given device and its user. The skin's properties are also known to be influenced by factors such as age, hormone
127 levels, cosmetics and humidity, and many other variations further complicate analysis.²⁷⁻²⁹

128 Mechanoreceptor activation have been quantified under direct loading on the skin,³⁰ including indentation,³¹ shear
129 loading^{32,33} and vibration.³⁴ More comprehensive studies of fingertip haptic interactions have also been conducted, combining
130 finite element analyses with experiments.^{35,36} Existing tools, such as extensometry, indentation, torsion, vibration and suction,
131 enable direct analysis of the skin's properties providing a better understanding of the mechanics at play.³⁷ Finite element
132 analyses have also aimed to capture nonlinear skin responses such as anisotropy and material properties of distinct tissue
133 layers.³⁸⁻⁴⁰ Of particular importance are the mechanics of devices breaking contact with the skin. Adhesion arising from
134 surface energy, a material property relating to the attraction between two materials on a molecular level, is an important
135 tactile stimulus in interactions with hard, planar objects.⁴¹ By contrast, for sensations that arise at the interface with biological
136 materials (that is, in medical contexts), those arising from viscoelastic effects such as stickiness and tack dominate.⁴² A more
137 thorough understanding of these interactions is a key area of research to improve our understanding of tactile mechanical
138 interaction and ensuring that the perception of an applied haptic stimulus is consistently experienced across users.

139 [H3] Tactile masking

140 Multi-sensory haptic devices also need to account for the influence of different haptic sensations in concert, which might
141 interact in unpredictable ways. The key phenomenon here is tactile masking - the obscuring of the perception of one stimulus
142 by the presence of another one.⁴³ For example, in single-sensory vibrotactile devices, tactile masking of simultaneously
143 transmitted vibration stimuli increases perceptual thresholds⁴³ resulting in more difficult spatial and temporal cue
144 differentiation.⁴⁴ Tactile masking is especially challenging to overcome in integrated multi-sensory haptic devices, where the
145 individual haptic stimuli (such as squeeze, vibration and skin stretch on the arm) are presented in spatial and temporal
146 proximity.⁴⁵ Different types of haptic actuation (such as stretch and squeeze) can decrease accurate perception of these
147 cues⁴⁶; for example, the physical spacing between stimulus locations and the relative intensity of these varied cues can further
148 influence the perceptual effects of this tactile masking.⁴⁷ More research in this area is needed to determine what methods
149 either in cue or device design - can be used to mitigate these masking effects.

150 [H3] User attention

151 User attention also influences a user's perception of tactile cues.⁴⁸ Indeed, the effect of attention has been observed in spatial
152 attention across the body^{49,50} and when attention is spread across multiple senses.^{51,52} Furthermore, this difference in haptic
153 perception has also been observed across categories of differing user volition in inducing haptic stimulation, namely active
154 and passive haptics. In active haptics, users cause an interaction on their skin, often by exploring surfaces or objects with
155 their hands, whereas in passive haptics users reflexively sense an interaction applied to their skin to receive tactile
156 information, such as when someone else strokes their arm.^{53,54} Additional research in this area is needed to inform haptic cue
157 and device design, in light of the development of more complex and compact haptic components and devices.

158 [H1] Engineering and design considerations

159 [H2] Actuation methods

160 Although all wearable multi-sensory haptic devices are designed to engage the same biological mechanisms of sensation, the
161 methods and strategies of actuation to induce haptic sensations vary widely. Many haptic devices incorporate
162 electromechanical actuators given their widespread commercial availability, ease of implementation and reliability. Other
163 actuation methods have also been employed in wearable haptic devices, including electrical, polymeric, fluidic and thermal.⁵⁵

164 [H3] Electromechanical

165 Electromechanical actuators are used ubiquitously to provide haptic feedback⁹. Most frequently, vibration is accomplished
166 by eccentric rotating mass (ERM) actuators or voice coil actuators, typically linear resonant actuators. ERM motors achieve
167 vibration by spinning an unbalanced mass attached to the motor shaft. Despite being inexpensive and capable of delivering
168 large vibrations relative to their size, they are driven by a single input voltage that couples vibration frequency and amplitude.
169 Compared to other vibration-type actuators (such as voice coils), stimuli generated with these actuators have longer response
170 times because it takes time to get the mass spinning at a constant speed when starting from rest. Voice coil actuators can
171 offer independent control over the frequency and amplitude of the output vibration but have natural resonant frequency
172 ranges outside of which they are less effective. Through closed-loop control, larger bandwidths can be realized. In both cases,
173 device performance is highly dependent on the physical design of the actuators used. Position- or torque-controlled DC
174 motors are often used to generate stretch and squeeze type haptic sensations. These actuators often integrate a lever arm,
175 pulley or other mechanisms to convert rotational motion to translational displacements of an end-effector against the skin.
176 Regardless of the type of cue being generated, a balance must be achieved between device performance and other factors
177 such as cost and weight. Although a more expensive, heavier motor may be able to provide a more accurate or powerful
178 stimulus, it may not be worth the cost. Typical figures of merit with a haptic-driving motor include speed, torque and power
179 draw. Pre-packaged Proportional – Integral – Derivative (PID)-controlled servomotors are an appealing option for
180 electromechanical actuation due to their low cost and ease of use.

181 [H3] Electrical

182 Other types of electrical actuation can also be used to provide haptic sensations. Electrostatic and electroadhesion
183 convert electrical signals into mechanical effect⁵⁶ and are ubiquitous in displays exhibiting variable surface friction, some of
184 which are being commercialized, for example, Tanvas's tactile touch screen technology. Electrotactile stimulation couples the
185 movement of charge directly to the generation of action potentials in afferent fibers terminating in the skin.⁵⁷⁻⁵⁹ In principle,
186 this modality could be used to generate nearly any sensation, provided the signal is appropriately targeted. Recent
187 demonstrations of electrotactile stimulation have embedded electrodes in a fingertip device⁶⁰ and in an armband.⁶¹ In
188 practice, however, the stimulation tends to activate several afferent and efferent types over the region covered by the
189 electrode(s) and is usually perceived by the user as nondescript 'buzzing'. This modality of haptic feedback is available in
190 commercial transcutaneous electrical nerve stimulation (TENS) devices, which are sometimes used therapeutically for pain
191 reduction in cases such as arthritis, chronic low back pain or sports injuries.⁶²⁻⁶⁴ Although promising for some applications,
192 this modality can produce galvanic reactions, damage to the skin or numbness when overused or used with overly aggressive
193 parameters. Advantages of the technique when used on the limbs include quick response and ease of programming signals
194 which can be easily distinguished by wearers, that is, rhythmic tapping.⁶⁵

195 [H3] Polymeric

196 Polymeric materials are ubiquitous in devices for human-machine interfaces,^{66,67} in the form of engineered plastics for
197 structural and active components. Active polymers – including shape memory, stimulus responsive, piezoelectric, and
198 electrically conductive or semiconductive – might lend themselves to future haptic applications. The advantages of polymeric
199 materials arise from the ability to tune the structure and properties by chemical synthesis.⁶⁸ That is, the density, modulus,
200 adhesion, tack, phase transitions and ionic or electronic conductivity can be imparted to the material at the level of the
201 molecular structure. However, polymeric actuators tend to have slow dynamic responses due to their mechanism of action,
202 which may make them unsuited to applications in which the response time to the haptic feedback is critical; for example,
203 providing an amputee with touch feedback from a prosthetic hand so that they can accurately control hand pose.

204 Polymers used in haptics can be actuated by thermal, optical, magnetic or electrical means, generally for a mechanical
205 response.⁶⁷ Polymers of this class include liquid crystal elastomers,⁶⁹ dielectric elastomers,⁷⁰ piezoelectric polymers and
206 ferroelectric polymers.⁷¹ Liquid crystal elastomers are flexible polymer chains whose backbone intermittently incorporates a
207 rigid mesogenic unit. When solidified from the melt under shear forces (that is, extrusion), the mesogens - rigid subunits
208 within the flexible structure - align along the sheared axis and form ordered domains.⁷⁰ If the polymer is crosslinked in this
209 aligned state, the solid contracts like a muscle when heated, and returns to the elongated, aligned state when cooled. Heat
210 causes the polymers to contract with actuation stresses close to those of natural muscle. Importantly, heat can be applied
211 discreetly using optical absorption and later dissipation using a dye sensitizer.⁷² Dielectric elastomers compress when placed
212 in between compliant electrodes and subjected to a high potential.⁷² Piezoelectric polymers such as poly(vinylidene fluoride)
213 (PVDF) and composites thereof can be actuated at rates of kilohertz, albeit with low displacement.⁷³ Such polymeric
214 structures provide unique opportunities for the construction of mechanical haptic devices with different profiles and
215 characteristics. Polymeric actuation does come with some limitations - devices may only provide weak haptic stimuli because
216 of low displacements, their dynamic response times can be slow, and their robustness for use in wearable devices may be
217 limited. These challenges are counterbalanced by their unique advantages; for example, polymeric materials can facilitate
218 fluidic logic⁷⁴⁻⁷⁶ and fluid-based electronics-free devices⁷⁷⁻⁷⁹. These control solutions do not suffer from issues with
219 washability⁸⁰ and bypass the need for rigid onboard components, enabling safer and more comfortable devices.

220 [H3] Fluidic

221 Fluidic haptic devices use pressurized fluid to deform the mechanical structure of an actuator to provide haptic stimuli. Fluidic
222 actuation has been the most prominent actuation method in the field of soft robotics⁸¹ and is lighter (particularly with
223 pneumatic systems) and more compliant than other approaches. Fluidic haptic devices include pump-driven surface dot
224 Braille displays,⁸² reed-based vibrotactors,⁸³ and inflatable elastomeric haptic displays based on integrated serpentine liquid
225 metal traces.⁸⁴ Other fluidic approaches rely on inextensible and non-elastomeric, yet compliant, 2D materials, such as sheets
226 of polymers. Devices based on these flexible sheets can both squeeze and vibrate⁸⁵ while applying forces at multiple length
227 scales simultaneously.^{86,87} Pressurized fluid can also be used for sensing and transmission of a signal to another location on
228 the body, without any electronic control or interface.⁸⁸ In cases where electronic control is desired, bulky infrastructure for
229 pressurization (pumps) and control (valves) of fluid can be avoided with local pressurization using hybrid electric-fluidic
230 approaches, including generation of standing waves with piezoelectric actuators⁸⁹ and amplification of fluid pressure based
231 on electrostatic attraction⁹⁰ in devices that can fit on the fingertip.⁹¹ Compliant microfluidic elastomeric Braille displays have
232 even used liquid metal electrodes to spark local combustion and generate tactile cues.⁹² Fluidic haptic devices have also taken
233 advantage of the textile format common in wearables⁹³; for example, squeeze and stretch cues have been demonstrated in
234 'fluidic fabric muscle sheets' that employ elastic tubing integrated into a textile sheet.^{94,95} A textile sleeve was fabricated with
235 internal plastic pouches that could be sequentially inflated with air to generate the illusion of lateral movement on the arm.⁹⁶
236 Similarly pneumatically actuated wearable haptic devices made entirely from heat-sealable textiles were fabricated in a
237 scalable manner.⁹⁷ Although the performance of these devices may vary and limitations still exist (such as portability, leakage
238 and the need for sources of compressed air), the availability of new materials and actuation methods that can be rapidly
239 fabricated and prototyped⁹⁸ provides a distinct advantage over traditional electromechanical actuation, and enables the
240 designer to realize a wide range of tactile cues.

241 [H3] Thermal

242 Thermal haptic devices use heating and cooling on the skin to provide information. They can complement other mechanisms
243 of tactile stimulation in a multi-sensory case to enhance a user's haptic experiences. For example, thermal feedback devices
244 combined with fluidic mechanisms take advantage of combined thermofluidic operation (that is, the working fluid acts as
245 both a pressure source and a thermal reservoir). For instance, a glove device was developed to apply both force and a set

246 temperature at the palm of a user's hand by mixing hot and cold air in an electronic valve-based control system.⁹⁹ Similarly,
247 another device used pressurized water delivered from a combination of a hot and a cold tank to a sleeve, with the
248 temperature of the pressurized fluid controlled by varying the proportions of hot and cold fluid delivered.¹⁰⁰ In another
249 approach, elastomeric bubbles arranged in an array were fitted with Peltier modules for heating and cooling.¹⁰¹ Thermal and
250 fluidic stimuli have also been combined synergistically to generate the illusion of thermal movement using a stationary
251 thermal stimulus and a moving pneumatic stimulus.¹⁰²

252 Thermal stimuli that do not rely on fluidic actuation have also been successfully deployed in wearable applications,¹⁰³
253 with form factors including a ring for a finger¹⁰⁴ and a bracelet-like wrist-worn thermal display.¹⁰⁵ These thermal approaches
254 need not be rigid; such as a stretchable, compliant, and comfortable design based on Peltier modules embedded in an
255 elastomer matrix.¹⁰⁶ Going beyond perceived temperatures, thermal haptic devices can also modulate sensations of surface
256 friction¹⁰⁷ and generate the illusion of surface wetness.¹⁰⁸ This capability relies on Joule heating, thermoelectric heat transfer,
257 or fluidic heat transfer; wearable thermal haptic devices can also leverage the electrocaloric and magnetocaloric effects, as
258 well as mechanocaloric and phase change materials.^{109,110} The limitations of thermal haptic devices vary, but do not preclude
259 their future use in wearable haptic systems. Peltier devices often require active cooling to operate within reasonable
260 temperature ranges, and other actuation schemes can have response times on the order of seconds, making them best suited
261 to specific applications where slower responses are acceptable⁸¹ (including thermoregulation in a broad wearable systems
262 context and low-priority cues in a haptics context).⁹³ Evaluating human perception and performance with thermally actuated
263 wearable haptic devices is an underexplored area in the field and may provide new avenues for haptic designs and strategies.

264 [H1] Implementation

265 Wearable haptic devices can be customized to fit and attach to almost any region of the body. Wearable implementation
266 must ensure effective attachment to the body so that the haptic stimuli are transmitted to the skin and long-term adoption
267 by the user. Absolute design characteristics (such as weight, size) might be misleading in evaluating the 'wearability' of a
268 haptic device. Rather, these properties must be considered with respect to where the device is worn and how it will be used.
269 A device that is unobtrusive on the shoulder may be cumbersome if worn on the hand, or vice versa. The device attachment
270 method can be considered effective if it is well-suited to location, well-grounded and comfortable. Device fit and
271 personalization are also important considerations that are key to long term adoption.

272 [H2] Body location

273 The choice of body location for a wearable haptic device is dictated by the application (for example, providing haptic feedback
274 to the residual limb for a person with limb loss using a prosthetic device) or by the perceptual acuity that is required for a
275 task (for example, simple and discrete haptic notifications may be satisfactorily perceived on areas of the body known for
276 having lower perceptual resolution, such as the arms or torso, whereas high density information transfer might require a
277 wearable to be located on a part of the body with better perceptual resolution, like the fingertip). In designing haptic feedback
278 for any purpose, one of the first key steps is in determining what locations are best suited to that application. Some of the
279 design objectives that have been defined are⁹: (i) form factor: wearable devices should alter the body size of the wearer as
280 little as possible; (ii) weight: they should tire the wearer as little as possible; (iii) impairment: they should limit the motion of
281 their wearers as little as possible; and (iv) comfort: they should be comfortable to wear and easy to adapt to the wearer limb
282 size and shape. The differences in skin characteristics, receptor density, and basic ergonomics result in highly varied design
283 requirements across the body (**Fig. 2**).

284
285 Critically, a wearable device should be designed to take advantage of the area of the body it is applied to. For example,
286 exoskeletons can apply kinesthetic feedback to the articulated joints they act on by means of electromechanical actuators or
287 locking mechanisms. A similar type of feedback can also be achieved through cutaneous-only approaches, conveying skin
288 stretch to the back of, for example, finger joints, the wrist or the elbow, eliciting proprioceptive sensations¹¹¹ in a more
289 compact package. The characteristics and degree of sensation elicited is strongly influenced by whether it is applied to
290 glabrous (the palms) or hairy skin, with glabrous skin typically more sensitive to touch stimuli.¹⁴ The best solution to adopt
291 depends heavily on the task and situation considered.

292 Sustained vibrations applied at the joints (such as, elbows and knees)¹¹² in correlation with motion, can convey the
293 sensation of joint movement¹¹³ as well as viscoelastic effects such as stick and slip sensations.¹¹⁴ The hand and the fingertip
294 are still the most popular places for wearable haptic interfaces^{9,59,115} because they are the most sensitive to tactile stimulation
295 and most often used for probing the environment. The upper and lower limbs are common places to locate wearable haptic
296 devices that provide squeeze,¹¹⁶ twist,¹¹⁷ and caress¹¹⁸ tactile sensations. In terms of available surface, the torso enables the

297 largest area of interaction and devices for this part of the body have existed since the 1990s.¹¹⁹ Hugging sensations around
298 the torso have been provided through haptic jackets via vibration¹²⁰ or pneumatic actuation.¹²¹ Haptic vests have been
299 produced with arrays of voice-coil motors positioned around the torso to help increase immersion in artificial
300 environments.¹²² Finally, belts and bracelets for the waist and wrist, respectively, are an often selected form factor, and can
301 be used to provide a variety of information cues using various means and for applications including communication, training
302 or guidance, and navigation.^{116,123–125}

303 [H2] Device grounding

304 A grounded interface typically refers to the alternative to a wearable device, where the device is located on a table or other
305 fixed platform, whereby only the forces associated with the haptic stimulus are felt by the user. Here, we expand the use of
306 this term, grounding, to describe how the reaction forces experienced by the actuator are channelled during a haptic stimulus.
307 The reaction forces in a grounded device are absorbed by the workbench or external framework. For a wearable device, this
308 includes how a device is attached to the body, and specifically how the reaction forces are transmitted to the user. Many
309 wearable devices, whether on the upper arm, ankle or fingertip, are simply strapped on to the area of the body where the
310 stimulus is applied.⁹ In these cases, the stimulus actuation is accompanied by the reaction forces, absorbed within the entire
311 assembly of the device frame, strap and part of the body to which it is secured. When cutaneous haptic stimuli are applied
312 to the skin in a wearable device, the reaction forces transmitted through the grounding mechanism are also perceivable by
313 the user, and may obscure the intended haptic experience.¹²⁶ This phenomenon of unintentional feedback also arises in body-
314 powered prostheses, where the harness rubs against the skin providing an indicator of hand closure,¹²⁷ or in fingertip haptics,
315 where the fingertip receives haptic stimuli on both the finger pad (intended cue) and the nail (unintentional reaction force).¹²⁸
316 This challenge can be overcome with mechanical design as demonstrated in antagonistic devices, where the cue design has
317 multiple stimulus points that counteract each other, such as in a wrist-worn device using pin-based radial squeeze¹²⁹ or the
318 coordinated stretch in a bracelet of four rockers.¹²⁵ As the design and integration of haptic devices progresses, hapticians
319 should acknowledge and take advantage of the totality of the haptic experience of the user.

320 [H2] Comfort

321 The comfort elements for wearable devices are similar to those of clothing, consisting of pressure, texture, thermal balance,
322 moisture transport and freedom of movement,¹³⁰ and are important for long term adoption of any device. In addition to
323 comfort, some of these elements are also related to the performance of the device. Pressure and moisture transport can
324 impact the effectiveness of frictional or adhered cue interfaces. Moreover, some parts of the body more naturally lend
325 themselves to delivery of haptic sensations.⁷ For example, from a user's perspective, the ears and wrists are considered the
326 most comfortable locations to stimulate with vibration, unlike the neck and ankle¹³¹. Similarly, examining the role of wearable
327 device weight, volume and surface area on user comfort and acceptance, revealed that proximal body locations (on the trunk
328 or torso) resulted in higher tolerances for each device characteristic compared to distal locations on the limbs.¹³² Moreover,
329 the comfort of the device presents many important design criteria regarding the interplay of material choices, attachment
330 methods, body location and haptic modalities.

331 [H2] Personalization and fitting

332 The design of haptic interfaces must consider the differences in the limbs' size, shape and perceptual characteristics across
333 humans. Age, sex and other factors influence these differences.^{133,134} Humans' sense of touch is highly sensitive to variations
334 in contact stimulation, making a good fit of the device important for the delivery of accurate sensations. For example,
335 rendering the same fingertip tactile cues to users with different finger sizes alters the accuracy in identifying cue locations.¹³⁵
336 Similarly, older adults have lower tactile performance than younger adults.¹³⁶ Rendering or software approaches aim to
337 personalize haptic feedback by adapting the way the interface renders the commanded sensations,^{137,138} whereas hardware
338 approaches modify the mechanical design of the interface to best fit the target limb.¹³⁹

339 [H1] Future directions for devices

340 The field of haptic technology has been in a constant state of development and reinvention over the last few decades, and
341 the recent proliferation of multi-sensory wearable devices has only accelerated this trend (Fig. 3, Table 1).

342 [H2] Soft haptic wearables

343 Designing comfortable architectures is essential for wearable devices. Thus, soft compliant structures with integrated sensing
344 are a very promising approach for achieving effective and comfortable designs.⁸ Miniaturization of these components – or

345 incorporation into a flexible form factor – is critical to make the whole device minimally obtrusive. Smart sensors capable of
346 modulating (that is, gating) the behaviour of tactile actuators can circumvent the use of integrated circuits. However, for
347 highly sophisticated tactile stimulation, integration of sensing and actuation may take advantage of not only integrated
348 circuits, but also batteries, wireless telemetry and the capacity to implement machine learning algorithms.

349 So far, soft materials for wearable haptic applications⁹⁷ have mainly been used for actuation, with few power sources and
350 controllers.⁸¹ Thus, many wearable haptic devices remain tethered, and untethered approaches typically employ a rigid
351 battery for power and a traditional hard plastic printed circuit board or microcontroller for onboard computation or wireless
352 communication with an external computer. For more comfortable devices, compliant electronic power sources are now being
353 developed using intrinsically stretchable platforms (such as all-hydrogel batteries) and also by incorporation of flexible fibre-
354 like structures such as cathodes and anodes, application of strain engineering techniques and platforms based on rigid island-
355 like structures wherein many small cells (that is, ‘traditional’ batteries) are interconnected and incorporated into a soft or
356 flexible matrix.¹⁴⁰ Furthermore, soft, stretchable electronic pumps¹⁴¹ have been developed that can drive the many soft fluidic
357 actuators currently available.¹⁴² Fully fluidic approaches (that is, without reliance on electronics) may further reduce the
358 overall size while remaining compliant. To this end, onboard fluidic energy harvesting¹⁴³ and fluidic digital logic⁸⁰ integrated
359 in textile-based platforms are promising for different haptics applications.⁹³ For example, an RC-like fluidic circuit was
360 deployed within textile sheets of a wearable for spatiotemporal control of haptic cues, resulting in reduced reliance on
361 electronic control infrastructure by over 60%.⁹⁷ Similarly, bypassing the need for electronic power and computation
362 altogether, a soft haptic system was developed in which sensing, transduction of a signal and actuation are all performed
363 fluidically.⁸⁸

364 [H2] Improving the realism of touch-based interactions

365 Researchers are continuously striving to improve the realism of haptic feedback that is provided by wearables, and the
366 proliferation of multi-sensory devices is an indicator of this. By incorporating a number of different actuation methods into a
367 wearable, the richness of the haptic feedback increases to better approximate natural touch interactions.¹⁴⁴ Compared to
368 kinesthetic devices that are often mounted to a desktop or take the form of exoskeletons, wearable haptic devices can provide
369 such experiences with a relatively low-cost of actuation. Kinesthetic devices must employ rigid kinematic linkages, large
370 motors and/or complex transmissions to transmit forces and torques to the musculoskeletal system. By contrast, the haptic
371 feedback provided by wearable multi-sensory devices, despite their relative simplicity, can provide similar sensation by, for
372 example, cutaneous stimulation if provided coherently with the other senses.^{111,129,145}

373 New approaches to improve realism are most often applied in virtual reality (VR) and augmented reality (AR) scenarios
374 where there is a strong desire to keep the hands and fingertips unencumbered while adding haptic feedback to a visual-
375 feedback dominated domain. One method, called referred haptic feedback, explores how haptic stimuli applied at one part
376 of the body are perceived as touch interactions at other locations, resulting in improved haptic experiences for the user when
377 compared to visual-feedback alone. For example, multi-sensory pseudo-haptics have been developed for rendering touch
378 interactions at the wrist correlating to interactions in VR that are experienced at the fingertip.¹⁴⁵ By modulating wrist squeeze
379 and visual feedback, users were able to consistently perceive virtual objects of varying stiffness. Vibrations provided at
380 discrete locations on the arm can also be perceived as a stimulus at locations that are not being stimulated, improving
381 wearability and comfort compared to hand-worn devices.¹⁴⁶ Similarly, electrotactile stimulation on the back of the hand can
382 be used to render haptic interactions that appear to occur in the palm of the hand, in a form factor that is lightweight and
383 portable.¹⁴⁷ These new approaches circumvent some of the implementation challenges related to comfort and wearability.
384 Although they may not be considered realistic when compared to real-world interactions with objects, these methods
385 enhance the immersiveness of the user in the VR/AR world by coupling intuitive haptic feedback with realistic visual feedback.

386 [H1] Application domains

387 In this section, we analyse and discuss the context in which different multi-sensory devices have been implemented and
388 identify key application domains with opportunities for development and utilization (**Fig. 4**).

389 [H2] Navigation

390 One application for wearable haptics is in personal navigation, wherein haptics can provide intuitive spatial information to a
391 user in a private manner. Touch is a spatial sense distributed across the body and has the advantage of having intuitive spatial
392 encoding based on the area of the skin that is stimulated. Personal navigation wearable devices have been developed in
393 various form factors on the body including on the back,¹⁴⁸ waist,¹⁴⁹ forehead,¹⁵⁰ and wrist,^{125,151} as well as with handheld

394 devices.¹⁵² Tactile feedback has also been used to provide information while driving¹⁵³ and obstacle navigation for people with
395 blindness.^{154,155}

396 [H2] Teleoperation

397 Haptic feedback strongly benefits robotic telemanipulation,¹⁵⁶ wherein a human operator carries out tasks by controlling a
398 remote robotic manipulator. However, modern commercial telemanipulation systems, such as the da Vinci surgical robot,
399 provide very limited haptic feedback.¹⁵⁷ This omission is caused, among others, by the cost that using the robot interface for
400 haptic feedback has on the stability of the control loop, potentially leading to undesired system oscillations.^{158,159} Complex
401 telerobotic systems have been developed that provide haptic feedback to the operator, including tactile telerobots.¹⁶⁰ For
402 example, teleoperation systems that deploy dexterous robots on mobile bases enable operators to complete a range of tasks
403 that depend on haptic feedback, such as discriminating textures or object weights.¹⁶¹ Cutaneous haptic devices have also
404 received some attention in this field, as delivering ungrounded cutaneous stimuli provides the human operator with
405 information about the forces exerted by the remote manipulator without impacting its safety.¹²⁸ The types of haptic stimuli
406 used in teleoperation include pressure and vibrations,¹⁶² pressure and kinesthetic cues,^{163,164} skin stretch and pressure,^{116,165}
407 as well as pressure, kinesthetic cues and vibrations¹⁶⁶ for applications of remote grasping, palpation and surface exploration.
408 Further development of wearable and multi-sensory devices could lead to solutions for intuitive, safe and comfortable
409 teleoperation.

410 [H2] Communication

411 A central objective of wearable haptic communication systems is to encode information, which is typically processed visually
412 or aurally, as tactile stimulation patterns presented to the skin.¹⁷² An advantage of these devices is that they can provide
413 private, salient information to the user. Wearable devices can transmit tactile languages by encoding phonemes,^{172,173} Latin
414 alphanumeric characters,¹⁷⁴ and spectral properties of acoustic speech signals,¹⁷⁵ although, to date, these devices have not
415 been commercialized. Communication need not be confined to language alone, and wearable haptic devices can be used to
416 communicate abstract information, such as the simple vibrotactile notifications we receive from our smart watches. For
417 example, multi-sensory haptic devices can transmit large sets of discrete cues that are more reliably perceived than single-
418 sensory haptic cues,¹⁷⁶ enabling complex content to be communicated to users, such as real-time task performance
419 feedback.^{177,178} Such findings expand the range of applications for which wearable haptic devices may be deployed.

420 [H2] VR and AR

421 VR simulations have already been adopted for education, entertainment and training applications.¹⁷⁹ In these spaces, VR
422 technology has been praised for adding much needed realism by immersing the user in the application or simulation.
423 However, current VR solutions are notably missing realistic haptic feedback, preventing users from receiving the added
424 realism and immersion benefits of being able to feel the environments in their simulations.¹⁵⁶ As such, the role of haptic
425 feedback in improving VR applications ranging from education programs¹⁸⁰ to surgical simulations is being investigated.^{181,182}
426 Current VR haptic solutions are typically handheld controllers which include simple vibration motors to produce the sensation
427 of contact with objects. However, these VR interfaces' make it difficult to imitate the complex and subtle set of tactile cueing
428 that occurs in real touch interactions with the environment.⁵⁵ To induce more realistic haptic feedback, haptic gloves,¹⁸³
429 fingertip devices,⁹ wrist sensory feedback devices¹²⁹ and even haptic shoes have been developed.¹⁸⁴ In AR, wearable haptics
430 has been used to haptically enhance the virtual content^{185,186} and to alter the tactile perception of tangible objects.¹⁸⁷⁻¹⁸⁹ In
431 all cases, multi-sensory solutions are rare and are an open area for further innovation.

432 [H2] Prosthetic devices

433 In cases of amputation, and especially upper-limb amputation, the loss of feedback in the form of touch sensation limits the
434 user's ability to control their replacement prosthetic device. Haptic technologies have been used to provide touch feedback
435 on the residual limb or on alternative body locations, such as providing skin stretch feedback on the proximal upper limb for
436 a transradial amputee.¹⁷⁰ Other methods, such as peripheral nerve stimulation¹⁹⁰ and cortical stimulation¹⁹¹ feedback, offer
437 high-quality solutions; however, many of these technologies are still highly experimental, invasive, expensive and with unclear
438 long-term effects. Haptic technologies are therefore valuable owing to their comparative low cost and non-invasiveness.
439 Multi-sensory haptic devices are a promising avenue this area because they can present multiple types of information
440 communicated via different haptic modalities, which can accommodate more advanced devices with greater available
441 sensory information to help inform user control.¹⁹² Additionally, haptic feedback can be used alongside new prosthetic

442 augmentation technologies, such as targeted muscle reinnervation which reroutes efferent nerves from the residual limb to
443 other sites to enable myoelectric control,¹⁹³⁻¹⁹⁵ providing new possibilities for feedback and control combinations.

444 [H2] Rehabilitation, re-education and training

445 Haptics have been employed to aid the rehabilitation and re-education of human limbs and movements. For the case of
446 rehabilitation following neurological injury, although limb movement rehabilitation usually involves situations where patients
447 are mostly passive and the therapists are in charge of moving the target limb, the direct involvement of patients in the
448 movement can improve cognitive-motor skills and motor learning.¹⁹⁶ Thus, exoskeletons that can provide variable movement
449 resistance or assistance could assist rehabilitation exercises,^{197,198} therefore reducing the physical load of therapists while
450 carrying out longer, more consistent and potentially less expensive rehabilitation exercise sessions. Machines can also track
451 the patients' progresses by analysing data such as the force applied, range of motion, frequency of exercises, enhancing
452 engagement, motivation and adherence to treatment. To date, the improvements in clinical outcomes of robotic
453 rehabilitation devices that incorporate haptic feedback to support limb movements have been modest, and additional
454 research is needed to truly leverage the potential benefits of such interventions.¹⁹⁹

455 For motor skill training with haptics, the haptic feedback provided during training of motor tasks can effectively foster
456 learning, although the outcomes are often task dependent.²⁰⁰ Positive outcomes are most often realized when the
457 information that is provided via the haptic channel cannot be provided using other modalities such as vision or auditory
458 stimulation.²⁰¹ Of critical importance in the design and application of these devices is the safety of the patient, both in the
459 operation of the haptic devices and their use in concert with other devices - an area which has seen relatively little
460 standardization in safety expectations across the field.²⁰²

461 Although most currently-available approaches use kinesthetic- or cutaneous-only interfaces providing resistance or
462 guidance forces for training or aiding a target movement, there has recently been an increasing interest for wearable multi-
463 sensory cutaneous solutions, mostly combining pressure and vibrotactile feedback²⁰³ or pressure and skin stretch
464 feedback^{169,204-216} for applications of motor rehabilitation and learning,^{169,203,205} grasping aid and augmentation and for
465 treating disorders of consciousness.^{204,207} Such approaches are generally easier and less expensive to deploy with respect to
466 haptic exoskeletons and might be even used by patients directly at home, ensuring broader access to these rehabilitation
467 technologies.²⁰⁸ Multi-sensory wearable haptic devices with a low cost cutaneous feedback could also incorporate squeeze
468 and skin stretch for haptic training, which was as effective as a complex kinesthetic haptic device at conveying desired
469 trajectories for complex motor tasks.²⁰⁶

470 [H1] Outlook

471 Our skin contains different mechanoreceptors that are tuned to respond to a range of haptic sensations. There is a good
472 understanding of human perception of single-sensory wearable haptic cues about factors such as detection thresholds,
473 discrimination thresholds, cue identification and the parameters of the cues themselves (amplitude, frequency) that are
474 necessary to ensure salience. The issues that face designers of single-sensory devices can present more intensely or in
475 different ways in multi-sensory devices, such as when perceptual masking is observed, or variations in the perceived intensity
476 of one type of stimulus compared to another (such as squeeze, stretch, vibration.) are presented concurrently. More research
477 is needed to further elucidate how our perceptual system can process multi-sensory cues to ensure that the information
478 provided to users is reliably perceived, information-rich and useful.

479 There is a large and growing number of haptic devices represented in the literature with more devices that offer multi-sensory
480 cues in a wearable form factor. This is attractive for a wide range of applications, however, it is vital to not only focus on the
481 mechanisms, but to also consider the interaction between device and end user, such as comfort, long-term wearability and
482 social acceptance of on-body devices. The grounding or attachment of the device to the body, the compliance of the body to
483 which the wearable is mounted and the effects of such compliance on the repeatability of the haptic experience of the user
484 are also important aspects to consider. To achieve more comfortable and compact designs, enable tetherless operation, and
485 facilitate a broad range of tactile sensations, engineers and scientists are developing and integrating new actuation methods
486 into wearables, shifting from the electromechanical actuation domain to include electrostatic, polymeric, fluidic actuation,
487 thermal systems and similar innovations.

488 There are numerous engineering design challenges when developing haptic devices, such as the wide range of touch
489 sensations experienced, the challenges of artificially creating these sensations, and the heterogeneity of user experiences
490 when interacting with haptic devices. In wearable multi-sensory haptic devices, the primary challenge is the lack of realism
491 of the haptic feedback currently provided. As seen in the visual and auditory domains, to work effectively for users, the
492 sensory feedback provided, regardless of domain (visual, auditory or haptic), must be high quality and realistic, a goal which

493 has not yet been fully realized for the haptic domain. As an example, the recent and wide-spread adoption of VR technologies
494 that involve immersive visual feedback is directly tied to technological improvements that overcame the limitations of early
495 prototypes. Improvements in display resolution and the substantial reduction of lag in the visual display improve the provision
496 of feedback, while miniaturization of component technologies enable more wearable VR headsets.

497 The lack of realism in current haptic feedback devices can be attributed to the unique nature of haptics and technological
498 limitations. First, there is a considerable mismatch between the artificial stimuli that are generated by wearable haptic devices
499 and naturally occurring stimuli encountered in everyday lives.¹⁷ The former are often limited to the amplitude and bandwidth
500 triggered by the method of actuation which may not excite all afferent classes in the same way that naturally occurring stimuli
501 in the skin do. For example, actuation methods aimed at providing vibration cues often rely on resonance characteristics of
502 the actuator to generate the vibration,²⁰⁹ and therefore may not achieve the full range of vibration frequencies and
503 amplitudes that occur naturally. To span a wider range of stimuli characteristics, multiple artificial stimuli might be needed
504 (such as vibration combined with normal indentation or shearing of the skin) which could be realized using a wide range of
505 actuation methods (such as electromechanical or pneumatic).⁵⁵

506 A second challenge is the distributed nature of humans' haptic sense. There are different types of cutaneous
507 mechanoreceptive afferents throughout the skin with varying densities across the body. In wearable haptic devices that
508 provide artificial stimuli to the skin, the application of the stimuli is directed to a particular region (**Fig. 2**). Even when multiple
509 types of actuation are integrated to generate several types of touch sensations, from a practicality standpoint, the stimuli are
510 usually applied in a distributed manner. For example, some actuators may be located more proximal and some more distal
511 along the arm, or some directed to the volar side and others to the dorsal side of the wrist. This is largely a packaging problem
512 - the body has a limited number of feasible locations for affixing wearable devices, and the selection of a location for a
513 wearable limit the experience that the user will have.

514 Underlying these considerations is the very real challenge to demonstrate that there is a tangible benefit to be gained
515 with the heightened complexity that comes with adding multi-sensory haptics to wearables. Incorporating sensors and
516 actuators adds cost and complexity that, without validation that the addition of haptics themselves is necessary or even
517 desirable for achieving a given outcome, may simply not be worth the effort. For example, in surgical and rehabilitation
518 robotics, patient outcomes when using robotic interventions have not been definitively shown to exceed those realized with
519 laparoscopic or open surgery²¹⁰, or with standard physical or occupational therapy.²¹¹ In the case of amputees who rely on
520 prosthetic devices to restore lost function, many users will abandon the prosthesis due to issues with comfort, aesthetics,
521 complexity or limits in functionality.^{212,213} Thus, hapticians will first need to demonstrate the benefits of incorporating
522 wearable haptic devices in a range of application scenarios. Simple solutions for haptic feedback that are integral to the
523 function of an existing technology, such as how a body-powered cable-driven prosthesis gives some haptic feedback through
524 interactions that occur between the skin and the prosthesis cable harness,¹²⁷ may be preferable to add-on wearable
525 technologies that seek to recreate realistic natural touch sensations.²¹³

526 There might also be cases where the haptic information being transmitted to the user does not need to be realistic, but
527 rather can bolster or replace other sensory modalities. For example, limitations of human haptic perception can be offset via
528 haptic illusions,^{214,215} pseudo-haptics,²¹⁶ or the combination of low-fidelity haptic cues with realistic visual and audio feedback
529 to enhance the haptic experience.²¹⁷⁻²¹⁹ Designers of wearable haptic devices have many opportunities for providing rich
530 information to enhance interactions with technology and overcome remaining problems of realism and dexterity. In addition
531 to considering the requirements for the haptic stimulus in an application, the physical requirements require attention as well.

532 As other hardware prototypes, to realize fully wearable devices, lightweight component technologies such as sensors,
533 actuators, microprocessors and batteries need to be small, robust and lightweight. Increasingly, the development of new
534 actuators will require inputs from fields which have not previously been prominent within haptics, such as chemistry and
535 materials science (**Box 1**). Moreover, if aimed for biomedical applications, medical devices are subjected to regulatory
536 approvals per their classification. In addition to clinical effectiveness, safety, reliability and security must also be ensured, and
537 the regulatory review process can slow the translation of products and prototypes to market.

538

539 References

540 *We acknowledge that papers authored by scholars from historically excluded groups are systematically under-cited. Here, we*
541 *have attempted to reference relevant papers in a manner that is equitable in terms of racial, ethnic, gender and geographical*
542 *representation.*

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1037 **Author contributions**

1038 J.J.F. and M.K.O. contributed substantially to the discussion, writing, and editing of this manuscript, and managed the
1039 submission process. J.J.F., Z.A.Z, and M.K.O. developed figures for the manuscript. J.P.C., D.J.P., D.J.L., C.P., and Z.A.Z
1040 contributed substantially to the writing and editing of this manuscript.
1041

1042 **Competing interests**

1043 The authors declare no competing interests.
1044












1045 **Peer review information**

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1048

1049 **Key points**

- 1050 • The translation of wearable multi-sensory haptic devices relies on a robust understanding of human haptic
1051 perception so that feedback modalities can be combined to optimally enhance user performance in a given
1052 application domain.
- 1053 • The contact mechanics at the haptic interface between device and skin varies between users with an unknown effect
1054 on haptic perception.
- 1055 • In addition to traditional electromechanical actuation, new methods such as polymeric, fluidic and thermal
1056 actuation now exists.
- 1057 • When designing wearable haptic devices, body location, the device interface to the body, user comfort and
1058 preserving the integrity of the haptic feedback must be considered.
1059

Table 1. Table of various multi-sensory wearable haptic devices

Haptic Channels: Stretch  | Pressure  | Vibration  | Thermal  | Electrical 
 Actuation: Mechanical  | Polymeric  | Thermal 
 Fluidic  | Electrostatic  | Chemical 

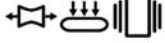











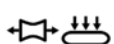







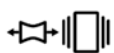











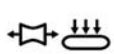

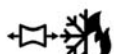

Device	Haptic Channels	Actuation	Location	Application
Aggravi Elastic Belt ¹¹⁶			Forearm	Teleoperation Prosthetics
Akther Acoustofluidic Actuator ⁸⁹			Fingertip	Navigation Communication
Animotus/Haptic Taco ¹⁵²			Hand	Navigation
ATH-Ring ²²³			Finger	VR
Bark Rotation Display ¹¹⁷			Forearm	Prosthetics Rehabilitation
Bellowband ⁸⁵			Forearm	VR
Bianchi Fabric-based Display ²⁰⁴			Forearm	Communication Affective
Bortone Fingerpad Display ¹⁶⁹			Fingertip	VR Rehabilitation
Buchmann Haptic Belt ²²⁴			Waist	Navigation VR
Cacucciolo Stretchable Pumps ¹⁴¹			Hand	General
Chinello Fingertip Device ¹¹⁵			Fingertip	VR
Chinello Skin Stretch Device ¹²⁵			Forearm	Teleoperation
CUFF ²²⁵			Upper arm	Navigation
Edwards Vibrotactile Belt ¹²⁴			Waist	Navigation Communication
Erp Vibrotactile Belt ¹⁴⁹			Waist	Navigation
Ertan Navigation Vest ¹¹⁹			Back	Navigation
Fluidic Fabric Muscle Sheets ⁹⁴			General	General
Gabardi Thermal Thimble ¹⁰³			Fingertip	VR

Table 1. Continued

Device	Haptic Channels	Actuation	Location	Application
Haptic Jacket ^{23,120}			Upper arm Chest	Communication Affective
Haptic Thimble ²⁰³			Fingertip	VR Rehabilitation
hBracelet ¹⁸⁶			Forearm	Teleoperation
Heisser Soft Microactuators ⁹²			Fingertip	Communication
Huggy Pajama ¹²¹			Chest Back	Communication Affective
Hussain hRing ²²⁶			Finger	Prosthetics
Jumet Squeeze Band ²²⁷			Forearm Upper arm	General
Kajimoto Electrotactile Display ⁵⁸			Fingertip	General
Keef Haptic Glove ⁶⁵			Hand	VR Teleoperation
Kitamura Vocal Cord Actuators ⁸³			General	General
Kuang Cutaneous Device ¹⁵⁰			Forehead Forearm Hand	Navigation
Lee Skin-Like Thermo-Haptics ¹⁰⁶			Hand	VR
Leroy HAXEL ⁹¹			Fingertip	VR
Lin Electrotactile Rendering System ²²⁸			Fingertip Hand	VR Communication Teleoperation
Lu Chemical Haptics ²⁰			Forearm Face	VR
Macklin Vibrotactile Sleeve ²²⁹			Forearm	Communication
McDaniel Haptic Belt ¹²³			Waist	Communication
Merrett Fingertip Devices ²³⁰			Fingertip	Rehabilitation
MISSIVE ^{45,172}			Upper arm	Communication
Mouillé ¹⁰⁸			Fingertip	VR

Table 1. Continued

Device	Haptic Channels	Actuation	Location	Application
PATCH ¹⁰⁰			Forearm	VR Affective
PneuMod ¹⁰¹			Forearm	VR Communication
PneuSleeve ⁹⁵			General	General
Prattichizzo Fingertip Device ⁹⁵			Fingertip	General
Readable System ²³¹			Fingertip	Communication
Shi Fluidic Feedback ⁸⁸			Forearm	Prosthetics
Shveda Textile Pneumatics ¹⁴³			General	General
Sonar SNA Skin ⁸⁴			Fingertip	General
TAPS ^{173,232}			Forearm	Communication
TASBI ¹²⁹			Forearm	VR
THED ¹⁰⁵			Forearm	VR
ThermAirGlove ⁹⁹			Hand	VR
ThermoCaress ¹⁰²			Forearm	General
VibroSleeve ²³³			Forearm	Rehabilitation Prosthetics
Wang Smart Shoe ²³⁴			Foot	VR
Wang Vision-Based Feedback ¹⁵⁴			Waist Fingertip	Navigation
Wu Pneumatic Sleeve ⁹⁶			Forearm	Communication Affective
Zhao Dielectric Communicator ⁷⁰			Forearm	Communication
Zhu Thermal Smart Ring ¹⁰⁴			Finger	General

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1064 **Figure legends**

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1066 **Figure 1. Wearable haptic device locations.** When designing wearable haptic devices, implications of body location must be
1067 considered because the density of touch receptors in the skin varies across the body. Location also brings other considerations
1068 such as how the device might interact with clothing, user comfort and device bulk and weight. In this figure, some of the
1069 trade-offs that exist for selected interaction sites are illustrated, which depend on the particular application scenario for which
1070 the wearable haptic device is used.
1071

1072 **Figure 2. Selected wearable multi-sensory haptic devices.** The devices use varying actuation types to accomplish feedback
1073 through the different haptic channels. Some channels, such as mechanical pressure, can be accomplished through different
1074 mechanisms. An extended list of devices is presented in a similar fashion in **Table 1**. Part ‘Copolymer glove’ is reprinted with
1075 permission from ref 65, CC BY 4.0 (<https://creativecommons.org/licenses/by/4.0/>). Part ‘Stretchable pumps’ is reprinted with
1076 permission from <https://www.epfl.ch/labs/lmts/lmts-research/stretchable-pumps-for-soft-machine/>, CC BY 4.0
1077 (<https://creativecommons.org/licenses/by/4.0/>). Part ‘Tasbi’ is reprinted with permission from ‘Pezent, E. et al. Tasbi:
1078 Multisensory Squeeze and Vibrotactile Wrist Haptics for Augmented and Virtual Reality. In 2019 IEEE World Haptics
1079 Conference (WHC), 1–6, DOI: 10.1109/WHC.2019.8816098 (2019). <https://ieeexplore.ieee.org/document/8816098>, IEEE.
1080 Part ‘Cuff’ is reprinted with permission from ref 225, IEEE. Part ‘Thermal thimble’ is reprinted with permission from ref 103,
1081 IEEE.
1082

1083 **Figure 3. Applications of wearable haptic devices in various domains.** Wearable multi-sensory haptic feedback systems have
1084 been incorporated into a range of application domains including virtual reality, navigation, training, teleoperation,
1085 rehabilitation, prosthetics and communication, among others. Part ‘VR’, image courtesy of Daria Trinitatova, Dzmitry
1086 Tsetserukou, ref 167. Part ‘Navigation’ is reprinted with permission from ref 97, CC BY 4.0
1087 (<https://creativecommons.org/licenses/by/4.0/>). Part ‘Training’, image courtesy of FundamentalVR, ref 168. Part
1088 ‘Teleoperation’ is reprinted with permission from ref 116, IEEE. Part ‘Rehabilitation’ is reprinted with permission from ref 169,
1089 IEEE. Part ‘Prosthetics’ is reprinted with permission from ref 170, IEEE. Part ‘Communication’, image courtesy of Alix Macklin,
1090 ref 171.
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Box 1: Science, engineering and art in haptics

The field of haptics is necessarily interdisciplinary. Traditionally, it has combined aspects of mechanical engineering, computer science and psychology. Increasingly, the development of new actuators will require inputs from fields which have not previously been prominent within haptics, namely chemistry⁴² and materials science.⁶⁷ Additionally, we envision that the field will evolve alongside the science of perception and the neurobiological basis of consciousness. Moreover, as the molecular and cellular basis for mechanotransduction continues to be understood (as recognized by the 2021 Nobel Prize),²²⁶ haptic tools may be developed that can stimulate the peripheral nervous system in a more precise way. For example, a deeper understanding of the response of the cell membrane to stimuli in different types of cells, the level of expression of the relevant proteins in different afferents and how this influences the mechanical thresholds needed for generating action potentials may be gained. Such developments could lead to a wider palette of sensations to be generated.

This broadening in understanding and capability may also offer the opportunity to interface with the arts and humanities. Although artwork designed to be touched has an ancient history, sculptures which can be safely handled are generally designed to be experienced along with the visual sense, or as a substitute for it (that is, artwork for the blind).²²⁷ However, as haptic sensations can convey information and generate thoughtful and emotional responses, the tactile experience might be worth exploring for its own sake. For example, textures, temperatures and the surface properties of materials elicit cross-modal correspondences in synesthetes²²⁸ (that is, touch is strongly associated with specific visual, gustatory or olfactory sensation). Such correspondences, which may exist in non-synesthetes as well, would provide the basis for a rich range of tactile experience in a new form of tactile artwork. In the area of biomedical haptics — including rehabilitation, medical training and surgical robotics — the connection of the research to human physiology is dual-facing. That is, the technology must be designed to interface with biological structures, whereas the outcome of the technology has a biomedical aim (such as surgery, rehabilitation).

Progress in these areas requires collaboration between fields that often have different methods, lexicons and venues for dissemination of their results. It is often necessary for all individuals involved in a cross-disciplinary collaboration to learn at least some of the history, open questions, and jargon of the fields with which they would like to interact. Reading introductory texts and attending conferences in fields outside one's own is a good place to start. Unfortunately, the siloed structure of academic research often produces unintended barriers to collaboration. For example, in electrical engineering and computer science, information is often disseminated first in the form of conference presentations and associated proceedings articles. In chemistry and materials science, conferences generally do not require papers, and publication of a journal article often precludes later submission of a conference paper, and vice versa. Moreover, researchers must acclimate to the pace of publication in other fields. For example, biology moves more slowly than engineering, and there are fewer journals in which to disseminate findings. These factors influence the breadth and depth of typical publications within a field and identifying these differences that may exist in a collaborator's field takes adjustment and empathy. Potential conflict can be avoided if one decides early on whether the aims are primarily related to engineering outcomes or to biological ones. Finally, the way governmental agencies, universities, and research organizations evaluate their academic staff is often strictly categorized by scientific fields, substantially impacting the career of multi-disciplinary researchers.

Short (40 word) summary

Haptic devices enable communication via touch, augmenting visual and auditory displays or by offering alternative channels of communication when vision and hearing are unavailable. This Review discusses multi-sensory wearable haptics, focusing on body-worn devices that convey multiple types of cutaneous haptic feedback.