Magnetosensitive E-Skins for Interactive Devices

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Electronic skins (e-skins) have established themselves as a versatile technology to restore or enhance human perception, and potentially enable softer robotics. So far, the focus has been mostly on reproducing the traditional functions associated with human skin, such as, temperature, pressure, and chemical detection. New developments have also introduced nonstandard sensing capabilities like magnetic field detection, to spawn the field of magnetosensitive e-skins. Adding a supplementary information channel—an electronic sixth sense—allows humans to utilize the surrounding magnetic fields as stimuli for touchless interactions. Due to their vectorial nature, these stimuli can be used to track motion and orientation in 3D, opening the door to various kinds of gestural control for interactive devices. This approach to tracking provides an alternative or complement to optic-based systems, which usually rely on cameras or infrared emitters, that cannot easily capture fine motion when objects are far from the source or the line-of-sight is obtruded. Here, the background, fabrication techniques, and recent advances of this field are reviewed; covering important aspects like: directional perception, geomagnetic field detection, on-site conditioning, and multimodal approaches. The aim is to give the reader a general perspective and highlight some new avenues of research, toward artificial magnetoreception.

1. Introduction

The evolution of modern electronic systems has given birth to ever more intelligent machines and systems, which are rivaling human intelligence. Notions like the Internet of Things (IoT)[3] and artificial intelligence (AI)[2] are increasingly spreading around the world and demand for new kinds of human-computer interactions (HCI).[3,4] Novel robots and computational systems are behaving more “human-like” due to the enormous amounts of data amassed by sensor networks and scrutinized by AI platforms.[5] At the same time, humans are more connected than ever thanks to the numerous portable and wearable gadgets continuously supervising and shaping our day-to-day life.[6,7] As these technologies move on, the boundaries between humans and machines are becoming vaguer, and new aspects of human perception and device interactivity are being noticed. Key to this expansion is the field of flexible electronics, which promises to bridge the living and digital worlds by means of electronic skins (e-skins).[8–11] These e-skins aim to maintain the functionality of conventional electronics while mimicking skin or tissue-like properties such as flexibility, stretchability and biocompatibility.[8,12–14] Reaching this vision could result in more natural human prosthetics, skin substitutes or even a second skin with additional functionalities. The efforts in this field have largely focused on the development of thermal, tactile and chemical sensors,[6,7,15] which address the natural aspects of human skin. Yet, recent works[16,17] on shapeable magnetoelectronics[18] have established a new sensory dimension to e-skins, namely, the ability to detect and interact with magnetic fields. These magnetosensitive e-skins have opened thrilling possibilities for human perception as they could become a supplementary information channel beyond the standard five senses. Utilizing this additional information channel could significantly influence both ends of the human-machine spectrum. On the human side, they could provide a way to systematically study the effects of magnetic fields in sensory perception. Exploring this field of research can help to better understand human magnetoreception,[19–23] sensory substitution,[24–29] and improve the treatment of individuals with sensory processing disorder (SPD).[30–33] In these cases, magnetosensitive e-skins together with active feedback could act as soft electronic aids to monitor the response to external magnetic field and their influence in cognition. On the side of devices, magnetosensitive e-skins exploit a typically neglected stimulus like magnetic fields, to enable new kinds of flexible and soft human-machine interfaces. Magnetic sensing can be used as an inherently touchless detection platform, due to the 3D pervasiveness of magnetic fields, which unlocks a wide array of interaction scenarios.[18] Moreover, as magnetosensitive e-skins do not require line-of-sight to operate, they do away with complex setups or cameras which optical systems typically use. In addition, magnetic sensors can operate using compact and “self-powered” sources like permanent magnets or exploiting...
non-localized sources like the geomagnetic field. Yet, to achieve their full potential as multifunctional and autonomous e-skins, they must be combined with state-of-the-art tactile approaches and on-skin energy harvesting modules. Recent review articles\textsuperscript{[34–38]} showcase the potential of these technologies and thoroughly detail the challenges toward achieving a full-fledged integration. Successfully merging magnetosensitive e-skins with these technologies could allow for more portable, lightweight, and mechanically compliant human-machine interfaces.

These existing application scenarios became possible due to the synergistic effort of fundamental- and application-oriented communities working in the field of curvilinear magnetism,\textsuperscript{[39]} which includes curvilinear ferro- and antiferromagnetism, curvilinear magnons, and curvilinear spintronics. Shapeable magnetoelectronics\textsuperscript{[18]} results from applying curvilinear spintronics to develop high-performance magnetic field sensors on ultraslim foils\textsuperscript{[17,40–43]} and realize electronic skins with magnetic functionalities.

Shapeable magnetoelectronics\textsuperscript{[18]} was introduced as a facet of flexible electronics and includes stretchable\textsuperscript{[44–50]} and imperceptible\textsuperscript{[7,40–42]} magnetosensitive elements. There are numerous reports in literature on the realization of flexible giant magnetoresistive (GMR),\textsuperscript{[44–49]} tunneling magnetoresistive (TMR),\textsuperscript{[50,51]} anisotropic magnetoresistive (AMR),\textsuperscript{[42,52,54]} magnetoimpedance (GMI),\textsuperscript{[54,55]} Hall,\textsuperscript{[56]} planar Hall effect,\textsuperscript{[57]} and stretchable spin valve\textsuperscript{[40,62,65]} sensors. Previous review articles compare pros and cons of different technologies of flexible magnetic field sensors for various applications.\textsuperscript{[18,63–66,67,73]}

However, they mainly focus on the evolution and mechanical properties of shapeable magnetic sensors, leaving aside the aspect of interactivity and human-machine interfaces. A recent review\textsuperscript{[70]} briefly mentions some examples of magnetosensitive e-skins in the context of virtual and augmented reality, however it only explores the aspects of directionality and multimodality. Other important aspects like geometric field sensitivity, different kinds of on-site conditioning and further examples of multimodality are left aside. Including these topics is essential to provide a more complete view of this field.

Here, we will primarily focus on the realization of magnetosensitive e-skins for interactive devices. We note that similar concepts of highly compliant magnetic skins, in contrast to magnetosensitive skins, are gaining strong attention in the community.\textsuperscript{[69,70]} Magnetic skins are applied to realize interactive electronics when combined with conventional magnetic field sensors. These works make a major contribution to the field of interactive electronics. Still, they are not related to magnetosensitive e-skins and will not be broadly addressed in this review. The structure of the review is as follows. In Section 2, we summarize relevant background about flexible e-skins and magnetosensitive e-skins in the context of interactive devices. Section 3 showcases the aspect of directionality in magnetosensitive e-skins based on permanent magnet sources and possible application examples of this technology.\textsuperscript{[69]} Section 4 is concerned with the working principle and applications of geomagnetic e-skins; magnetosensitive e-skins which only need the earth’s magnetic field as a stimulus to operate.\textsuperscript{[42]} In the Section 5, we review recent demonstrations of on-site conditioned magnetosensitive e-skins using oxide-based\textsuperscript{[71]} and organic-based flexible electronics.\textsuperscript{[72]} Finally, in Section 6 we address new developments of multifunctional magnetosensitive e-skins.\textsuperscript{[53,54]} In the summary section, we show an overview of the future strategies to further improve and develop the field of magnetosensitive e-skins.

2. Background

Electronics is one of the essential pillars of the modern world and arguably the most subversive technology of the last 50 years. Its constant evolution keeps on driving our society forward in ways which were unthinkable when the first transistor was fabricated.\textsuperscript{[71]} As this technology advances, the modern trends of our civilization require novel kinds of functional electronics which are flexible\textsuperscript{[6,9,74–76]} and stretchable\textsuperscript{[12,13,75]} and wearable.\textsuperscript{[76–78]} These innovative electronics aim to integrate with and mimic biological entities or structures, while preserving their functionality and becoming a seamless link between machines and the living world.\textsuperscript{[80]} Traditional electronics manufacturing is not suitable to address these societal needs, due to the restrictions imposed by its usually rigid substrates and fabrication techniques. Therefore, to bring mechanical flexibility to electronics, researchers shifted their attention toward thin film fabrication methods, which are at the core of what is now called flexible electronics.

2.1. E-Skins

At the end of the 90s, flexible circuits were a reality and researchers were migrating toward plastic-based electronics, as seen in the review article “putting it on plastic”.\textsuperscript{[79]} However, it was not clear yet where to employ the mechanical advantages of this emerging technology. During the 1999 “Sensitive Skin Workshop”, it was recognized that developing the field of “sensitive skins” was crucial for robotics and textile electronics to be able to operate in unstructured environments.\textsuperscript{[80]} In the following years, researchers began integrating different kinds of sensors onto these artificial skins, propelled by the ideas of this workshop. The first appearance of the expression electronic skins in the context of flexible electronics occurred in an article by Wagner and coworkers.\textsuperscript{[81]} In this work, they discussed the use of stretchable metallization on elastomeric substrates to interconnect rigid islands hosting functional cells of electronic circuitry and sensors. This rigid-island approach became one of the most used topologies, as it preserves the integrity of the functional elements while the rest of the skin stretches. At the same time, the possibility of having multiple islands with different functionalities opened the door for multisensory electronic skins. From there, a subsequent paper by Someya et al.\textsuperscript{[82]} introduced the term e-skins and combined temperature and pressure mapping for the first time in flexible electronics. Further efforts from Rogers and coworkers consolidated the field by establishing a wide range of fabrication methods for flexible, high-performance semiconductors and epidermal circuits.\textsuperscript{[53,83–86]} Contributions from Bauer and coworkers have explored the use of soft dielectrics,\textsuperscript{[89–91]} ferroelectrets and solar cells.\textsuperscript{[92]} Kaltenbrunner et al. introduced in 2013 the concept of imperceptible electronics, where reducing substrate thickness renders the fabricated devices virtually unbreakable.\textsuperscript{[93]} Based on this concept,
the groups of Someya and Bauer have explored numerous applications in photonics,[94,95] biosensing,[96,97] and photovoltaics.[98] In parallel, the groups of Rogers and Bao have initiated the field of transient and bioresorbable electronics,[99–101] in line with modern environmentally-friendly policies. Recent developments in this field have incorporated wireless and battery-free functionalities,[102–104] which have broadened the scope of flexible electronics to medical implants and in-vivo applications.

2.2. Interactive Devices and Magnetosensitive E-Skins

One of the aspects explored in this review is the interaction between humans and computers using magnetic fields from the surroundings. However, interactivity and the need to communicate with computers started far back with very different mechanisms and devices, giving birth to what is now human–computer interaction (HCI).[4,105,106] The history of HCI started in 1963 with the breakthrough dissertation of Ivan Sutherland,[107] that first showcased direct manipulation of objects on a screen. His system, called the Sketchpad was a multifunctional “light pen” capable of writing, moving, and scaling objects, among other functions. During the next decades, a plethora of works would propose and demonstrate concepts like virtual[108–110] (VR), and augmented[111] reality (AR), giving rise to the modern era of HCI. This last era has been characterized by the emergence of smartphones, tablets and infrared (IR) motion capture systems for gaming environments. Current efforts are focused on the integration of haptic systems with VR to deliver a more complete experience to the users.[112–114]

Delivering such an experience requires a combination of tactile and touchless interactive devices, which can capture most of human motion and perception. Currently available sensor types have all intrinsic advantages and disadvantages, which implies that the best motion tracking solutions should use a combination of them.[115–117] Accomplishing wearable and body compliant interactive devices requires transitioning to e-skin fabrication methods, which transfer tactile and touchless interactivity into a flexible format. Numerous works have covered recent advances in tactile sensing for e-skins, pointing out the need to incorporate neuromorphic computing, and energy harvesting to achieve true autonomy.[34–36,118–120] These principles are paramount to establish a common platform for all kinds of e-skin sensors to thrive. Regarding touchless detection, it is typically accomplished by capacitive, optical, or magnetic sensing. Capacitive sensors are easy to manufacture and robust, but they require a more complex readout scheme in comparison with standard resistive measurements. Optical sensors are accurate and reliable, but they need line-of-sight to a source, which is not always easy to implement, especially for e-skin applications. Recent works have shown the potential of these technologies within the framework of e-skins.[121–123] Magnetic field sensors have also desirable characteristics for touchless interactive devices; compactness, no requirements for line-of-sight, and they are driven by ubiquitous sources like permanent magnets or the geomagnetic field.[115] Furthermore, they can be fabricated in a thin film format, which facilitates their integration into flexible, soft, lightweight, and portable designs.

The first building blocks toward this vision were provided by Parkin et al. who first grew GMR multilayers on Kapton[44] and Mylar,[45] yet, with a reduced performance. Further development was carried out by Chen et al. in 2008,[46] who significantly enhanced the response of GMR sensors on flexible substrates. Some years later, Melzer and coworkers created the first stretchable magneto-telelectric sensors based on GMR multilayers on PDMS.[60] Enabling works on stretchable spin-valves,[65] printable magneto-electronics,[57,58] flexible magneto-electronic analytical platforms,[53] transfer printable magnetic field sensors[66]; consolidated the field of flexible and stretchable magneto-electronics. The next milestone for interactive devices came in 2015 when Melzer et al. demonstrated wearable interactive devices based on Hall effect sensors.[16] This work first hinted toward interactive pointing devices which could be worn as an electronic skin and even map the surrounding magnetic field. In parallel, other approaches combining GMI sensors with Fe nanowires established the first magneto-mechanical e-skins.[54] Further developments led to the development of direct transfer methods[61] and the introduction of imperceptible magneto-electronics.[17] This latter concept enables magneto-telelectric sensors to withstand massive deformations while attaching conformally to the human skin and remaining fully functional. Additional efforts have facilitated the on-site conditioning of these flexible magneto-electronic circuits, opening the door for higher circuit complexity and integration.[71] Recent works have proposed the use of these magnetosensitive e-skins as flexible and lightweight virtual reality devices, which respond to permanent magnets[80] of the geomagnetic field.[42] Moreover, current works are building upon this idea to provide enhanced interactivity by combining multiple actuation modes[43] or integrating sophisticated organic transistor matrices.[72] A general overview of these developments is presented in Figure 1.

3. Magnetosensitive E-Skins with Directional Perception

Standard magnetosensitive e-skins usually behave as proximity sensing devices, such as touchless gauges[7] and mapping platforms,[16] based on shapeable magneto-electronics.[18] However, these e-skins cannot reliably perceive the spatial orientation of incident magnetic fields, an aspect which so far limited their interaction possibilities. Typically, human–computer and human–device interactions rely on buttons and dials which respectively select and regulate variables within the user interface. Buttons can be likened to the point-like functionality offered by previous magnetosensitive e-skins, yet, to emulate dials it is crucial to harness the directional nature of magnetic fields. Adding this new layer of interaction requires detecting the angular components of magnetic fields directly.

Though some magneto-telelectric sensors can detect angular variations by nature, not all of them are suited to work as steady angle sensors. AMR sensors provide small (1–3°) MR effects and their angular dependence is square sinusoidal, which limits their angular discrimination to only 180°[124,125] Conventional GMR multilayers are highly sensitive but display an isotropic response with respect to the angle of the external magnetic field, which prevents their use as angle sensors. Tunnel
magnetoresistance TMR devices offer MR effects in the range of 100–600% \[126\] but upon growing them on flexible polymers, their performance usually decreases. \[50,51\] Recent efforts have boosted their performance as flexible sensors, \[126\] but they utilize thinned silicon substrates which are not compliant enough for e-skin applications. Furthermore, TMR requires usually non-ductile isolators and a current out of plane fabrication geometry, which complicates their integration in flexible applications. On the other hand, spin-valve sensors combine the ease of integration of GMR systems with a constant resistance operating range, which renders them an ideal option for flexible angle sensors. \[124\] However, to optimally detect the x and y components of an external magnetic field, eight spin-valve sensors must be combined in two perpendicular Wheatstone bridges. \[124,127\] Arranging them in this configuration allows to maximize their signal output and thermal properties. The main challenge arises because of the anisotropic nature of spin-valves, which means that each of them must be placed with a specific exchange bias (EB) direction. The exchange bias is the preferential magnetization of the reference layer of the spin valve, pinned by the underlying antiferromagnet. Modifying the EB locally is demanding for conventional fabrication as either several material deposition rounds or high precision local annealing would be required. There have been reports of spin-valve angle sensors fabricated via local laser annealing, \[127\] yet, this fabrication method is not easily adapted to ultrathin e-skins.

We have previously demonstrated a pick-and-place approach which combines thin film and transfer printing technologies to overcome these manufacturing challenges. \[40\] In this approach, an array of spin-valve meander-shaped sensors is fabricated with...
a preferential EB direction on a 1.5-µm-thick polyimide foil and then cut into small flexible chips. The chips are then bonded to another polyimide foil hosting the contacts and arranged so that the EB directions of adjacent chips are antiparallel, thus constituting two perpendicular Wheatstone bridges (Figure 2a,b). The inner bridge outputs a voltage $V_{\text{cos}}$ proportional to the cosine of the angle $\theta$ between the bridge magnetization axis and the orientation of the external magnetic field (Figure 2b). The outer bridge generates a voltage $V_{\text{sin}}$ proportional to the sine of $\theta$. Combining these two output signals the angle $\theta$ is determined via $\theta = \tan^{-1} \left( \frac{V_{\text{sin}}}{V_{\text{cos}}} \right)$. Bending the single spin-valve chips to a curvature radius of 1 mm did not affect the GMR performance of the sensors. After fabrication, the free-standing 3-µm-thick device can digitize the angle of external magnetic field sources under static (Figure 2c) and dynamic (continuous rotation, Figure 2d) conditions. This method is applied to assemble 2D angular magnetic sensors and ultimately enable magnetosensitive e-skins with directional perception. The resulting devices work at low power together with permanent magnets that do not need external energy for operation. Possible future applications range from motion tracking in robotics, navigation, sports and gaming to interaction in supplemented reality.

3.1. Application as Touchless Interactive Devices

These on-skin directional sensors allow controlling the physical properties of objects in virtual reality relying on the interaction with ambient magnetic fields. This concept can be illustrated with a setup consisting of a magnetic source, playing the part of a touchless mouse, which is approached by the user. One on-skin angle sensor is fixed to the palm of the hand and connected with a computer for visualization purposes (Figure 2e). The software calculates the angles from the acquired voltages and assigns the angles into seven luminescence regions according to predefined thresholds. This information is used to control an on-screen virtual light source. The screen also displays a virtual gauge spanning a color spectrum from red to green, which represents the current position of the hand on the physical magnetic dial. Here, angles between 0° and 180° are encoded to replicate the typical movement of a hand when operating a real dial. In the absence of an incident magnetic field on the sensor the dial does not react and there is no dimming response (Figure 2e). When the hand is placed over the magnetic dial at a suitable distance range, the virtual dial displays a signal proportional to the angle between sensor and magnetic field axes (Figure 2f). As the encoding is limited to 180°, when the user reaches the limit value, the virtual dial and light bulb show maximum intensity (Figure 2g). This platform demonstrates the first on-skin human-machine interface, which uses magnetic fields and their orientation as a directional input stimulus for virtual applications.

4. Geomagneto-sensitive E-Skins

The magnetosensitive e-skins of the previous section exploit the potential of common magnetic field sources, yet they require additional items like permanent magnets to create interactive stimuli. Eliminating these requirements enables magnetosensitive e-skins to freely operate in any environment and ubiquitously interact with their surroundings. One way of reaching this goal is to tap into an omnipresent source of magnetic fields around us, like the earth’s magnetic field or geomagnetic field. To this end, a new on-skin sensing concept relying on e-skin sensors capable of detecting the earth’s magnetic field, must be developed. Numerous applications like artificial magnetoception or e-skin geomagnetic VR devices are envisioned to stem from this concept. To achieve this feat, the operating range of these new gadgets must match the small geomagnetic field of about 50 µT, which is out of reach for previously introduced magnetosensitive e-skins. Consequently, a different technological approach must be implemented.

Technologies like flux-gate and Hall effect can be employed to measure the geomagnetic field. However, flux gate sensors cannot be easily manufactured in a thin film format and Hall effect sensors entail the use of overly complex readout circuits, which limits their application in flexible electronics. GMI approaches have also shown some promise, but they require the use of AC power supplies, which is not translated easily into a flexible format. MR methods, on the other hand, are straightforward to manufacture into thin films and their readout reduces to conventional DC resistance measurements. Nevertheless, not all MR sensors are suitable to detect the earth’s magnetic field.

GMR and spin valve sensors offer large effects and potentially high sensitivity, but their operating range (>1 mT) is way over the geomagnetic field. Some biasing or enhancing techniques can be applied to tune their response for smaller fields, but the increase in fabrication complexity renders this endeavor too cumbersome for flexible technologies. A more viable alternative is to use AMR sensors, which are smoothly integrated in flexible electronics and can be readily adjusted to detect the earth’s magnetic field. For AMR sensors to detect the geomagnetic field, they must be geometrically conditioned to modify their intrinsic response, typically by using the barber pole method. This method consists of stripes of ferromagnetic material, which are covered with slabs of a conductive material, oriented at 45° with respect to the long axis of the stripes. This modification forces the current to flow at 45° in the stripes, which effectively linearizes their AMR response around zero magnetic field. This approach was first transferred into a flexible format by Wang and collaborators (Figure 3a), who used the enhanced sensitivity for magnetic pattern recognition. Their flexible sensor was shown to achieve a limit of detection of 150 nT and be bendable down to a curvature radius of 10 mm without degrading its performance (Figure 3b). Moreover, it was shown to successfully detect the magnetic fields <80 µT stemming from commercial magnetic card strips with a thickness of 10 µm. This sensitivity was sufficient to recognize specific magnetic field distributions over arrays of the strips, thus establishing a magnetic pattern recognition platform (Figure 3c).

We have advanced beyond this idea to create highly flexible e-skins that exploit not only the intensity but also the orientation of the geomagnetic field for interactivity, thus behaving as on-skin electronic compasses. In this work, the barber pole structures were fabricated on ultrathin polymeric foils of Mylar, permalloy (Py) was selected as the ferromagnetic material and gold (Au) for the conductive slabs (Figure 3d). The device was fabricated as a full Wheatstone bridge where each of the 4
Figure 2. Magnetosensitive e-skins as interactive devices for virtual reality. a) Standard lithography is used to pattern the contacts and main structure of the e-skin. Polymeric acid droplets are dropcasted on the corresponding transfer spots of the chips. The chips are placed on the droplets and press bonded at 140 °C using a weight. After the chips are secured in place, a photoresist-based sacrificial layer is removed in acetone to expose the meander-shaped sensors, which are electrically connected to the underlying contacts. Water-aided delamination yields a freestanding magnetosensitive e-skin. b) Single spin-valve sensors are positioned according to their EB direction in two Wheatstone bridges, each encompassing four spin-valve sensors to form a 2D magnetic field sensor. The output voltage of the inner/outer Wheatstone bridge (indicated in white/red) is proportional to the cosine/sine of the angle θ between the axis of magnetization of the Wheatstone bridge and the orientation of the external magnetic field, H. c) Snapshots of the angular reconstruction experiment. A permanent magnet is moved along the perimeter of the sample holder to provide angular input. The most important reference angles are included as reference labels (0°, 90°, 180°, 270°). The three magnetic orientations of the frames (180°, 225°, and 315°) are subsequently reconstructed. d) Output voltages of the inner (Vcos) and outer (Vsin) Wheatstone bridges of the 2D sensor as a function of time. The period of the signals matches to the rotational speed of a rotating permanent magnet (1.6 revolutions s⁻¹) underneath the setup. e) On-skin angle sensor applied on the palm of a human hand. f,g) Turning the hand above a permanent magnet dial allows dimming the light intensity of a virtual bulb. Adapted with permission.[40] Copyright 2018, American Association for the Advancement of Science.
Figure 3. Overview of geomagnetically sensitive e-skins. 

(a) Micrograph of a Wheatstone bridge structure consisting of four AMR sensors with a differential voltage output. 
(b) The resulting flexible AMR sensors on flexible PET foil can be readily bent. 
(c) Output voltage of the Wheatstone bridge upon crossing over magnetic patterns with one and two magnetic strips, respectively. Black (red) traces show the measurements for strips magnetized upward (downward). Figures a-c are reproduced with permission. Copyright 2016, Wiley-VCH Verlag GmbH & Co. 
(d) Fabrication scheme and connection layout for an on-skin electronic compass. 
(e) Micrograph of the fabricated device and close-up SEM images of one meander structure. The scale bars are 500, 20, and 5 µm long respectively. 
(f) AMR response of meander sensors with (red and blue) and without (black) barber pole conditioning. 
(g) Output voltage of the Wheatstone bridge as a function of an angle of the on-skin compass axis with respect to magnetic north. 
(h) AMR performance and resistance change of a single meander of the bridge as a function of the number of bending cycles. The blue dots show the variation only upon mechanical cycling, without a magnetic field. Upon application of a magnetic field the change of resistance is much larger than that due to mechanical disturbances (plateaus and valleys on the trace with black open circles). The red dots represent the average values at the valleys and the plateaus. 
(i) Geomagnetically sensitive e-skin attached to the finger of a person. 
(j) Snapshots of a movie showing the instants when the person points to N, W, and S. 
(k) Temporal variation of the output voltage of the on-skin when the person rotates back and forth from the magnetic north (N) to magnetic south (S) via west (W). 

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elements is a geometrically conditioned AMR sensor based on Py meander stripes (Figure 3e). By controlling the orientation angle of the barber pole slabs, the sensor response can have a positive (for slabs oriented at 45°) or negative (for slabs oriented at 135°) slope (Figure 3f). In contrast, if no conditioning is applied the sensor response is flat in the sub-mT range (black trace on Figure 3f). Measuring the output voltage of the bridge as a function of the angle between the bridge axis and magnetic north indicates the orientation of the e-skin in the geomagnetic field. The maximum and minimum of the response arise when the bridge axis coincides with north and south respectively (Figure 3g). Furthermore, taking into account the output voltage noise of the device, which is limited by the readout electronics used, a limit of detection of about 50 nT was established. Bending the single meander structures to a radius of curvature of 1 mm did not degrade their AMR performance, which remained stable at 1.4%. Even after 2000 bending cycles, the change of the electrical resistance due to mechanical deformations does not exceed 0.2% (Figure 3h). The attained performance is a tenfold boost in bendability compared to AMR sensors prepared on thicker substrates.[52,56]

4.1. Application Examples

An important advantage of geomagnetic field detection is removing the need of man-made magnetic sources for operating the e-skins. Therefore, we devised an outdoor experiment in the forest, for which the e-skin was attached to a person’s index finger indicating his current orientation. Throughout the experiment, the finger with the geomagnetic e-skin (Figure 3i) remained parallel to the ground to acquire only the in-plane component of the field. The output voltage of the e-skin sensor allowed to track the orientation of a person when pointing to different cardinal directions north (N), west (W), and south (S) (Figure 3j,k), with all the orientations being verified by a reference compass. These results show for the first time an on-skin device, which can replicate the functionality of a compass and enable artificial magnetoeception for humans.

We have employed the same principle to set up a human-machine interface for AR or VR. In this case, the output voltage of the on-skin compass controlled the heading of a virtual panda inside a python-based game engine(Panda3D).[144] A python script instructed the virtual panda to walk forward at a constant speed, while the angular rotation was defined by the relative angle of the hand of the user to the magnetic north. Sequential rotation of the hand in the air led the panda to move within a defined trajectory in the virtual environment (Figure 3l). The trajectory of the panda is shown as a dotted line and the frames of interest are correspondingly labeled with the times $t_1$ to $t_5$. These results represent the first on-skin and fully compliant gadget which uses the geomagnetic field as input stimulus to interact with a virtual environment.

5. On-Site Conditioned Magneto-sensitive E-Skins

In the view of numerous exciting demonstrations of flexible, stretchable and even imperceptible functional elements, one of the primary difficulties remaining in the field of shapeable electronics is to amplify or multiplex signals using compliant devices. Typically, cables are used to connect flexible and rigid parts, which obtrudes measurements, narrows the system bandwidth, and brings noticeable disadvantages in terms of the signal-to-noise ratio. Specifically, the poor noise performance arises from the fact that the signals are amplified together with the noise, which is either picked up upon the signal transmission using long cables or produced by power supplies and electronic circuits itself. To improve the response and sensitivity of an acquisition system, the output of a sensory system should be amplified in the vicinity of the sensor, that is, within the same carrier substrate or board. This so-called front-end signal conditioning is a standard for conventional rigid microelectronics, but is not yet readily available for flexible electronics. This section presents two possible approaches for integrating this on-site conditioning with magneto-sensitive e-skins.

5.1. Conditioning with Flexible Inorganic Electronics

Previous work by Münzenrieder et al. has showcased highly sensitive magnetic field sensorics combined with high performance InGaZnO based readout electronics[71] in a fully flexible platform (Figure 4a,b). Although entirely flexible, the sensory devices outperform in responsibility commercial rigid magnetic sensor systems by at least an order of magnitude. This remarkable performance is achieved by designing magnetoresistive sensor bridge, consisting of GMR sensors, connected to a differential operational amplifier and a power amplifier acting as readout circuitry (Figure 4c–e). This allows the introduction of differential signal processing techniques, low noise thin-film electronics, and front-end signal conditioning to the field of flexible electronics. All components are fabricated on the same 50 µm thick polyimide substrate and stay fully operational while bend to a radius of 5 mm. The record high gain of 48.6 dB and signal-to-noise ratio of 56 dB enables the system to detect magnetic fields with a sensitivity of 25 V/V/kOe. Furthermore, this flexible sensor system can be used as magnetic proximity sensor or magnet switch whereas the power consumption stays as low as 250 µW.[71]

This work constitutes the major milestone in the development of flexible electronics. Indeed, this work shows that it is possible to realize high performance electronic systems without the need for bulky or rigid standard electronic components. Foreseeable applications of this technology are far reaching: integrated flexible magneto-sensitive devices can be used to track motion and provide feedback as needed, for example, for smart implants, body worn navigation systems, acoustic virtual reality for visually impaired people, proximity sensors for on-skin or wearable electronics, or for realizing actively controlled soft actuators.

5.2. Magneto-sensitive E-Skin Arrays Conditioned with Flexible Organic Electronics

To achieve their full potential, electronic skins (e-skins) should be able to spatially perceive the relative position of external...
objects like robots or humans, in a reliable manner. Among the available types of sensors, flexible magnetic sensors are inherently suited to sense proximity and position. However, single-sensor approaches are limited to detect objects under simplified or ideal conditions. Real life applications require the detection of objects with irregular or highly deformed shapes under less-than-ideal conditions. Sensor arrays and matrices driven by active transistors circumvent this problem by precisely mapping the magnetic field over large areas with increased granularity. However, it comes at the cost of excessive interconnections, complexity and high power consumption. Furthermore, for applications in large-area plastic substrates, organic thin-film transistors (OTFTs) are better suited than their inorganic counterpart, as they are intrinsically flexible and compatible with low-cost printing processes. One of the concerns when implementing sensor arrays, is the possibility of device-to-device variations. However, most of the magnetosensitive e-skins rely on relative resistance ratios, which are very reproducible, even if the nominal resistance changes from sensor to sensor.

Recent work by Kondo et al. has demonstrated an imperceptible 2 x 4 magnetosensory matrix (MSM), which addresses these issues (Figure 5a). The system comprises a set of giant magnetoresistive sensors, a bootstrap organic shift register driving the matrix, and organic signal amplifiers; all integrated in an entirely flexible format (Figure 5b). A key aspect is the use of a bootstrap circuit, which ensures the exclusive use of p-type OTFTs and facilitates the low-power operation of the MSM system. In addition, the topology of the circuit requires only three wires to drive the matrix and it eliminates the need for supply and ground terminals by reusing the clocking signals. All in all, this work managed to reduce static and dynamic power consumption down to 0.8 nW and 0.23 µW, respectively, which are both lower than for conventional designs. These improvements allowed the authors to connect the system to a battery-powered wireless module and operate at supply voltages below 4 V and frequencies up to 100 Hz. Moreover, the system showcased real-time mapping of weak magnetic fields in 2D with remarkable flexibility and lightness (Figure 5c,d). This study paves the way for the development of highly complex, low power magnetosensitive e-skins which can find direct application in soft robotics, human-machine interfaces and biomedical science.

6. Magnetosensitive E-Skins with Multimodal Capabilities

The transformative emergence of smart electronics, human-friendly robotics and supplemented or virtual reality will revolutionize the interplay with our surroundings. The complexity that is involved in the manipulation of objects in these emerging technologies is dramatically increasing, which calls for e-skin that can conduct tactile and touchless sensing events in a simultaneous and unambiguous way. Integrating multiple functions in a single sensing unit offers the most promising
path toward simple, scalable and intuitive-to-use e-skin architectures. However, by now, this path has always been hindered by the confusing overlap of signals from different stimuli.

### 6.1. Bimodal E-Skins for Tactile and Touchless Interactivity

Recently, Ge et al. have demonstrated for the first time, bifunctional e-skins with a single sensory unit able to simultaneously transduce tactile and touchless stimuli.[43] All this while unambiguously discriminating between both input signals in real time. These bimodal e-skins are based on a compliant magnetic microelectromechanical platform (m-MEMS) combining ultrathin magnetic field sensors and soft magnetic composites with micrometric pyramidal structures (Figure 6a). Due to its specifically tailored geometry, it allows distinguishing between two operating modes without knowing the signal history and relying only on the electrical output of a single sensor unit. Owing to its intrinsic magnetic functionality, this compliant m-MEMS platform is able to discriminate magnetic versus non-magnetic objects already upon touchless interaction. As it is also highly selective, it addresses the long-standing problem in the field of touchless interaction—namely, the interference from objects, which are irrelevant or disturb the interaction. In addition, the interaction process is programmable. The sensitivity of the two interaction modes could be tuned by adjusting the magnetic field of the objects able to meet the requirements of different interaction tasks.

Using tactile and touchless sensing functions simultaneously, m-MEMS e-skins enable complex interactions with a magnetically functionalized physical object supplemented with content data appearing in the virtual reality. For example, the authors showcased data selection and manipulation with m-MEMS e-skins to realize a multi-choice environment for augmented reality through 3D touch (Figure 6b,c). Moreover, this smart skin allows reducing the number of physical “clicks” needed compared to state of the art gadgets, by introducing an additional touchless interaction layer. Beyond the field of augmented reality, m-MEMS will bring great benefits for healthcare, for example, to ease surgery operations and manipulation of medical equipment, as well as for humanoid robots to overcome the challenging task of grasping.

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**Figure 5.** Magnetosensitive e-skins as active matrices conditioned with organic electronics. a) MSM circuit attached to the human skin, acting as a wireless interactive device which can detect the position of the magnet-equipped fingers. The transistors and GMR sensors in the MSM can conform to bending radii of b) 145 µm and c) 2 mm, respectively, while retaining their performance. d) Schematic describing the main components of the MSM: the bootstrap shift register (I), the organic thin-film transistors (II), The GMR sensors (III), the current mirror (IV), and the common-source amplifier (V). Adapted under the terms of the CC BY 4.0 license.[72] Copyright 2020, American Association for the Advancement of Science.

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**Figure 6.** An example of the combination of tactile and touchless interactions. a) Schematic illustration of m-MEMS compliant device. b) The finger fixed with the bifunctional e-skin can interact with the magnetic field functionalized object (glass plate) in touchless mode and enables the selection of virtual options (i.e., room light, humidity, room temperature). c) Once the option is chosen, the corresponding value (i.e., temperature) can be changed in tactile mode by using the pressure sensing function of the e-skin, to either decrease the temperature by a gentle press or increase the temperature by a strong press. Adapted under the terms of the CC BY 4.0 license.[43] Copyright 2019, Springer Nature Limited.
6.2. Magnetosensitive E-Skins with Multiple Tactile Sensing Modes

Previous examples of magnetosensitive e-skins with multimodality, like the work of Alfadhel et al., explore the combination of compliant nanocomposites and magnetic sensors for accessing a wide range of mechanosensing modes. Their nanocomposites are made of iron nanowires (NWs), which are permanent magnetic in nature, incorporated into polydimethylsiloxane (PDMS) and shaped as cilia (Figure 7a). As they retain their magnetization, no additional magnetic field is needed for magnetizing them, thus simplifying the system and reducing power consumption. Furthermore, the nanocomposite is highly elastic, easy to pattern and corrosion resistant. For magnetic field detection, this work employed multilayered giant magneto-impedance sensors, which can readily detect changes in the average magnetic field whenever the cilia bend (Figure 7b,c). Using this principle, this platform can detect vertical forces from 3 to 1200 mN, the texture of objects and the heart rate of a person (Figure 7d,e). Besides, it can also be used in liquids to detect flow without modification, which can be exploited to seamlessly perform detection in microfluidics. Overall, this work highlights another facet of magnetosensitive e-skins, one which utilizes magnetic fields as the background signal for mechanical detection. Due to the wide range of forces detected, this system could find numerous applications in biology, microfluidics and industry.

We note that working with magnetic composites poses challenges on the reproducibility and calibration of these hybrid magnetosensitive e-skins. Nevertheless, in the case of bimodal e-skins, the sensor detects signals in two operating ranges depending on whether there is a tactile or touchless stimulus.

These two ranges do not overlap and produce opposite changes in the sensor readout, which means that possible hysteretic variations might not play such a big role in the discrimination power of the sensor.

7. Summary and Outlook

In conclusion, we provide an overview of recent achievements in the field of shapeable magnetoelectronics with a specific focus on smart skin applications for interactive electronics. Some of the most important parameters for these magnetosensitive e-skins are presented in Table 1. The topic has already numerous exciting demonstrations, yet it is still in its technological infancy and numerous developments are still needed.

Below, we identify some relevant directions and challenges for this field to evolve and expand in the future:

7.1. Breathable Magneto-electronics

Advancing beyond the conventional optics-based detection approaches for the manipulation of virtual objects requires the realization of novel on-skin wearable gadgets, which are haptically not perceived while worn on skin and do not disturb everyday activities. This statement necessarily means that the prospective shapeable magneto-electronics should become not only mechanically compliant but also breathable, for example, enabling water evaporation and transport of oxygen. The most commonly used substrates for i) sensors and ii) permanent magnets as relevant for this purpose are polymeric foils like polyethylene terephthalate (PET) or elastomers such as
polydimethylsiloxane (PDMS). Use of elastomers has certain advantages—their elastic modulus is close to that of skin (few MPa), they undergo large and reversible deformation. On the other hand, elastomers and PDMS in particular considerably restrict heat/mass transport to/from the body that results in discomfort. The ideal substrate for sensor must be porous to allow water evaporation and oxygen transport. It also must be strong and undergo multiple cycles of deformation without considerable wear. From this point of view, fibrous materials appear as suitable substrates for the realization of breathable shapeable magnetoelectronics. Still, there is no data available on the fabrication of high-performance magnetic field sensors on fibrous materials.

7.2. Wireless Communication and Powering

The most obvious limitation of the e-skins described in this work is the use of wired interfaces for power and read-out, which reduces their autonomy and flexibility. In this respect, two approaches can be adopted for achieving circuit autonomy, respectively, the use of passive or active circuitry. In the first case, using radio frequency (RF) power harvesting units[88,104,145] coupled with low-power microcontrollers[146] could simultaneously provide energy and communication capabilities to magnetosensitive e-skins. In the second scenario, the use of active circuits would increase the measurement possibilities and transmission range of the system at the cost of increasing the bulkiness and compliance of the circuitry. Due to the low-power nature of magnetic sensors, the first alternative would be the preferred way to go.

7.3. External Magnetic Disturbances

In most of the cases, the stray magnetic fields of external devices are in the order of 100s of μT, which is way below the sensitivity range of most of the magnetosensitive e-skins. However, extremely sensitive ones (with operating ranges below 1 mT) could be affected by these disturbances in the same way as standard analog or electronic compasses do. In this case, possible mitigation strategies could be to include in-built modules providing short set/reset pulses to tune the sensor response. Nevertheless, as magnetic fields decay very fast with the distance to the source, typical operation in VR environments should suffice to guarantee proper performance.

7.4. Out-of-Plane Magnetic Sensing

So far, all the sensors that this work explored are sensitive to the in-plane component of the magnetic field. However, achieving a full 3D mapping of the magnetic field would allow a whole new set of interaction and gesture control possibilities. To achieve this, out-of-plane sensors like Hall effect devices would need to be combined with the current method. Possible routes to this goal would imply the use of thin film semimetal-based Hall effect sensors using Bismuth[16] or graphene.[56] Another possible mitigation strategy could be to include in-built modules providing short set/reset pulses to tune the sensor response. Nevertheless, magnetic fields decay very fast with the distance to the source, typical operation in VR environments should suffice to guarantee proper performance.

7.5. On-Site or Direct Sensory Feedback

Up until now, magnetosensitive e-skins rely on additional electronic interfaces like computer screens to provide feedback to the user. Nevertheless, to be really portable and integrated with the human body, they would require ultrathin displays or actuators to communicate the detected signals to the user. Recent works have demonstrated how to achieve ultrathin photonic skins[95,149] and actuating circuits,[150] which could readily be combined with magnetosensitive e-skins. Moreover, this feedback could be extended to the biological interfaces of humans like nerves or muscles, as shown in recent works on neural[151,153] and muscular[152] stimulation. If this feat could be
accomplished, magnetosensitive e-skins would become a full-fledged “sixth sense”.

We hope that this review will stimulate further critical thinking not only in the scientific material science community but also will spark an interest in R&D oriented companies, which can benefit from some of these ideas.

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Conflict of Interest

The authors declare no conflict of interest.

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compliant magnetic field sensors, flexible electronics, interactive electronics, magnetosensitive smart skins, shapeable magnetoelectronics

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