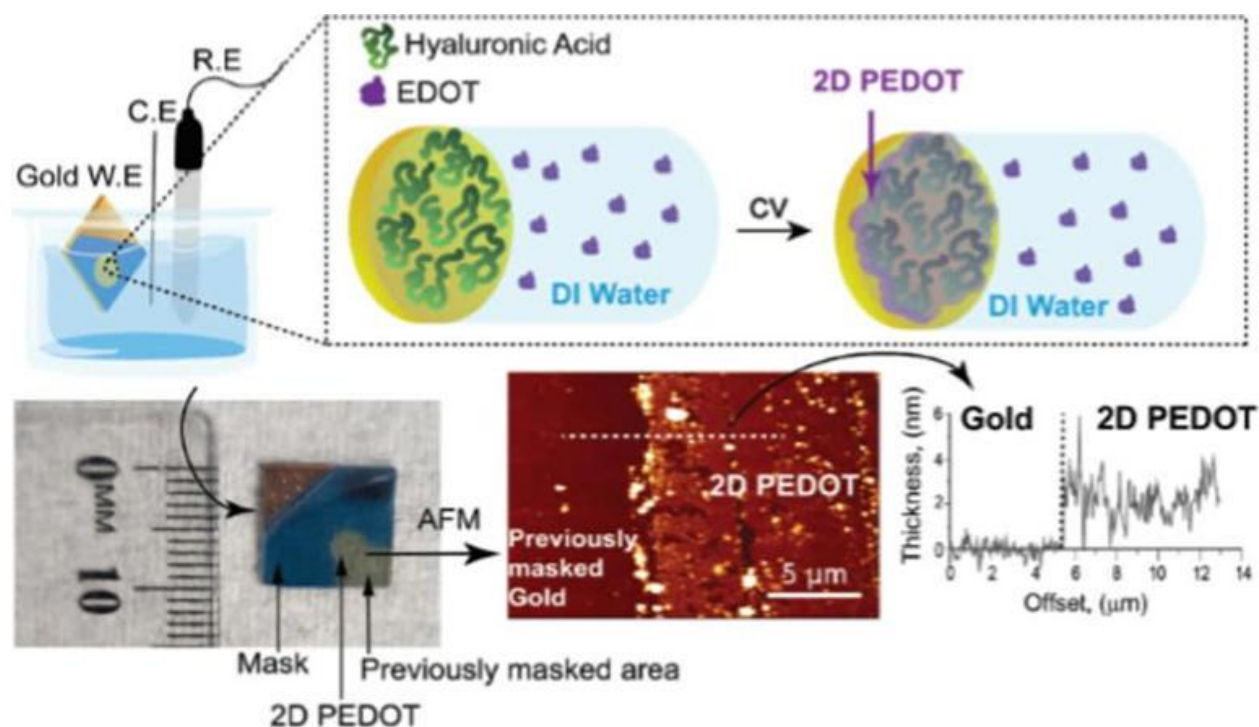


Invisible material brings a new era of touch screens and wearable devices

A face-serum staple just helped a research team build an invisible film that conducts electricity like a metal. At [La Trobe University](#) in Melbourne, the group used hyaluronic acid to guide the growth of a new two-dimensional polymer on gold.

The ultrathin coating, called 2D PEDOT, could boost touchscreens and make medical wearables smaller, tougher, and more precise. The work appears in [ACS Applied Materials and Interfaces](#) and was led by Associate Professor Wren Greene with senior researcher Dr Saimon Moraes Silva and PhD candidate Luiza Aguiar do Nascimento at the Biomedical and Environmental Sensor Technology Research Centre.

"Conductive polymers as we know them were developed nearly 50 years ago, and although they're exciting, they haven't lived up to their potential in that time. Often they are difficult to fabricate, as thin films don't conduct electricity very well, aren't transparent, and can have highly variable properties," Dr Greene said.



Graphical study abstract: The development of 2D materials is rapidly advancing beyond traditional graphene and metal oxides and into new functional organic materials including conducting polymers (CPs). (CREDIT: ACS Applied Materials & Interfaces)

Tethered Dopant Templating

“Through our method, called ‘tethered dopant templating’, we’ve created a robust way of making a conductive polymer that is flexible, durable, can conduct electricity as well as metals and is easily reproduced – so it’s scalable.”

The team reports films about three nanometers thick that cover square-centimeter areas with uniform performance. The [hyaluronic acid](#) acts as a bound dopant layer on the gold. That anchored layer steers the polymerization of EDOT monomers into longer, cleaner chains. The result is a transparent, flexible conductor that handles charge like a metal but behaves like a soft coating.

“We were very excited to find that not only did the polymers form when we tethered directly to the gold, but that these polymers were thinner, more powerfully conductive, and almost foolproof to reproduce,” Luiza Aguiar do Nascimento said.

“Currently, it is difficult to consistently reproduce conductive polymers at the high quality needed for health and medical monitoring and drug delivery devices,” Dr Moraes Silva said. “I’m excited that we have created new capabilities for these materials, which are scalable, affordable, and reproducible.”

What the new film changes

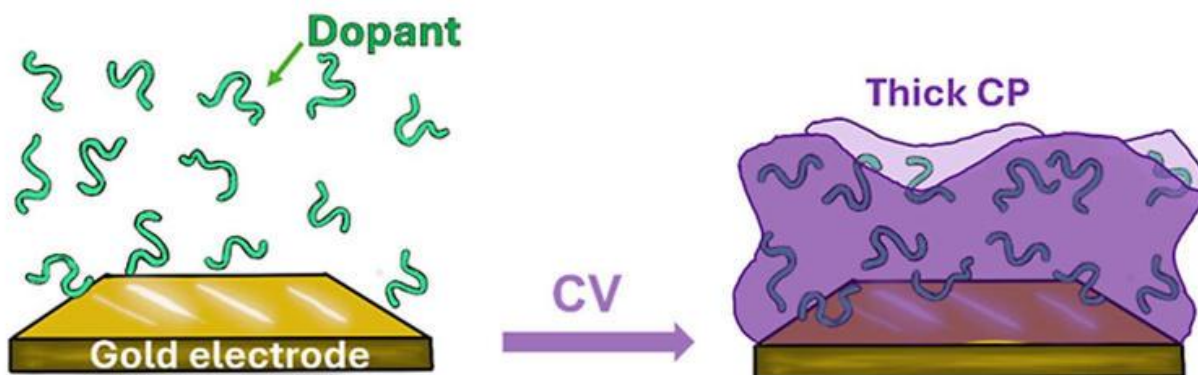
Phones, watches, and [medical patches](#) rely on conductive layers that move charge while staying clear and thin. Today’s standards include indium tin oxide and variants of PEDOT:PSS. Each option has tradeoffs. Indium tin oxide is brittle. PEDOT:PSS is soft but often loses conductivity when made thin or stretched. The La Trobe group reports metal-class conductivity in a film that is thinner than a virus, yet remains transparent and uniform. That mix could shrink sensors, cut power loss, and reduce material costs.

The film also forms in open space rather than in cramped stacks or pores. Past 2D polymer methods confined growth between lipid bilayers, oil films, or clays. Those cramped routes slowed reactions to many hours or days and produced only flakes or colloids. The La Trobe method uses electricity and a “tethered” dopant layer to grow a continuous 2D film across a [flat electrode](#) in minutes. The process offers patterning control, scale, and strong batch-to-batch repeatability.

a Tethered doped electropolymerization



b Free doped (traditional) electropolymerization



Scheme representing (a) the tethered doped electropolymerization approach where the dopant molecules are tethered to the electrode surface through physisorption or chemisorption and offer 3D control over the CP growth and (b) the traditional doped electropolymerization approach using a free (codissolved) dopant that grows thick CP with an uncontrolled doping level and homogeneity. (CREDIT: ACS Applied Materials & Interfaces)

How ‘tethered dopant templating’ works

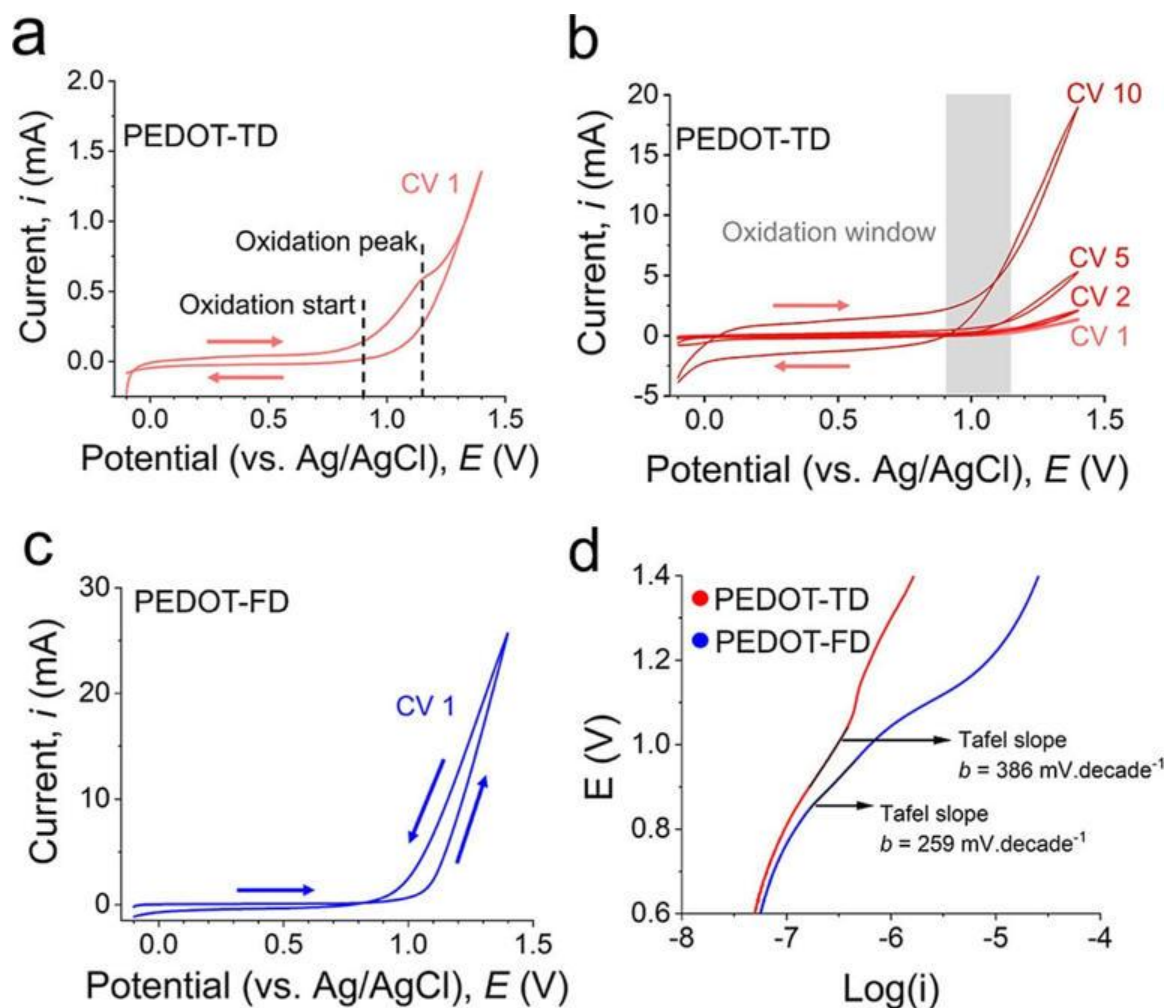
In standard electropolymerization, chemists dissolve a dopant along with the monomer. That soup produces variable films with uneven doping and mixed chain lengths. By contrast, tethered dopant templating attaches a dense, anionic

macromolecule—here, hyaluronic acid—directly to the [gold surface](#). When voltage is applied, monomers oxidize at the interface and link up into PEDOT chains that grow along the anchored dopant.

As chains extend, the bound dopant guides growth and suppresses chain termination. Longer chains raise mobility. The dopant also packs into the film at very high ratios—reported up to eight parts dopant by mass for each part polymer. That “hyper-doping” increases the number of charge carriers. Together, long chains and high carrier density push the film into metal-like conductivity while keeping it molecular-scale thin.

Why this matters for wearables and implants

Wearable biosensors must be soft, stable, and clear. They also need signal fidelity and low power loss. The 2D PEDOT film is invisible to the eye yet conducts like a wire. Hyaluronic acid is already used in skin care and injectable gels, which supports biocompatibility goals. The film’s uniformity at sub-micrometer scales should reduce hot spots and noise in [bio-signal](#) pickup. The method could also pattern electrodes at high density, enabling richer mapping of heart, muscle, and brain activity with less irritation.



First CV cycle for electropolymerization of PEDOT-TD, and first (CV1), second (CV2), fifth (CV5), and tenth (CV10) CV cycles for electropolymerization of PEDOT-TD. (CREDIT: ACS Applied Materials & Interfaces)© The Brighter Side of News

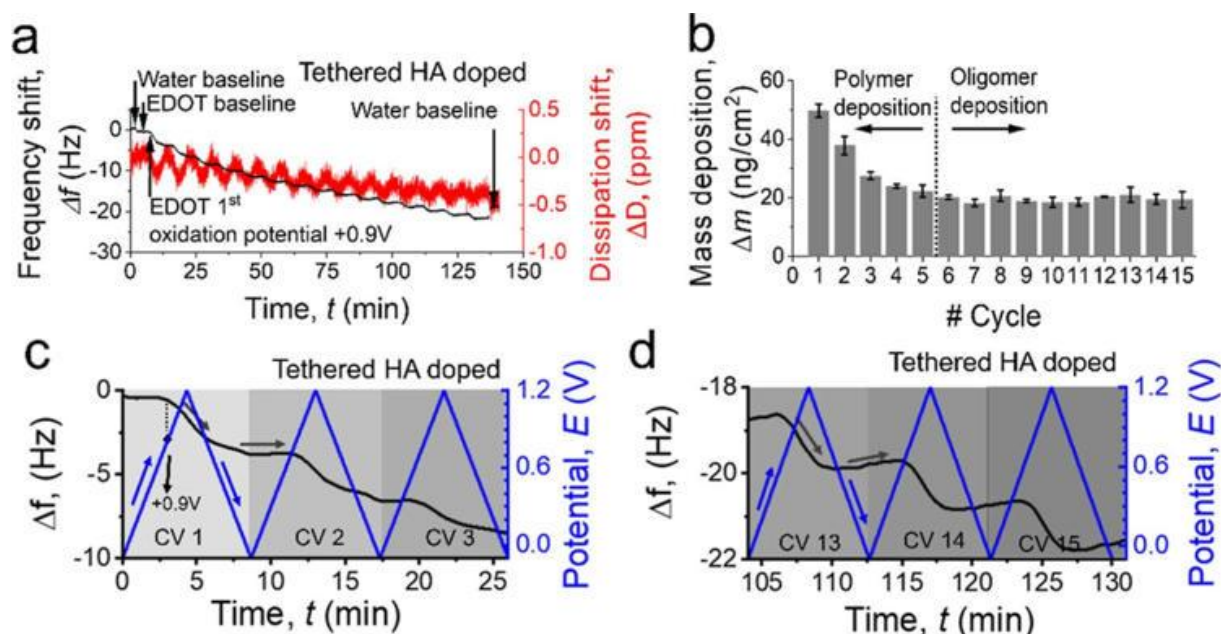
Drug delivery patches and implant leads stand to gain as well. A tougher, thinner conductor can reduce device bulk and improve comfort. Metal-like performance in a polymer could [extend battery life](#). It may also enable stretchable interconnects that survive repeated bending, sweat, and body heat without losing function.

Tethered dopant templating in focus

Tethered dopant templating underpins each reported gain. The surface-bound hyaluronic acid shapes growth in three dimensions and sets a hard stop on thickness. That control yields smooth, continuous films at nanometer scale with even properties. Direct tethering also removes the need for [salt](#)

electrolytes during growth. That step avoids later rinses and cuts ionic residues that often cause drift in sensors.

The team's results show tight control over charge transport and optical clarity. With conductivity in the metal range, the film handles high-speed signals without added thickness. With molecular-scale height, it stays almost perfectly transparent. Those traits open a path to next-gen transparent conductors for displays and optical biosensors.



(a) Frequency and dissipation measured in situ for PEDOT-TD, (b) calculated mass deposited per cm² at each potential cycle for PEDOT-TD electropolymerization, (c) frequency shift after a Fast Fourier Transform (FFT) filter overlap with an applied potential for first three CV cycles for PEDOT-TD, (d) frequency shift after the FFT filter overlap with an applied potential for last three CV cycles for PEDOT-TD (CREDIT: ACS Applied Materials & Interfaces)

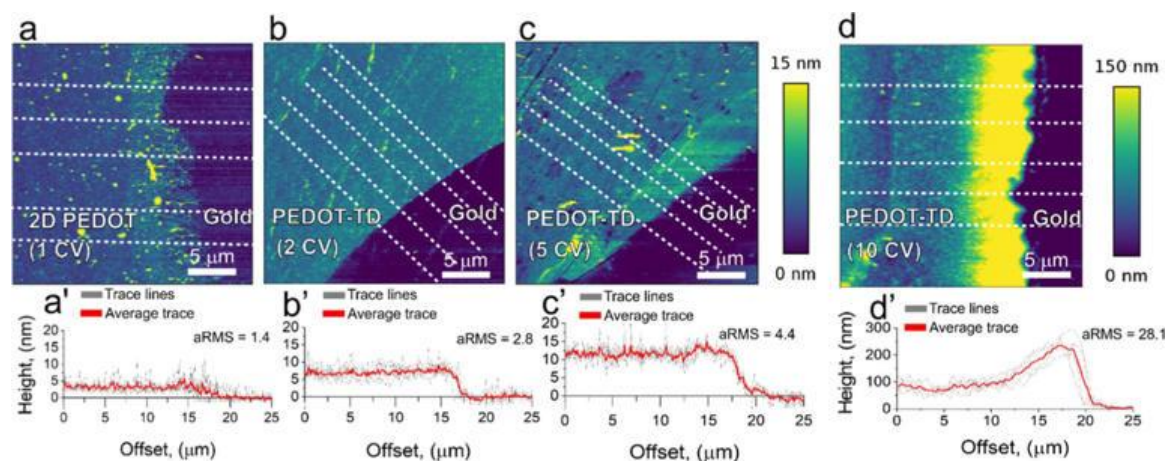
From lab method to production line

The group reports growth over areas measured in square centimeters using standard electrodes. The approach fits with wafer-scale tools and roll-to-roll plating. Because the dopant is pre-grafted to the surface, each cycle starts from a known state. That makes inline quality control more reliable. The process also enables direct patterning by printing or masking the dopant layer before growth, avoiding brittle etch steps after deposition.

The researchers emphasize scalability. They showed that films grown with tethered dopant templating present near-identical properties across a sample and across repeats. That uniformity is essential for mass production of [touch panels](#) and biosensor arrays. If production moves forward, it could reduce reliance on indium and cut the embodied energy of display stacks.

Where the field stands now

Conductive polymers have matured over five decades, but thin, clear, and very conductive films remain rare. Recent work on PEDOT:PSS has improved performance by acid rinses and salt treatments, raising conductivity and long-term stability. A parallel thread focuses on hybrid films with silver nanowires or graphene to boost both clarity and conductance. Reviews of bioelectronic interfaces highlight PEDOT's value in brain and nerve monitoring. Yet many routes still struggle with roughness, pinholes, and drift.



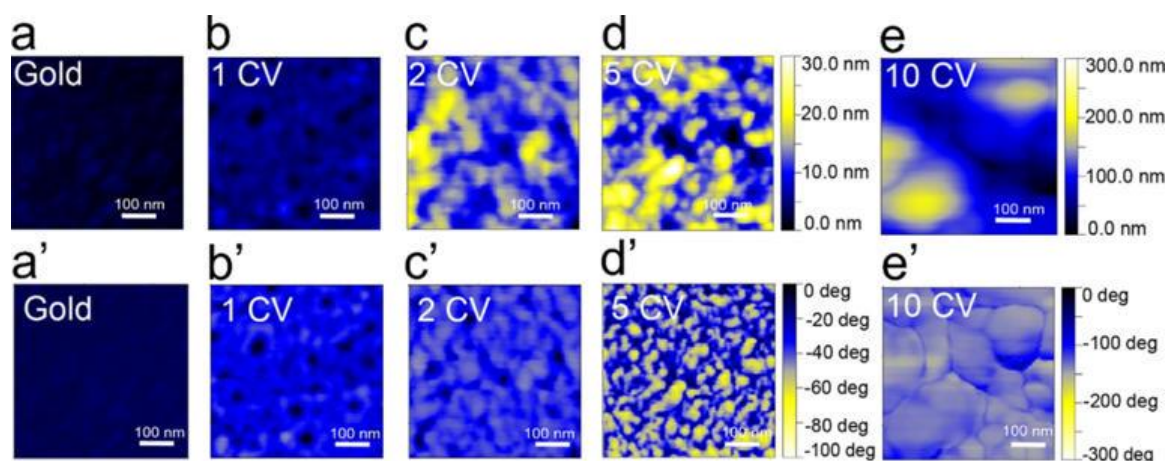
AFM images obtained in contact mode in air for PEDOT-TD electropolymerized with (a) 1 CV (2D-PEDOT), (b) 2 CVs, (c) 5 CVs, and (d) 10 CVs with its correspondent height traces. (CREDIT: ACS Applied Materials & Interfaces)© The Brighter Side of News

The La Trobe study advances a distinct idea: control the reaction from the surface outward using a tethered dopant. By doing so, it achieves stable metal-like behavior in a film only a few molecules thick. That combination—molecular scale, metal-class conductance, and large area—could reset expectations for soft electrodes in medicine and consumer tech.

What comes next

Key tests will probe aging under sweat, [UV light](#), and thousands of bends. Adhesion to glass and polymers used in screens must be proven. Biocompatibility will need direct studies in tissue models and animal systems. If those hurdles are cleared, the films could appear first in high-end touch sensors and point-of-care test strips. Clinical devices may follow after safety and reliability trials.

The team's BEST Centre sits at the intersection of materials and sensing. That setting suggests rapid spin-outs in biosensing and optical readouts. With partners in display and medical device manufacturing, this method could reach pilot production in the near term.



AFM height images obtained in tapping mode in air for (a) gold, (b) 2D PEDOT, (c) PEDOT-TD 2 CVs, (d) PEDOT-TD 5 CVs, and (e) PEDOT-TD 10 CVs with its respective phase images. (CREDIT: ACS Applied Materials & Interfaces)© The Brighter Side of News

Past Studies and Findings

Researchers have spent years tuning PEDOT:PSS films with acid and salt treatments to boost conductivity and stability. A 2025 study in [ACS Applied Materials](#) and Interfaces reported metal-like conductance in acid-treated PEDOT:PSS using a simple process, hinting at routes to rival brittle oxides in transparent electrodes.

[Work in 2024 and 2025](#) refined PEDOT:PSS electrodes for durability. Sequential treatment with nitric acid and cesium chloride enhanced long-term stability, a key need for implants and long-wear sensors. These efforts show how chemical control can raise charge mobility and lessen drift in thin films.

Other teams combined PEDOT:PSS with silver nanowires to balance clarity and low sheet resistance. Hybrid films achieved strong optical and electrical metrics, while recent methods engineered vertical phase separation to tune surface chemistry for tissue contact. [These strategies](#) show the wide push to merge high conductivity with soft mechanics for biointerfaces.

In parallel, reviews of wearable biosensors traced steady gains in polymer electrodes, hydrogels, and stretchable conductors. These studies, published in [ScienceDirect](#) and [MDPI](#), described how PEDOT and related polymers capture faint biochemical and electrical signals during motion. New hydrogels improved self-healing and comfort, matching the need for sports and health tracking.

The [La Trobe group's approach](#) differs by growing a true 2D conducting polymer in open space. It uses hyaluronic acid tethered to gold to guide chain growth, producing uniform, ultrathin, "hyper-doped" films with dopant-to-polymer mass ratios up to 8:1 and thickness near three nanometers across centimeter-scale areas. The team attributes the metal-like behavior to both longer chains and higher carrier density, with submicrometer homogeneity confirmed by localized electrochemistry and imaging.

Practical Implications of the Research

Better transparent conductors could extend battery life and shrink wearable devices. A few nanometers shaved from each display or sensor stack can reduce weight and improve comfort. Uniform, metal-class conductive polymers may also lower cost by replacing brittle oxides that demand careful handling and rare elements.

In health care, consistent and clear electrodes can boost signal quality for heart and [brain monitoring](#). Thin and soft coatings reduce skin irritation, support longer wear, and improve adhesion to curved surfaces. If biocompatibility holds, implantable leads and stimulation pads could move toward softer, safer materials. The method also invites greener processes, since it avoids heavy baths of mobile salts and enables precise growth with fewer rinse steps.

What We've Learned

- A tethered dopant layer can grow a uniform, three-nanometer 2D PEDOT film with metal-like conductivity.
- The method improves scalability, patterning, and reproducibility for clear, flexible electrodes.
- Wearables and medical sensors could gain longer life, smaller size, and better signal quality.

Smart Textiles: A New Era of Wearable Technology

Researchers develop washable magnetic smart textiles for touchless interaction, revolutionizing wearable technology.

[JOSHUA SHAVIT](#) Published Mar 8, 2025 11:07 AM PST

Seamless navigation in a virtual reality environment using a knitted sleeve with overbraided magnetic field sensors and a magnetic ring. (CREDIT: Free University of Bozen-Bolzano)

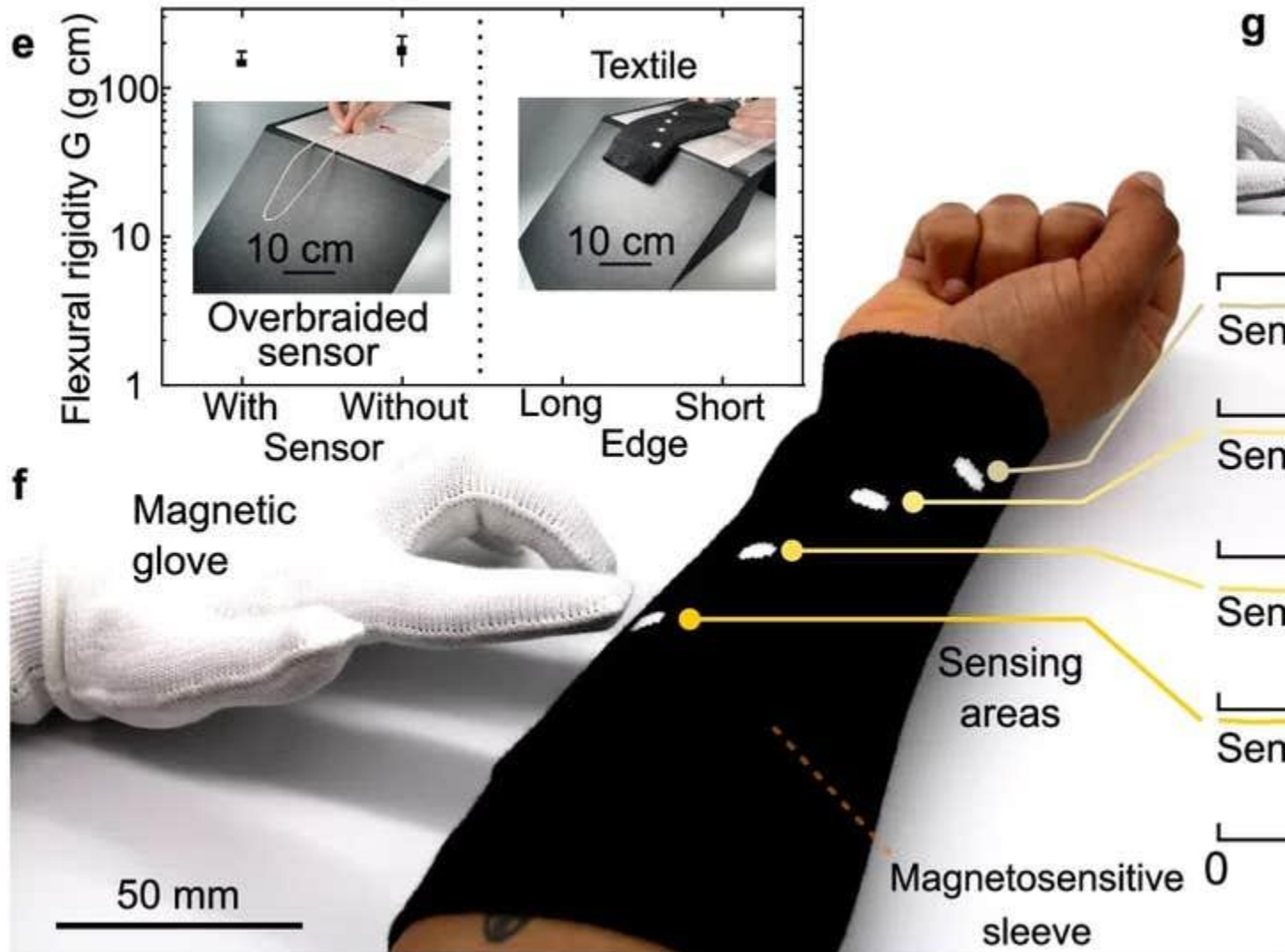
Smart textiles are changing the way people interact with their environment, blending electronics seamlessly into everyday clothing. These innovative fabrics have applications in personalized healthcare, flexible displays, and even interactive gaming.

Unlike rigid [electronic devices](#), smart textiles integrate sensors directly into fabric, allowing users to monitor physiological data and control digital interfaces with simple gestures. Despite their promise, these textiles face challenges, including durability, sensitivity to environmental conditions, and accidental activation.

Researchers have now developed a breakthrough solution—washable and touchless interactive textiles, powered by magnetic field sensors, that could redefine wearable technology.

Overcoming Limitations in Wearable Technology

Electronic textiles, or [e-textiles](#), must withstand frequent washing, bending, and shearing without losing functionality. Traditional approaches—such as weaving conductive yarns, attaching rigid devices, or coating fibers with electronic components—often compromise fabric flexibility and longevity.

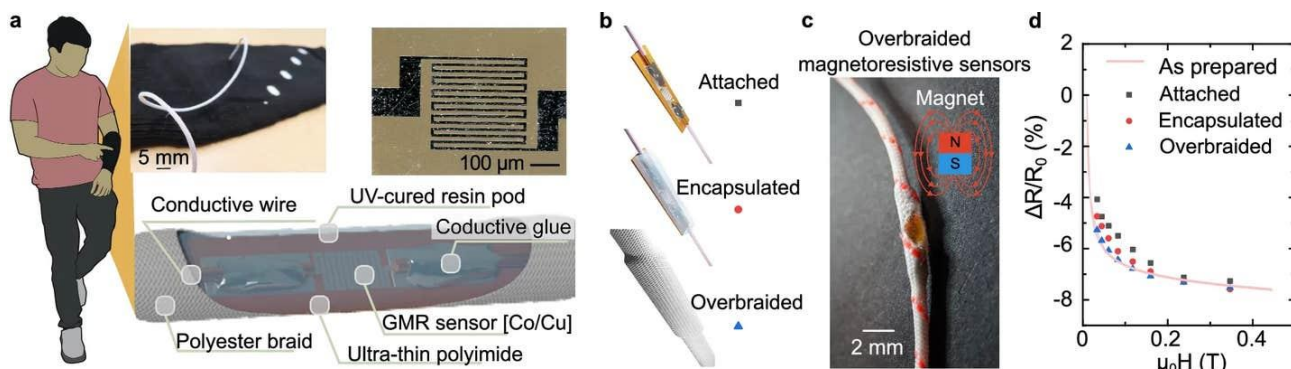


The concept of highly flexible overbraided magnetoresistive sensor involves embedding a miniature flexible magnetoresistive sensor within the core of a textile braid. (CREDIT: Nature Communications Engineering)

Many current smart textiles rely on tactile sensors that detect mechanical stimuli through resistive, capacitive, triboelectric, optical, or piezoelectric mechanisms. However, these sensors are prone to accidental activation, particularly in wearable applications where fabrics constantly rub against surfaces.

To address these limitations, researchers are shifting toward touchless interactivity, which minimizes wear and tear while enhancing user experience. One of the most common touchless technologies, capacitive sensing, captures electric fields and functions as a [proximity sensor](#).

However, capacitive sensors can still be triggered unintentionally by nearby objects, limiting their effectiveness in textiles. Other touchless methods require users to learn specific gestures and rely on extensive signal processing, making them less practical for everyday use.



Measurements from the Shirley stiffness test, which indicate the bending rigidity of both the overbraided magnetoresistive sensor and a textile fabricated using them. An interactive textile system created using a knitted sleeve containing four overbraided magnetoresistive sensors and a glove embedded with a miniature magnet. (CREDIT: Nature Communications Engineering)

A Magnetic Approach to Smart Textiles

Magnetic field sensing provides a promising alternative for touchless textile interaction. Miniature permanent magnets generate magnetic flux densities significantly greater than [Earth's geomagnetic field](#), enabling precise and reliable detection. Unlike capacitive sensors, magnetic sensors do not require physical contact and can operate in a variety of environmental conditions, including underwater.

Researchers from Nottingham Trent University, Helmholtz-Zentrum Dresden-Rossendorf, and Free University of Bozen-Bolzano have developed a groundbreaking washable electronic textile that integrates flexible magnetoresistive sensors within fabric. By embedding nanostructured Cu/Co giant magnetoresistive (GMR) sensors into braided textile yarns, the team ensured compatibility with standard textile manufacturing processes while preserving fabric aesthetics and comfort. These overbraided magnetoresistive sensors maintain exceptional sensitivity, [detecting magnetic fields](#) with sub-microtesla accuracy, even after repeated washing and exposure to moisture.

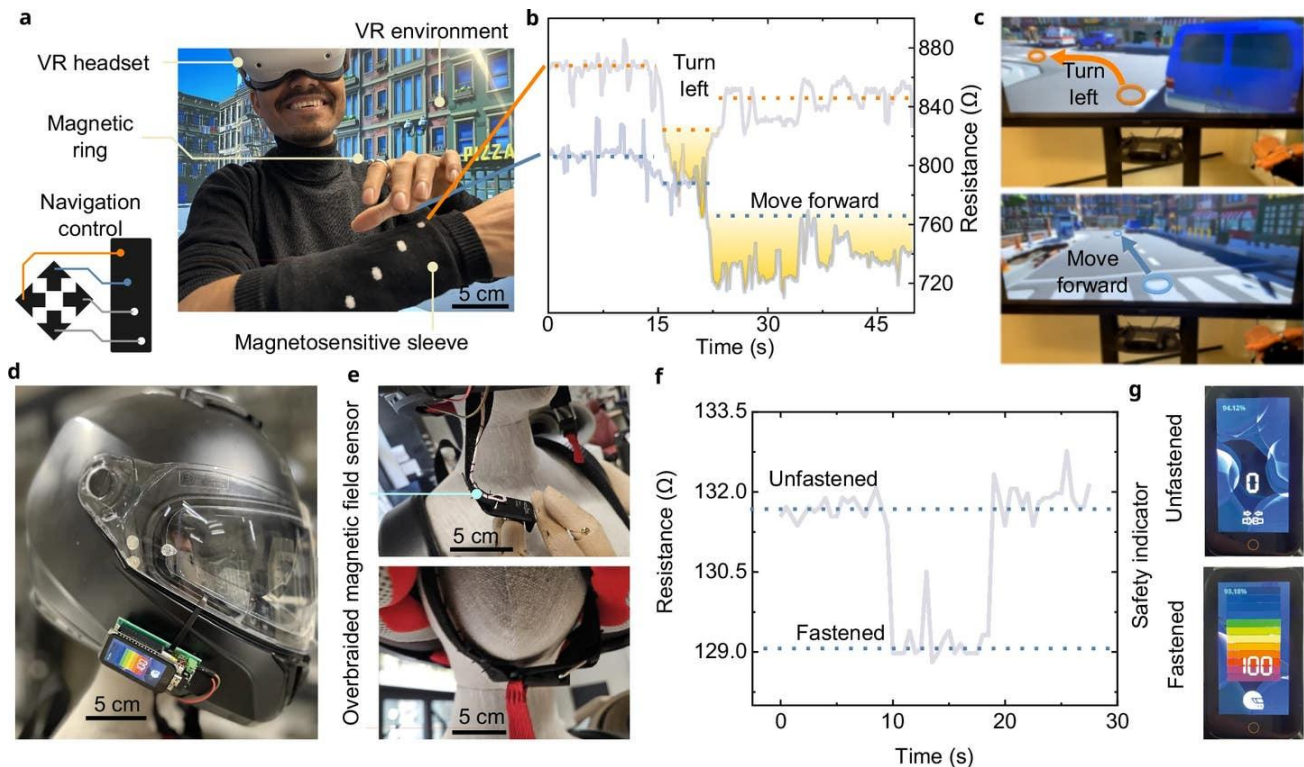
Dr. Denys Makarov from the [Institute of Ion Beam Physics and Materials Research at HZDR](#) explains, "By integrating the technology into everyday clothing, people would be able to interact with computers, smartphones, watches, and other smart devices, transforming their clothes into a wearable human-computer interface."

Real-World Applications and Future Possibilities

This new technology enables users to interact with smart textiles using a small magnetic ring or glove, triggering sensors without physical contact.

The sensors can be integrated into various garments, such as armbands for virtual reality control, safety straps for helmets, or even textile-based keyboards. Unlike existing tactile sensors, the magnetoresistive sensors are resistant to accidental activation and can function in diverse conditions.

Lead researcher Dr. Pasindu Lugoda, from [Nottingham Trent University's Department of Engineering](#), highlights the practical benefits: "Tactile sensors on textiles vary in usefulness as accidental activation occurs when they rub or brush against surfaces. Touchless interaction reduces wear and tear. Importantly, our technology is designed for everyday use. It is machine washable and durable and does not impact the drape, or overall aesthetic appeal of the textile."



Use case scenarios for overbraided magnetoresistive sensor embedded textiles. (CREDIT: Nature Communications Engineering)

Smart textiles are already finding applications in healthcare, fitness, and fashion. This new magnetic-based sensing technology expands these possibilities further, offering a more intuitive, durable, and efficient method of interaction.

As researchers refine and commercialize these innovations, everyday clothing could become an essential component of human-computer interaction, transforming how people engage with technology in their daily lives.

Research findings are published in the journal [Nature Communications Engineering](#).

Submersible touchless interactivity in conformable textiles enabled by highly selective overbraided magnetoresistive sensors

Published: 25 February 2025

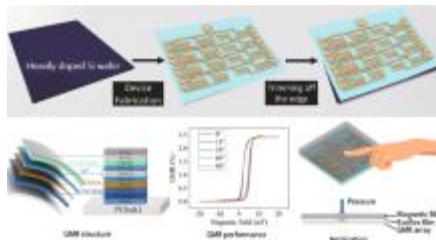
[Pasindu Lugoda](#), [Eduardo Sergio Oliveros-Mata](#), [Kalana Marasinghe](#), [Rahul](#), [Niccolò Pretto](#), [Carlos Oliveira](#), [Tilak Dias](#), [Theodore Hughes-Riley](#), [Michael Haller](#), [Niko Münzenrieder](#) & [Denys Makarov](#)

[Communications Engineering](#) **volume 4**, Article number: 33 (2025)

Abstract

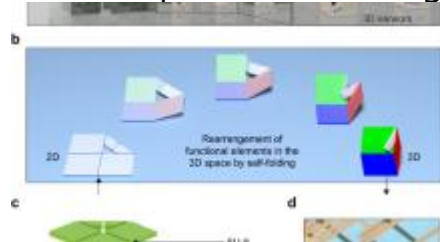
Miniature electronics positioned within textile braids leverages the persistent flexibility and comfort of textiles constructed from electronics with 1D form factors. Here, we developed touchless interactivity within textiles using 1D overbraided magnetic field sensors. Our integration strategy minimally impacts the performance of flexible giant magnetoresistive sensors, yielding machine-washable sensors that maintain conformability when integrated in traditional fabrics. These overbraided magnetoresistive sensors exhibit a detectivity down to 380 nT and a nearly isotropic magnetoresistance amplitude response, facilitating intuitive touchless interaction. The interactivity is possible even in humid environments, including underwater, opening reliable activation in day-to-day and specialized applications. To showcase capabilities of overbraided magnetoresistive sensors, we demonstrate a functional armband for navigation control in virtual reality environments and a self-monitoring safety helmet strap. This approach bridges the integration gap between on-skin and rigid magnetic interfaces, paving the way for highly reliable, comfortable, interactive textiles across entertainment, safety, and sportswear.

Similar content



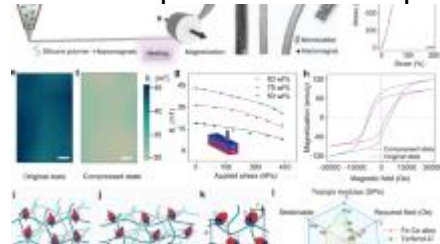
[An ultrathin, rapidly fabricated, flexible giant magnetoresistive electronic skin](#)

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[A new dimension for magnetosensitive e-skins: active matrix integrated micro-origami sensor arrays](#)

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[Soft fibers with magnetoelasticity for wearable electronics](#)

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Introduction

Electronic textiles are becoming increasingly popular and have seen use in applications ranging from personalised healthcare to flexible displays^{1,2,3,4,5}. The reasons for this are manyfold: Fabrics are typically shapeable, pleasant to look at, and comfortable to feel. For wearable applications in particular, clothes are in a persistent intimate contact with the human body which makes them an ideal platform to collect physiological data, as well as to act as an unobtrusive interface between the physical reality of humans and the virtual domain. This becomes progressively more important for entertainment and professional applications. The fusion of electronic functionality and textile

fabrics present challenges due to the different mechanical properties of textiles and traditional electronics⁶. Textiles have benefited by the evolution of the form factor of electronics that have evolved from bulky three-dimensional (3D) devices through 2D film based flexible electronics all the way to 1D fibre-like formats. 1D form factors increase the conformability of constructed textiles by leveraging the increased flexibility in the plane perpendicular to the fibre⁷. Integrating electronic components in a fibre stimulated a new research and technology field^{8,9}.

There is an active research on the realization of unobtrusive smart textiles relying on soft and flexible materials^{1,10}. Some of the explored approaches include constructing sensors from conductive yarns¹¹, attaching miniaturised rigid devices on textile substrates¹², printing components on textile substrates¹³, weaving flexible electronics into fabrics¹⁴, or by coating and functionalizing individual fibres^{15,16}. While these strategies may enable discreet integration of electronics into textiles, most are not mechanically robust enough to endure washing, bending, and shearing of the textile without compromising the device's functionality.

Due to the unobtrusive nature of electronic textiles, they have been recent efforts to use them as interactive controls for robots¹⁷, touch displays², and augmented/virtual reality¹⁸. A variety of electronic textiles has been developed for monitoring temperature^{19,20}, strain^{21,22,23}, pressure^{20,24}, moisture/humidity^{25,26}, or acceleration²⁷. There are already established smart textile technologies for illumination²⁸, energy harvesting^{29,30}, and sensing physiological parameters^{1,31}. Currently the domain of textile based interactive surfaces is dominated by *tactile* sensors capturing mechanical stimuli^{5,32}. The advantage of tactile sensors is that these can be manufactured using diverse transduction mechanisms such as resistive/piezoresistive^{33,34,35,36,37}, capacitive^{38,39,40,41,42,43}, triboelectric^{33,44,45,46}, optical⁴⁷, and piezoelectric approaches^{48,49}. This variety of approaches in turn opens the possibility to utilize many different materials and process, some of which are compatible with textiles, for the fabrication of such interfaces. There is, however, a disadvantage associate to this approach, namely that these technologies are prone to accidental activation when integrated into wearable systems for conformable textiles. Accidental activation may occur when the sensor comes

into contact or rubs against another surface. This limits their usefulness when used in textiles which constantly rub or brush against different surfaces when used in everyday scenarios. Therefore, there has been a recent trend towards touchless interactivity in textiles.

Touchless interaction effectively reduces the wear and tear, has gesture recognition capabilities and allows for increased aesthetic control of functional textiles. Table 1 showcases the latest technologies utilized in this area. Capacitive sensing technology, capable of capturing electric fields and functioning as proximity sensors, emerges as one of the most utilized technologies in creating touchless interactive textiles⁴⁰⁻⁴¹⁻⁴²⁻⁵⁰. Many of the technologies listed in Table 1, including capacitive ones, can be unintentionally activated by nearby objects. This makes them less suitable for smart textile applications, where textiles come into close proximity with multiple objects during daily wear. Meanwhile, other touchless interactive technologies require users to remember specific gestures to interact with the textile⁵¹. This also entails extensive post-processing of sensor signals to ensure activation through these gestures. Integrating touchless interactivity into textiles presents unique challenges towards real applications. The design must account for the demanding mechanical properties, constant deformation, washing requirements, and operation in humid conditions inherent to textile materials.

Table 1 Comparison of various smart textiles with touchless interactivity functions

Maintaining the mechanical behaviour of a textile is far more achievable when electronics take on a 1D geometry, such as a fibres or yarns, rather than the classical 2D patches⁷. These formats are compatible with the interweaving of the textile, resulting in excellent flexibility in the plane perpendicular to the fibre or yarn. However, this ease of deformation often leads to unstable readout during deformation making the system unreliable during bending and stretching. Furthermore, the need for washing textiles increases the risk of failure for electronics that cannot be fully encapsulated. Finally, interactive wearable textiles are frequently exposed to humidity from rain, sweat, and even underwater scenarios, posing challenges for classical touchless

approaches based on capacitive activation. No single platform currently satisfies all these requirements in a 1D form factor for smart textiles.

Utilizing magnetic fields for the activation of sensors may provide a more suitable approach to enable intuitive, reliable, and selective textile integrated interfaces⁵². Magnetic flux densities that are significantly larger than the geomagnetic field (25–65 μT)⁵³ can easily be created by miniaturized permanent magnets and be used to trigger magnetic sensors. This allows for the creation of more selective interfaces when compared to conventional approaches. Furthermore, the detection of such fields does not require direct physical contact⁵⁴⁻⁵⁵. Magnetic sensors integrated into textiles allow to quantify the absolute position, orientation, and the relative movement in a static or dynamic magnetic field⁵²⁻⁵⁶⁻⁵⁷⁻⁵⁸. The challenge towards the realization of these prospects is to fabricate and integrate magnetic field sensors that are mechanically compatible with textiles and with sufficient sensing performance. Hence, there is only limited work around the combination of magnetic sensors and textiles. Supplementary Table [S1](#) presents a comparison of our magnetic sensing technology against other available magnetic sensing technologies in textiles. In fact, washable and mechanically conformal 1D magnetic sensors have never been unobtrusively integrated within textiles and used for human computer interactions. In the past, rigid magnetic field sensors have been applied for motion tracking systems of smart gloves by companies such as HaptX⁵⁹. However, attaching such solid devices to the textiles surface makes the textile rigid and uncomfortable to wear. Additionally, proximity detection was permed by a spandex fabric coated with Fe_3O_4 nanoparticles³⁷. Such textile coatings change drastically the mechanical properties of the textile and are generally impacted by hysteresis, low speed and are typically not resistant to abrasion⁶⁰.

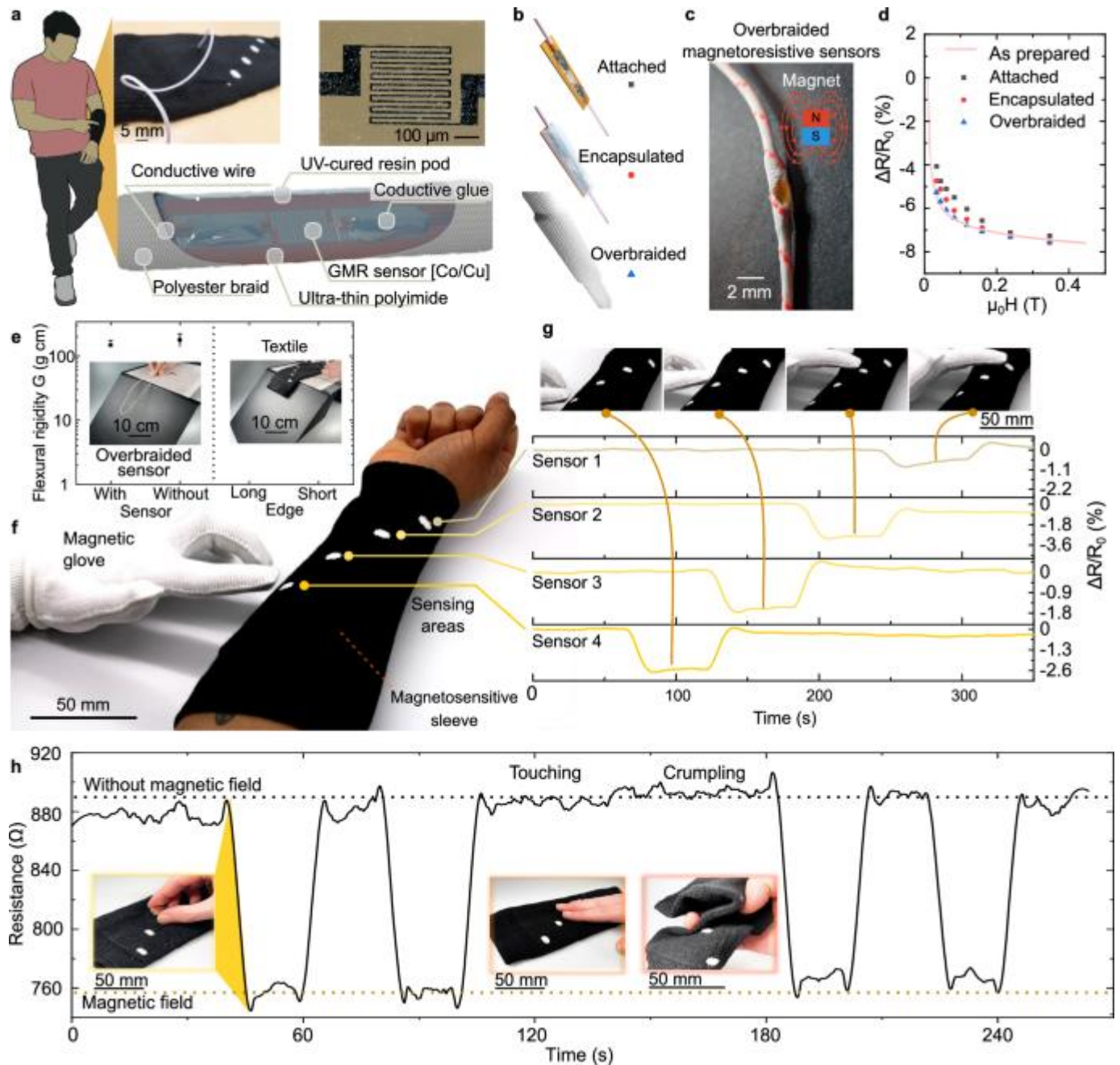
Here, we demonstrate seamless integration of the reliable touchless interactivity into everyday and specialized clothing using flexible, high-performance magnetoresistive sensors. Nanostructured Cu/Co giant magnetoresistive (GMR) sensors fabricated on flexible substrates were integrated within a braided textile yarns to ensure compatibility with conventional textile manufacturing equipment, continuous and reliable electrical connections, as well as to encapsulate the devices, and to preserve

the feel and the aesthetics of the textile. These braided textile structures will henceforth be referred to as overbraided magnetoresistive sensors. These overbraided magnetoresistive sensors exhibit exceptional sensing performance with sub- μT detectivity, can be cleaned in a conventional washing machine, and remains functional underwater. The operation of overbraided magnetoresistive sensors underwater enable new application scenarios where sweat, rain, or totally submerged conditions can interfere with sensing of the device. Multiple of these overbraided magnetoresistive sensors were positioned within knitted channels of a textile sleeve to form a sensing surface, which demonstrated its capability as an interface for a virtual reality environment. Additionally, a overbraided magnetoresistive sensor was sewn onto a helmet strap to showcase its potential for safety applications.

Results

The concept behind the touchless interactive magnetosensitive textile is illustrated in Fig. 1 (see also Supplementary Note 1). This textile was fabricated using overbraided magnetoresistive sensors which have the ability to bend, shear and twist. These braided structures were created by incorporating flexible thin film magnetoresistive sensors^{52:56:57:58} within its core. A close-up image of the sensing area of the magnetoresistive sensor is shown in Fig. 1a. The sensor layout features a meander structure with 20- μm -wide tracks, which increases the total resistivity, thereby reducing the electronic readout requirements. Thin film giant magnetoresistive (GMR) sensors were fabricated using fifty bilayers of 1 nm Co and 2.2 nm Cu deposited on a 50- μm -thick flexible polyimide foil (Supplementary Fig. S1). The fabricated thin-film GMR sensors exhibited excellent stability, with negligible change in performance after cyclic bending (Supplementary Fig. S2).

Fig. 1: Concept of a magnetoresistive textile.



a The concept of highly flexible overbraided magnetoresistive sensor involves embedding a miniature flexible magnetoresistive sensor within the core of a textile braid. **b** The fabrication stages of the overbraided magnetoresistive sensor. First, the sensor is attached to litz wires, followed by encapsulation, and integration within a textile braid. **c** Photograph of a overbraided magnetoresistive sensor with an opening to reveal the embedded sensor within. **d** Performance of a representative GMR sensor at various fabrications stages when subjected to varying magnetic fields perpendicular to the sensor

element. Data represents eight discrete measurement steps. **e** Measurements from the Shirley stiffness test, which indicate the bending rigidity of both the overbraided magnetoresistive sensor and a textile fabricated using them. **f** An interactive textile system created using a knitted sleeve containing four overbraided magnetoresistive sensors and a glove embedded with a miniature magnet. **g** Results from an experiment where the finger of the glove containing the magnet is positioned initially away from the sleeve thereafter above each of the four sensing areas. **h** Measurements from a overbraided magnetoresistive sensor obtained before, during and after a mechanical manipulation (crumpling and touching) with the sleeve.

The GMR layer stack of alternating ferromagnetic and nonmagnetic metal thin films was coupled at the 2nd antiferromagnetic maximum and exhibits a large change in resistance when exposed to a small magnetic field⁵⁷. This GMR layer stack also demonstrates consistent performance across different substrate materials, including Si wafers and various polymeric foils. Supplementary Fig. [S3](#) compares the magnetoresistive performance of Co/Cu-based GMR multilayers deposited on different substrates. The impact of varying the number of Co and Cu bilayers on GMR sensor performance has been thoroughly investigated in a previous research⁶¹. For this study, we have used a GMR layer stack configuration that has been successfully employed in this prior investigation⁶¹. The homogeneity of the Co/Cu deposition was evaluated through transport measurements, indicating consistent GMR values across different radii of the substrates. This consistency suggests uniform deposition and sensor properties across the substrate area (Supplementary Fig. [S14c](#)). Additional confirmation of layer homogeneity was obtained through profilometer measurements using a Dektak device and this is presented in the Supplementary Fig. [S4](#).

This structure was selected for its notorious magnetoresistive effect⁵⁷, primarily falling within a dynamic sensing range that stays below the 40 mT safety limit for magnetic fields, established by the World Health Organization (WHO)⁶². Additionally, we extend the technology also to anisotropic magnetoresistive (AMR) sensors based on 100-nm-thick Fe₁₉Ni₈₁ alloy that has

increased sensitivity at smaller fields but possess overall smaller magnetoresistance (Supplementary Fig. [S5](#)).

There are three crucial steps (attached, encapsulation, and braided) during the fabrication process of overbraided magnetoresistive sensors (Fig. [1b](#) and Supplementary Note [1](#)). The overbraided sensors were initially fabricated by connecting individual flexible GMR sensors to litz wires using a conductive epoxy. Then, the flexible sensors are encapsulated using a UV curable polymer and positioned within a polyester textile braid. Polyester was chosen for the braid as it is the most used textile fibre globally[63,64](#). The overbraided magnetoresistive sensor has an elliptical shape at the sensor location with the major axis having a length of 2.52 ± 0.12 mm and the minor axis having a length of 1.53 ± 0.07 mm. Figure [1c](#) displays an image of the overbraided magnetoresistive sensor, revealing a section where the textile braid has been cut out to expose the embedded thin-film sensor. The performance of a GMR sensor when a magnetic field is applied perpendicular to the sensor element at each fabrication stage is presented in Fig. [1c](#). The sensor demonstrates a stable response when the magnetic field was varied at each fabrication stage (attached, encapsulation, and braided). The sensitivity changed only slightly during the overbraided magnetoresistive sensor manufacturing process. The individual resistance values of 15 overbraided magnetoresistive sensors were within the range of 100–1000 Ω , when exposed to a magnetic field strength of 14 mT. The difference in resistance in between individual overbraided sensors is mostly due to manufacturing deviations and strain on the flexible sensors.

An important feature of wearable textiles is their drapability[65](#), which is the textile's ability to conform onto contours of a surface or body. However, the current drape testing methods and established standards, are not well-suited for evaluating the drape of E-textiles[66](#). As a result, we opted for a bending rigidity test, which offered some insights into drape behaviour, even though it's not a direct measurement. To understand the impact of embedding sensors on the bending rigidity of the overbraided magnetoresistive sensor and textile, a Shirley stiffness test was conducted, and the results are displayed in Fig. [1e67](#). The data indicate that the bending rigidity of the textile braid increased by 23% after the integration of the magnetoresistive sensor. Nonetheless once the overbraided sensors were inserted into a fabric, the

bending rigidity was measured at (3155 ± 437) mg cm along the vertical axis and (1670 ± 160) mg cm along the horizontal axis of the textile sleeve. This level of rigidity falls below that of certain woven structures crafted from heavy yarns⁶⁸. While these magnetoresistive textiles may not be as flexible as traditional fabrics, they offer a reasonable level of conformability, ensuring that they don't compromise wearer comfort.

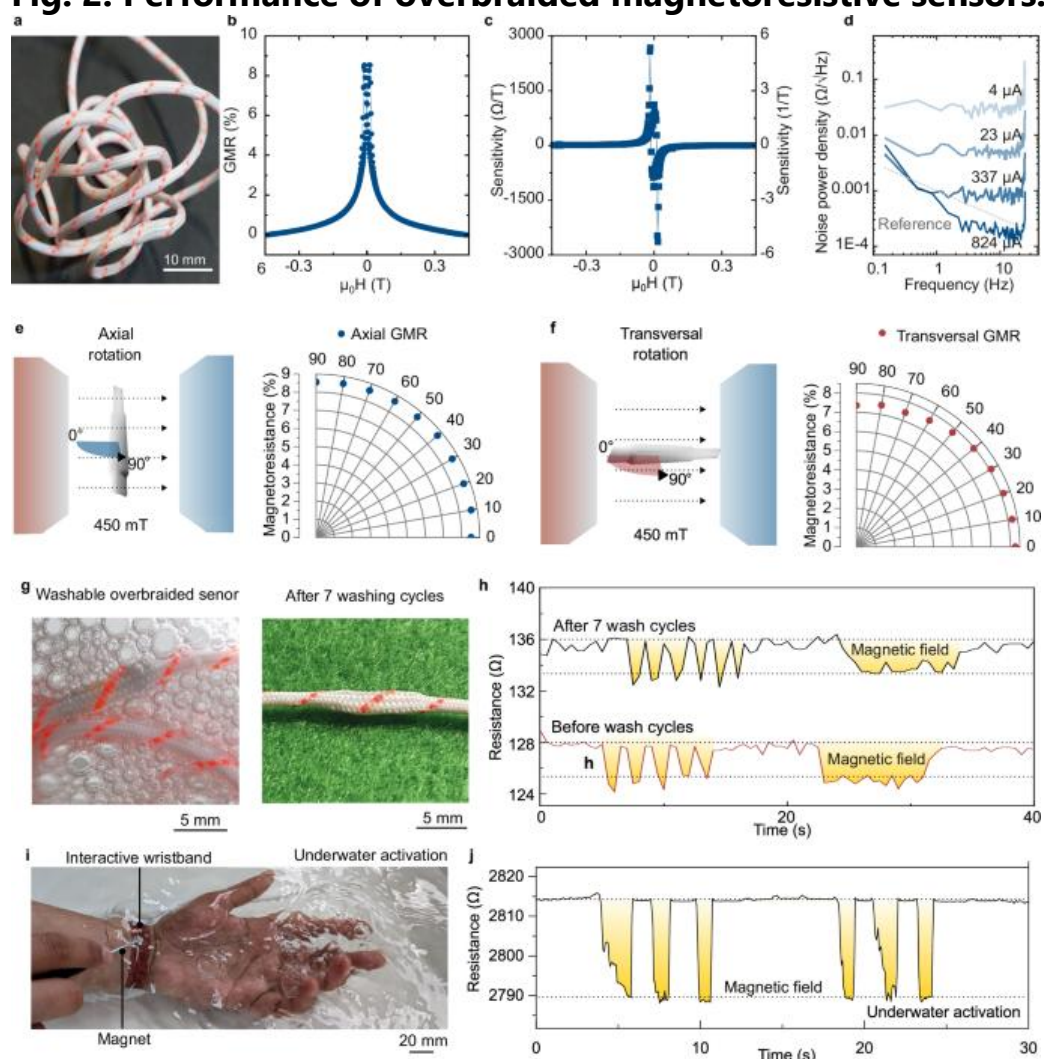
To showcase the capabilities of this technology, Fig. 1f illustrates an interactive system consisting of a textile glove embedded with a magnet and a knitted textile sleeve with four integrated overbraided magnetoresistive sensors. While overbraided magnetoresistive sensors can be directly woven into the sleeve, we opted for a knitted sleeve design with integrated channels. The overbraided sensors were positioned within these integrated channels. This design allowed for easier removal of the overbraided magnetoresistive sensors, facilitating separate recycling of the sensors and the fabric components. In the textile sleeve the sensing areas of the four overbraided magnetoresistive sensors were positioned (30.1 ± 1.7) mm (along the horizontal axis of the sleeve) and (18.7 ± 1.5) mm (along the horizontal axis of the sleeve) apart from each other. The glove contained a miniature magnet (3 mm diameter and 1 mm thickness) positioned on the index finger. Both the sleeve and the glove consist of fully wearable structures and were knitted seamlessly in a digital knitting machine. Detailed explanations of the structures can be found in Supplementary Notes 2, 3. Supplementary Fig. S11 displays images of the textile sleeve containing the overbraided magnetoresistive sensors conforming around a mannequin forearm. An experiment was conducted to evaluate the performance of the sleeve. Here the index finger was initially positioned away from the sleeve for 60 s. Then the finger was moved over sensor 1 for 60 s and then sensor 2 and so forth. Lastly, the finger was taken away from the sleeve for the final 60 s. It can be observed in Fig. 1g that the overbraided magnetoresistive sensors are able to accurately distinguish when the finger within the glove approaches each of the sensors. The sensors are activated without any relevant interference or cross talk between them. The suitability of the sensor to operate at frequencies up to 10 kHz is demonstrated in the sensor's frequency response given in Supplementary Fig. S13. This demonstrates its suitability for real-time interactive applications. The knitted sleeve demonstrates key textile properties

such as bending, and sheering. Figure [1h](#) demonstrates the performance of overbraided magnetoresistive sensors while they were being touched and crumpled. Supplementary Video [1](#) demonstrates the ability of our smart textiles to avoid accidental touch activations and deformations.

Scaling up the production of several metres of this braid (Fig. [2a](#)) can be achieved by fabricating magnetic field sensors on large-area flexible substrates, up to 300 mm in diameter (Supplementary Fig. [S14](#)). With a sensor footprint of 1 cm², a 300 mm wafer, which has an area of about 70,650 mm², can accommodate roughly 7000 sensors. Assuming one sensor is placed per centimetre of braid, this allows for the production of approximately 70 m of braid from a single substrate wafer. Their stable magnetoresistance output upon deformation (Supplementary Fig. [S15](#)) enables the reliable sensing during mechanical deformations of smart textiles. An analysis of the overbraided magnetoresistive sensor's performance was conducted for different magnetic field strengths. Here an external magnetic field was applied along the main axis of the braid and the response of the overbraided magnetoresistive sensor was recorded (Fig. [2b](#)). Being consistent with the behaviour of the GMR multilayer systems, the resistance decreased with an increasing magnetic field strength and tapered off for magnetic field strengths of > 100 mT. The overbraided magnetoresistive sensor had a maximum sensitivity at 17 mT (Fig. [2c](#)) and exhibited noise levels down to 753 $\mu\Omega \text{ Hz}^{-1/2}$ (Fig. [2d](#)). Based on these sensor parameters, a sensor limit of detection of 380 nT was achieved for overbraided magnetoresistive sensors based on GMR effect. Since there is limited information of other textile-integrated magnetic field sensors, we compared our overbraided magnetoresistive sensors performance with other flexible magnetic field sensors used for interactivity. This comparison is provided in Supplementary Table [S2](#). The analysis of the AMR sensors can be found in Supplementary Fig. [S16](#). Relevant for proximity measurement applications in smart textiles, the change of magnetoresistance was close to isotropic for magnetic fields applied from different angles along (Fig. [2e](#)) and transversal (Fig. [2f](#)) to the braid axis. This outcome represents an appealing characteristic achieved following the incorporation of the sensors within the overbraid, since the GMR effect in thin film is known to be barely sensitive to the out-of-plane magnetic fields. When applied practically, the employed permanent magnet can be

brought near the overbraided magnetoresistive sensor from any orientation, and the sensor will show the same total amplitude change regardless of the direction from which it is approached. Still, when the full curves are analysed, they show a slight degradation of sensitivity upon transversal rotations (Supplementary Fig. S17). On the other hand, overbraided magnetoresistive sensors based on the AMR effect show strong anisotropy with respect to the direction of the applied field making them good candidates to be applied for directional sensing (Supplementary Fig. S18).

Fig. 2: Performance of overbraided magnetoresistive sensors.



a Photograph of a long overbraided magnetoresistive sensor that is highly flexible (bendable and twistable). **b** GMR response obtained from a overbraided magnetoresistive sensor exposed to an external magnetic field. **c** The sensitivity of a representative overbraided magnetoresistive sensor

and **(d)** the noise power density of the signal from the overbraided sensor after applying different current levels. The full GMR response up to saturation at about 450 mT of a overbraided magnetoresistive sensor showed isotropic response amplitude upon rotations of the sensor **(e)** along and **(f)** transverse to the main symmetry axis. **g** Photograph of a overbraided magnetoresistive sensor during washing and after seven wash cycles in a washing machine. **h** Response of overbraided magnetoresistive sensor to an approaching permanent magnet before and after seven machine wash cycles. **i** Activations of a smart wristband in underwater conditions. **j** The overbraided magnetoresistive sensor is activated reliably in underwater conditions when a permanent magnet is approached.

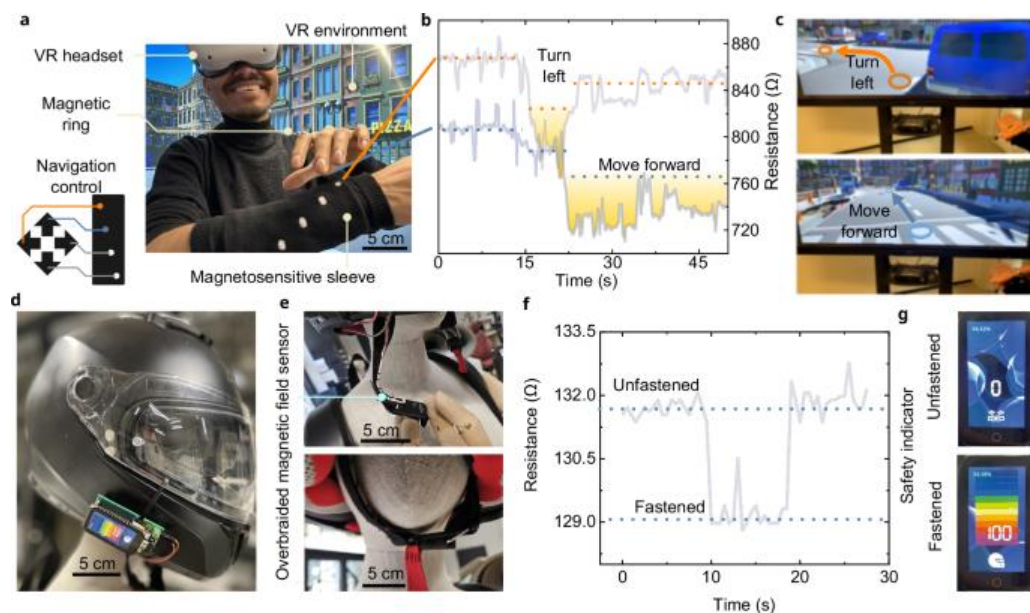
Next, the impact of washing on the overbraided magnetoresistive sensor's performance was studied, based on the method proposed by Rotzler et al.[69](#). This method exerts a high amount of stress on the textile. Overall, seven wash cycles were performed. After each cycle, the measurement procedure mentioned in the methods section was carried out. There was no visible damage to the overbraided sensor during and after the washing procedure (Fig. [2g](#)). The results from before and after the wash tests are given in Fig. [2h](#). The results indicate that the overbraided magnetoresistive sensors response to an approaching magnet is not altered by the wash test at all. The sensor before and after wash testing was able to measure when a magnetic field was directed towards it for 1 s and then withdrawn for 1 s in a repetitive manner. In addition, the sensor was able to detect when it was exposed to a magnetic field for 10 s. After the washing process, there is a slight 6.4% rise of the absolute sensor resistance when no magnet is in its proximity. This change may be due to changes in resistance of the litz wire or the contacts during the washing process.

Wearable textiles must function in everyday conditions where humidity is a factor. They could be even submerged in underwater environments like when the user exercises or during a rainy day. Avoiding losing functionality in these common activities is crucial to provide reliable interfacing. Magnetic fields are pervasive in humid environments and virtually immune to the change of medium from ambient air to submerged in a water bath (Fig. [2i](#)). We

embedded a overbraided magnetoresistive sensor into a smart wristband to test their performance in underwater conditions (Supplementary Video [2](#)), where other non-contact capacitive interfaces fail. The resistance changes of the overbraided magnetoresistive sensor when a permanent magnet is approaching the smart wristband submerged in tap water is significantly higher than the signal changes caused by unwanted taps and the normal motion of the sensing element during wear (Fig. [2h](#)).

The potential of these overbraided magnetoresistive sensors to add a new dimension to everyday clothing is demonstrated using two applications. Figure [3a](#) showcases a knitted sleeve used to navigate through a virtual reality environment. Supplementary Video [3](#) shows the sleeves functionality in real time, while the graph in Fig. [3b](#) illustrates the resistance changes of two of the overbraided magnetoresistive sensors (utilized for turning left and moving forward illustrated in Fig. [3c](#)) when approached by a magnetic ring. Figure [3d](#) showcases another use case scenario. Here the overbraided magnetoresistive sensor is used in a strap of a magnetic buckle on a helmet (Fig. [3e](#)) and can detect whether the helmet is secured on. Supplementary Video [4](#) demonstrates the functionality of the helmet. The change of the sensor resistance of the overbraided magnetoresistive sensor on the helmet strap is displayed in Fig. [3f](#). As shown in Fig. [3g](#), the screen attached to the helmet serves as a safety indicator by determining whether the helmet is securely fastened or not based on the input of the safety strap.

Fig. 3: Use case scenarios for overbraided magnetoresistive sensor embedded textiles.



a A virtual reality environment navigable using the knitted sleeve and a magnetic ring. **b** The measurements from two overbraided magnetoresistive sensors when they are used to navigate the VR environment. **c** The two overbraided magnetoresistive sensors in the sleeve were utilised to move forward and turn left. **d** A helmet equipped with a magnetic buckle and a overbraided magnetoresistive sensor stitched onto its strap as shown in a close-up in **(e)**. **f** Measurements obtained from the overbraided magnetoresistive sensor stitched on the helmet strapped on or off. **g** The screen indicates whether the helmet is strapped on or off.

Discussion

This paper introduced a new technique of incorporating flexible magnetoresistive sensors within the core of a textile braid. It is the first time where magnetic sensitivity has been successfully incorporated into smart textiles in a mechanically resilient and conformal way, making them suitable for everyday use. The 1D overbraided magnetoresistive sensors and textiles produced from these overbraided sensors exhibit the ability to bend, undergo shear and to be washed in a conventional washing machine without deterioration in their sensing performance. The overbraided magnetoresistive sensors also remained functional underwater. Interactive textiles created using magnetic field sensors demonstrate enhanced selectivity and would eliminate

false activations in comparison to previously reported touchless interactive textiles. Moreover, the overbraided magnetoresistive sensor is isotropically activated with magnetic fields from different orientations which is an attractive trait, since the permanent magnet can be brought near the overbraided magnetoresistive sensor from any orientation. This will be the case when these overbraided sensors are incorporated into textile and used in everyday scenarios. Two demonstrators were developed utilizing these overbraided magnetoresistive sensors: A knitted sleeve capable of serving as a VR environment interface, and a helmet strap designed to detect if it is securely fastened.

The implementation of touchless magnetic interactivity into wearable and interactive applications extends beyond entertainment, establishing its relevance in safety-critical contexts. This includes protective suits, underwater garments, and situations where gloves are in use such as surgery rooms and industrial settings. The power requirements of these sensors are compatible with energy harvesters developed for wearable textiles^{29,30}, making them fully operational as textile magnetic interfaces. This integrations strategy can be extended to other functional magnetosensitive elements like AMR sensors, where their high sensitivity to small fields and anisotropic behaviour can be potentially used to detect motion activity, biological signals and orientation.

Methods

Fabrication of the flexible GMR sensors

Flexible magnetoresistive sensors were fabricated on polyimide foils (HD Microsystems, USA) with a thickness of 50 μm . The foils were temporarily fixed to a PDMS (polydimethylsiloxane, Sylgard 184, Dow Corning) coated $5 \times 5 \text{ cm}^2$ glass slide. The patterning of meander structures was done via direct laser writing (DWL 66 Laser Writer, Heidelberg Instruments, Germany) using AZ5214e (MicroChemicals GmbH, Germany) resist. The photoresist was spin-coated at 4000 rpm, and soft baked at 110 $^{\circ}\text{C}$ for 60 s. After exposure, the sample was post-baked at 120 $^{\circ}\text{C}$ for 120 s, flood exposed with a UV lamp for 30 s (proMa 140 017, Germany) and developed using a 1:4 solution of AZ351B (MicroChemicals GmbH, Germany) and deionized water. Ar sputtering

deposition was employed to fabricate multilayers of 50 bilayers of [Co (1 nm)/Cu (2.2 nm)], coupled at the 2nd antiferromagnetic maximum (Ar pressure: 10^{-3} mbar, base pressure: 10^{-7} mbar, deposition rate: $2 \text{ \AA s}^{-1}$). The liftoff of the sensors was carried out in an acetone bath removing the remaining photoresist. We also prepared AMR sensors (Supplementary Figs. [S5](#), [S16](#), [S18](#)) using identical photolithography process and deposition via magnetron sputtering of 100 nm of Fe₁₉Ni₈₁ (Ar pressure: 8×10^{-4} mbar, base pressure 10^{-7} mbar, deposition rate $3 \text{ \AA s}^{-1}$). Tests for large area fabrication of these sensors (Supplementary Fig. [S14](#)) were done on 100 mm diameter flexible substrates (125- μm -thick PET, Melinex ST 504, Dupont Teijin Films, USA), and polyimide foil (50- μm -thick, HD Microsystems, USA).

Fabrication of overbraided magnetoresistive sensors

Overbraided magnetoresistive sensors were fabricated by attaching the flexible sensors onto litz wires (outer diameter: 254 μm [70](#), resistivity: $1.329 \pm 0.002 \text{ } \Omega/\text{m}$, BXL2001, OSCO Ltd., Milton Keynes, UK). The ends of litz wires had their enamel and fibre coating removed using a contact soldering iron (Antex XS25; Antex Electronics Limited, Plymouth, UK), and a small amount of solder was applied (SA305 solder wire; RS Components Ltd., Corby, UK). The wires were adhered to the magnetoresistive sensors using CW2400 conductive epoxy (Chemtronics, Kennesaw, Georgia, USA) as illustrated in Supplementary Fig. [S7](#). Once attached, the sensors and interconnects were encapsulated using a UV curable encapsulant (Dymax 9001-E-V3.5; Dymax Corporation, Torrington, CT, USA) as displayed in Supplementary Fig. [S8](#). These devices were then positioned within a braided tube with 4 polyester yarns (48 filaments/150 denier). The covering braided tube consisted of 24 carriers with polyester yarns (2×36 filaments/167 dtex; Ashworth and Sons, Cheshire, UK) and was produced using a suture braiding machine (RU1/24-80, Herzog GmbH, Oldenburg, Germany) as shown in Supplementary Fig. [S9](#).

Magnetoresistance characterization

For the experiments shown in Fig. [2b-d](#), overbraided magnetoresistive sensors were placed in the magnetic field of an electromagnet to register their resistance changes. The electromagnet created a homogeneous field up to 450 mT. A Tensormeter measurement unit (HZDR Innovation GmbH, Germany)

was applied to measure the longitudinal resistance of the overbraided sensor using a 2-point configuration. The employed current and frequency for characterization was between 1 μ A and 1 mA and 1775 Hz, respectively. The magnetoresistance (MR) was calculated as $MR = 100\% (R - R_{sat})/R_{sat}$ and was measured with the overbraided sensors oriented along the braid main axis (axial direction), as well perpendicular to it (transversal direction). A rotating holder allowed to measure the MR response at different angles with respect to these rotation axes (Supplementary Figs. [S17](#), [S18](#)). A 3D printed bending holder with clamps with tunable distance was used to measure the magnetoresistance response upon different bending radius (Supplementary Fig. [S15](#)). The bending performance measurements were carried along the current directions of the sensors.

For the experiments shown in Fig. [1d](#) a bespoke Perspex rig was designed. The design was made such that a N42 permanent magnet (16.5 kg pull; 20 mm thickness, Magnet Expert LTD, Newark, UK) was placed at the bottom of the rig in an enclosed area. The height (distance) between the samples and the magnet was increased by adding Perspex plates in between them (the plates included a whole larger than the sensor to ensure that the rig did not interfere with readings). Measurements were taken at different heights. At each height the samples were left for 15 s to reach a steady state prior to taking the measurements. A DAQ6510 data acquisition/multimeter system (Keithley, Cleveland, Ohio, USA) was used to measure the resistance of the samples. The magnetic field strength at each height from the magnet was measured using a gauss metre GM07 (Hirst Magnetic Instruments Ltd, Falmouth, UK).

Fabrication of the prototype textile garments

The seamless jacquard sleeve was knitted on a Stoll CMS ADF 32 W E7.2 (Reutlingen, Germany) digital knitting machine with a rib structure on both ends to ensure a snug arm fit. The 3D structure of the sleeve was knitted in one seamless process, and it is explained in Supplementary Note [2](#). As shown in Supplementary Fig. [S10](#), four channels were created on the knitted sleeve to incorporate the four overbraided magnetoresistive sensors. A fluid yarn (1PLY 2% Elastane, 7% Nylon, 91% Viscose, Yeoman Yarns, Leicester, UK) was used to knit the sleeve. The knitted seamless glove that contained the magnet (N52

permanent magnet, diameter 3 mm and thickness 1 mm, surface magnetic field: 4105 G, pull force: 0.14 kg, Magnet Expert LTD, Newark, UK) was also created on the Stoll CMS ADF 32 W E7.2 machine. Similar to the sleeve, the glove was knitted in one seamless process as further detailed in Supplementary Note [3](#). Three different types of yarn were used for the glove: fluid yarn (1PLY 2% Elastane, 7% Nylon, 91% Viscose, Yeoman Yarns), cotton yarn (1/24 combed cotton 1 ply, Yeoman Yarns) and Nylon 2/78/68 (CONTIFIBRE S.P.A., Tobagi, Italy). The glove was knitted with a channel for a miniature N52 permanent magnet as illustrated in Supplementary Fig. [S12](#).

Wash test procedure

The wash test was conducted using a Bosch TitanEdition Series 6 (Gerlingen, Germany) washing machine. A neutral soap and 1 kg of support fabric was used in every wash cycle. The washing machine was set to 800 rpm, with a water volume of 12 L, and temperature of 30 °C, using 1% by weight of soup, and washed for 35 min, followed by a spin cycle (2 min at 500 rpm and 5 min at 800 rpm), and rinsing (3 min, 20 °C, 40% on-time, 12 L of water – 3 min, 20 °C, 40% on-time, 12 L of water). All tests were performed at ambient conditions (ambient relative humidity). After each washing cycle, the sample was air dried at room temperature for 30 min. To test the sample, the following measurement procedure was performed following each wash cycle: Initially for 5 s, there was no magnet near the overbraided magnetoresistive sensor. Subsequently, within the next 10 s, the magnet with a surface flux density of 0.414 T was brought towards the overbraided sensor for 1 s, then removed for 1 s, and this process was repeated for 10 s. Afterward, the magnet was moved away for 10 s. Following this, the magnet was brought close to the overbraided sensor and held in place for 10 s, followed by a withdrawal for an additional 10 s.

Shirley stiffness test procedure

The bending rigidity, $G = M L^3$, was determined by measuring the textile's specific weight per unit area, M , and the bending length L , as defined by the Shirley stiffness test^{[71](#)}. This is an established method to quantify the stiffness of smart textiles. Here, the overbraided magnetoresistive sensors and the fabric were manually moved over a horizontal plane towards an edge with a

declining ramp at the angle of 41.5° . As the samples' ends reached the horizontal plane's edge, they begin to bend downward due to gravity. The moment the textile tip touches the angled plane, movement is halted, and the length of the bent textile, L , is measured. All measurements were repeated 5 times and the average was obtained.

Underwater demonstrator

For the underwater demonstrator (Supplementary Video [2](#)), a Tensormeter measurement unit (HZDR Innovation GmbH, Germany) was used to track the resistance changes of an overbraided magnetoresistive sensor. The sensor biased with 2 V and 1 mA was measured at a rate of 200 ms. The overbraided magnetoresistive sensor was integrated to a wristband. The interconnections from litz wires to BNC connectors of the Tensormeter measurement unit were done in air. A plastic container was filled with tap water to test the touchless activation when the wristband was submerged and approached by a permanent magnet (300 mT at the surface). The data was acquired and indicated through a visual interface developed in LABView software (National Instruments, USA).

Virtual reality (VR) simulator

For the VR demonstrator (Supplementary Video [3](#)), an Adafruit HUZZAH ESP32 board (New York, USA), with a 12 bit ADC for sampling the voltage dividers was used to interface with the sensors. A reference resistor with a value of $R_{\text{ref}} = 350 \, \Omega$ was used and connected to a 3.3 V source through the four GPIO pins on the ESP32 board. To reduce measurement noise, we used the Exponentially Weighted Moving Average filter with:

Readings were gathered within 100 ms. This was then sent over the OSC protocol to a Unity 3D application controlling the locomotion.

Fabrication of the prototype helmet

For the helmet strap demo (Supplementary Video [4](#)), we used a Fidlock magnet snap (Hannover, Germany) for closing the helmet combined with the overbraided magnetoresistive sensor. For sensing the signal, a LilyGO ESP32-S3 board (Shenzhen Xinyuan Electronic Technology Co., Shenzhen, China) was

chosen, using the on-board 12 bit ADC for sampling. For the voltage divider a reference resistor with a value of $R_{\text{ref}} = 500 \, \Omega$ was used and connected to a 3.3 V source through a separate GPIO pin on the ESP32, with their configurations defined in the firmware to regulate the flow of current. The signal was filtered using the Exponentially Weighted Moving Average filter.

Ethics

We applied a permanent magnet to a finger of a user in several studies reported in this manuscript. This magnet is not an electronic component. Furthermore, in several studies, a sensor is applied on skin of a user (two volunteers; male). These studies are done accordingly to the ethic approval #SR-EK-459122024 from the ethics committee at the Technical University of Dresden. We have written consents from volunteers to participate in this study including the publication of identifiable images of the research participant. The current lines are always isolated and are not in touch with the skin. The sensor is not worn on skin for any extended duration.
