

Smart Wound Dressing: The Future Of Advanced Wound Management: Review

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Abstract: Healthcare is moving towards term personalized care based on continuous physiological monitoring. This shift increases the need for bioelectronic technologies. Bioelectronics has developed through three generations. First-generation systems used materials, which often failed to match the softness of tissue. Gaps could form at the interface triggering inflammation. Second-generation systems used stretchable materials to improve tissue contact and reduce mechanical stress. However stable attachment to moving tissue remained difficult limiting use. Recent work has therefore focused on third-generation bioelectronics. These systems combine soft electronic materials with multifunctional, adaptive human-machine interfaces that respond to mechanical and biochemical cues in the body. This review covers progress in adaptive interfaces grouped into mechano-adaptive and biophysiological adaptive approaches. We first discuss shape programmability, injectability, anti-swelling structures and self-healing. We then examine controlled permeability, anti-fibrotic design, tissue adhesion and biodegradability. Representative wearable and implantable systems are also reviewed. Finally, we consider the main challenges and future work needed to support long-term clinical use.

Keywords: interfaces | bioelectronics | human-machine interfaces | wearable and implantable electronics

I. Introduction

As the global population ages and chronic diseases become more common healthcare is shifting towards term patient-centered care. This change is speeding the move from hospital-based treatment to at-home care supported by time physiological monitoring [1–3]. Advances in bioelectronic technologies are central to this shift. These technologies have progressed from stationary systems to biocompatible platforms that conform to different tissues, including the brain, heart, nerves, muscles and skin. They can record changing signals and deliver targeted stimulation [4–7]. Combined with Internet of Things (IoT) systems and artificial intelligence (AI) they can analyse volumes of physiological data over time. This can support detection of disease tailored treatment feedback and timely care [8–9]. By reducing the time and distance barriers of clinical care these technologies could improve access, lower healthcare costs and support quality of life through timely treatment and automated medical support [10, 11].

Bioelectronic systems can be grouped into three generations according to their design and methods of tissue contact. Early first-generation platforms mainly used materials such as silicon and metals forming stiff electrodes and bulky chip-based devices. Examples from the 2000s include metal microwire arrays for neural recording and stimulation as well as implantable cardiac devices, including ventricular assist systems with substantial metal components [12–15]. These technologies laid the groundwork for bioelectronics but their rigidity limited long-term use [16]. Stiff electrodes cannot conform to the curved surfaces of biological tissue. This can leave gaps at the interface. Reduce recording quality and stimulation efficiency [17]. Rigid devices also move

differently from tissue causing repeated motion at the interface. This can trigger inflammation and over time, encapsulation, which further reduces signal stability and device performance [18].

To address these limits researchers developed second-generation systems designed to match the properties of soft tissue. Early methods reduced the thickness of materials to lower their bending stiffness. Others used structures such as interconnects and buckled shapes to allow stretching [19–22]. One key advance combined ultrathin silicon. Serpentine interconnects on a skin-like base enabling conformal, multifunctional physiological sensing [23]. More recent work has moved beyond design towards intrinsically soft electronic materials. These materials can. Conduct electricity without relying only on device geometry. They often combine fillers, such as metallic nanomaterials, carbon-based allotropes or two-dimensional nanoflakes with conducting polymers or ionic conductors in a soft elastomer matrix [24–27].

Second-generation systems have improved sensing and stimulation by making contact with curved tissue surfaces. Several barriers still limit their clinical use [28]. Tissue and organ movement can disrupt the interface. Without attachment devices may detach or produce motion artefacts during movement lowering signal quality. Sutures can secure devices. May cause bleeding and are unsuitable for fragile organs such as the brain and heart. The body's complex biochemical environment also threatens long-term performance. Biofouling and biofilm growth occur as macromolecules, bacteria and acid ions build up on device surfaces. This can gradually weaken performance and structural integrity [29, 30]. In implants such damage can require removal after a period placing physical and emotional strain on patients.

Since the 2020s research has increasingly focused on third-generation bioelectronics to improve long-term stability and reliability. These systems use soft electronic materials and engineered interfaces that adapt to human tissue in multiple ways. Here an adaptive interface means an interface that actively or dynamically changes its mechanical, structural, chemical or physiological interactions with the surrounding tissue. These changes help maintain contact and long-term function. Interfaces that offer passive mechanical softness without adaptive interactions remain part of second-generation bioelectronics rather than adaptive bio interfaces. Adaptive interfaces can be grouped into mechano-adaptive and adaptive types. Mechano-adaptive interfaces use structural and material design to provide changing mechanical compliance, strength and stable physical coupling. They allow device structures and shapes to adjust to wet, curved moving surfaces maintaining close contact as tissue shifts or deforms. Examples include shape- devices that respond to cues such as humidity or temperature along with self-healing interfaces.

Early bioelectronics mainly sought to reduce the mismatch between stiff devices and soft tissues [31,32]. The varied continuous movements inside the body pose challenges beyond static mechanical compatibility. Biological tissues deform in ways: neural tissue makes subtle movements the heart expands rhythmically and skin undergoes strains in several directions. Each has amplitudes and frequencies [33, 34]. To work reliably over time artificial systems must handle these changing shapes and mechanical loads while limiting impact. Generation soft human-machine interfaces (HMIs) therefore need mechano-adaptivity: the ability to fit tissue surfaces as they move maintain close contact and function under complex changing mechanical forces.

Advances in materials science and microfabrication have produced ways to give soft HMIs mechano-adaptive properties. Four common approaches are shape programmability, injectability, resistance to swelling and self-healing. Architectures guided by geometry with built-in actuators or responsive materials can follow set patterns of movement. This helps them fit curved or moving organs and maintain contact and function over time [35-40]. Injectable platforms and materials that form in place reduce impact. They can be delivered with invasive methods and create soft interfaces at targeted sites, including confined or irregular biological spaces [41-45]. Anti-swelling hydrogel matrices retain their size and electrical function in water- ionic settings. This prevents changes in stiffness separation from tissue and declining signal quality over time which are concerns for wearable and implantable devices [46-49]. Self-healing materials can also restore electrical continuity after repeated movement or long-term implantation. By limiting fatigue, small cracks and lasting structural damage they can extend device life. Improve reliability [56-59]. Together these methods move HMI design beyond passive flexibility towards active mechanical adaptation changing how electronic devices maintain contact with living tissue.

1. Shape Programmability

Soft HMIs must fit target tissues while covering area for accurate sensing, effective stimulation and local treatment. Shape-programmable systems meet this need by changing form. They can shift shape, unfold or fit themselves within confined or complex spaces. Their actuation methods fall into two groups: mechanically triggered shape change and stimulus-responsive morphing. Both aim to create minimally invasive bio interfaces that adapt to tissue shape.

Mechanically triggered systems use carefully designed geometries with built-in actuators or pre-strained parts. These store mechanical energy while held in a form. When an external cue, often heat or air pressure activates the system the stored energy is released and the structure moves into its deployed shape. This allows a device to pass through an incision then expand or unfold in a controlled way across the target tissue.

Wei et al. Developed a shape-changing electrode array for invasive large-area electrocorticography (ECoG) mapping [35]. The ultra-thin array used gold/carbon hybrid conductors on a Parylene-C base. It was linked to a nitinol shape-memory actuator set to recover its expanded form at body temperature 37°C. For implantation the array was rolled into a strip that could pass through a 2 mm opening in the skull. It then unfolded on its own to cover an area of the cortical surface. Pre-set strain in the actuator drove this change. A dissolvable polyethylene oxide adhesive controlled the unfolding speed allowing deployment. The design enabled mapping across cortical regions with limited surgical impact.

Coles et al. Reported an origami-inspired fluidic actuator for large-area ECoG [36]. The system used parylene-C chambers within a polydimethylsiloxane (PDMS) layer. These chambers enabled controlled pressurization and expansion without leakage. Folded the electrode sheet could be inserted beneath the dura through a burr-hole opening, about 6 mm wide. Internal air pressure then expanded it to cover an area of the cortex. This soft robotic actuation produced controlled unfolding and close contact with the brain. By combining electronics with fluid-driven movement the platform offered a practical route, to minimally invasive large-area neural recording.

Stimulus-responsive systems change shape because the material reacts to signals like moisture, heat, light or magnetic fields. The material changes its shape when the conditions change. This helps the device to put itself into place and stay close to the body after being put in. Yi et al. Created water- super contractile polymer films (WRAP) inspired by the way spider silk contracts a lot [37]. WRAP films are made from polyethylene oxide and PEG alpha-cyclodextrin inclusion complexes. When they get wet, they get smaller by than 50%. They go from being dry and hard so they can fit with parts to being soft and like a hydrogel with a hardness of about 100 kPa. This shrinking allows films with electrodes to wrap tightly around nerves, muscles and heart tissue. This helps with electrical recording and stimulation. The change caused by water is quick and safe for the body. It does not use outside signals. This makes WRAP films a good choice for bioelectronic interfaces that can adjust on their own.

Another study by Agno et al. Made a temperature- intravenous needle that becomes soft for good use in the body. The device had a frame made of gallium inside a material [38]. The gallium part was hard at room temperature so it could be put in. It melted at about 30 degrees Celsius. This change made the device soft and easy to shape to fit tissue. The change in hardness because of temperature helped reduce harm to tissue. The chance of needle injuries. It still kept its strength. Allowed fluid to flow well. This method gives a way to have biomedical tools that can change their strength in a practical way.

2. Injectability

Shape-programmable structures can fit to tissues by changing shape. Putting them in usually needs surgery. Injectability offers another way to make it less invasive and reach hard to get to tissues. Flowing. Materials that start as something else go through small holes. Then they become stable. Work well in the body. Injectable systems are divided into two groups: pre-made injectable electronics and materials that form in the body.

Pre-made injectable electronics use shape or design to go through narrow channels. Then they go back to their shape and work after being put in. Liu et al. Showed this method with electronics that can go in through a syringe. The electronics were a centimeter-thin mesh with small holes. The shape of each part controlled how stiff it was in directions [41]. The mesh could be

rolled up without breaking and go through glass needles with a size as small as 95 micrometers. Once it came out it went back to its shape. The team tested how well the device worked and its electrical features, like resistance and how well it let electricity flow through needle sizes. The results showed that it went back to its shape and worked. How well it could go in depended on the way the mesh was shaped. The bending stiffness of the thin network allowed a solid electronic system to go through thin needles and form good lasting connections after being put in.

Permanent fluidic magnets (PFMs) offer a way using liquid. Zhao et al. Made PFMs by mixing -Brownian neodymium-iron-boron (NdFeB) nanomagnets in a sticky silicone. Then they used a field to form a 3D network of magnetic shapes [48]. This design kept the material stable without moving. It stayed easy to put in and had a magnetic pull. After being put in through a needle the PFM's magnetic pull worked with a coil. This allowed monitoring of the heart without wires. A needle could also take out the PFM from where it was put.

Materials that form in the body can be put in as something that's soft and then changes into something solid. This happens when they get into the body and use reactions or forces. These include things like hydrogen bonds, electric attraction and the way some molecules stick together. Ren et al. Showed this with adhesives that can be put in and then heal themselves. The way they formed was through a reaction without a catalyst or UV light. This made a material that only made water as a by-product [50]. Extra parts of the material reacted with tissue to make a connection. For example, 7% of the material made a connection of 27.6 ± 3.9 kPa. The changing bonds also let it fix itself and handle energy. This helped with wounds that did not need stitches and stuck well to tissues after being put in.

Using ways to change Jin et al. Made a material that can be put in and used as a tissue replacement. The material had ways to link together. These included strong but able to change bonds and ways that could come back. At the time the material made gold particles that gave it fast two-way electricity flow. Tests showed that the best mix turned into a solid in one minute. It had a strength and a low loss of energy. These features let it flow through needles and return to its shape quickly. The replacement could fill shapes link to nerves and help with fast recovery by having good contact.

3. Anti-swelling

Soft HMIs in salty environments get water. If they get much, they get bigger. This can make them not fit right make the strength not match cause stress at the edges weaken the grip to tissue and break the way electricity flows. All these problems can make the signals not as good. The device not last as long. So, ways to stop swelling are needed. They should stop water getting in. Still keep the grip, strength and the way they work with electricity.

Tian et al. Made a material that does not get bigger and sticks to tissue. They added something that does not like water called hydrophobic poly (vinyl butyral) (PVB) to a network made of acrylic acid, gelatin and a special kind of cysteine [46]. Unlike ways that make the material fuller or add parts that stick to the material this way added PVB without changing the way the parts link. The PVB made areas that did not like water. These stopped water from getting in. Let the parts that stick to tissue move. The material did not get much. It had a grip to wet tissue almost ten times more than other materials that do not get bigger. The grip did not drop much after being put on and taken off many times. This was helped by parts that can change and go back in the tissue. The material also helped reduce inflammation and kept the connection between the device and the body when it moved. These results show that making parts that do not like water can stop swelling without making the stickiness or how well it works with the body worse.

Yang et al. Took a way. They made the structure more stable of making a part that does not like water [48]. They made a material that does not get bigger can be put in and can carry electricity. They used a part that had ways to link, called thiol-maleimide PEG with a part that can carry electricity called multiscale MXene/PEDOT:PSS. A part called acid helped control the way the parts stuck together. It made the way they joined happen slowly so they could be put in. It also made bonds and ways that can happen more than once between the parts. The electricity parts make it stop getting bigger and help with electricity. The best mix had an amount of swelling. It had a grip and worked well for a long time. It worked as a band around a nerve for a long time. The way it

stopped getting bigger came from both ways that stick together. These made the material stronger but still soft and easy to put in and fit with the body.

4. Self-healing

Soft HMIs can get damaged from being bent times or staying in the body for a long time. This damage can break the way electricity flows. Make the material not work as well. This makes the device not last long. Self-healing materials can help by fixing the damage through changing parts. These materials are split into two groups: those that use extra parts to help fix and those that have parts that can fix themselves. Extrinsic self-healing systems have parts that can help fix in bags, tubes or small pieces. When cracks form these bags or tubes open up. Let out parts that can stick the cracks together. Then they become solid again [50, 54–56].

Even though this can work well it has some problems for parts in the body. The fix can only happen once because the parts get used up. The bags or tubes might change how soft the material is. Some parts that help fix might not be safe for the body. The speed at which they work and the way they move through tissue can also be a problem. These systems are not good for long-term use where the parts need to fix themselves again without changing how they work. Intrinsic self-healing systems have parts that can fix themselves. These parts can make the material come back together without extra parts [56].

The types of parts that can change include ways to link that can break and come back like parts that can change and make links. They also include parts that can stick together like ways that use water, electric charge or the way some parts fit together. These parts can fix times under the body's conditions. They can make the material soft and stretchy. Still work for long time. Song et al. Made A-SEE, a material that has parts that can change. It helped the material not get damaged stay dry and fix itself. The material wrapped around a nerve without using stitches or glue. It fit well. Did not cause stress when the body moved. The way the parts changed helped it stay working and stretchy. In the body this kind of fix helped with signals and using the nerve. The results show how fixing by itself can make the device work longer be more reliable and fit better, with the body. Jiang and their team created a self-healing polyurethane elastomer that uses dynamic oximeurethane exchange and hydrogen bonding [53].

Changing the crosslink density helped control the properties. Tensile strength could be between 33 kPa and 4.383 MPa while Youngs modulus ranged from 172 kPa to 3.724 MPa making the material suitable for biomedical uses. Softer versions in the range allowed suture-free nerve connections through self-healing on their own. Harder versions in the range provided support for blood vessels or bones including wrapping aneurysms and stabilizing the breastbone. This wide range of properties allows self-healing polymers to be adapted for different medical needs.

5. Bio physiologically Adaptive Bioelectronic Interfaces

Even though mechano-adaptive interfaces reduce problems caused by differences in stiffness and movement they alone do not guarantee long-term stability in the body [57]. Living tissues have proteins, fats, enzymes, reactive oxygen species and signals that cause inflammation. These elements interact with implants leading to things like fouling breaking down and the body wrapping the implant in a layer of tissue. Over time these things raise the resistance at the interface. Limit how well the device works, even for soft and well-fitted devices. Without the way to handle these problems long-term implants might separate or become unstable making the sensing and stimulation less accurate. Bio physiologically adaptive interfaces solve these issues by making the material longer controlling the immune system and helping the tissue and device work together. These methods manage the movement of gases, water and ions reduce inflammation and create wet sticking without needing to make holes [58].

Biodegradable materials are another option: devices that disappear after the treatment time ends removing the problem of a body. Together these changes help the device stay connected work over time and function properly in the active inside environment. They also help create a base for long-term use and using generation soft bioelectronic systems.

6. Permeability

Flexible wearable electronics can fit the shape of the skin and support checking health over time. If they do not allow air to pass, they can make the skin irritated when used for a long time. To fix these researchers in the Someya group made electronics with a

nanofiber structure that fits the skin and allows air to move through [59]. Their PVA nanofiber conductors helped watch temperature and pressure on the finger while keeping the risk of irritation low. The simple material setup however limited making complex parts and the number of components in the device.

To fix these limits three-dimensional electronics that let air and water through were made by using liquid metal circuits with materials [60]. Rigid chips were attached to stretchy liquid metal paths inside a matrix. The final structure looked like fabric. Let air and moisture through while being safe to use and able to grow in size. These breathable electronic skins also do than one thing, like sensing sending electricity and talking wirelessly.

Both air and water movement are important to keep the skin healthy and stop irritation when using electronics. The way these systems are built lets moisture move quickly making a place for the skin to be better than old ways of connecting. Hydrogels have also been added as layers to help with water movement and being kind to the skin [61]. Their water-rich structures help move ions and molecules across the skin help signals go through and reduce contact between the device and skin which limits inflammation.

For example, Lim and their group made a system using hydrogels that can check oxygen levels and resistance give electricity and send medicine through the skin [62,63]. The parts made with hydrogels carry the electricity. The wet environment also helps reactions for checking oxygen and moving medicine through the skin. This setup allows ways to check and send signals in the body.

7. Anti-Fibrosis

Materials that are not natural including implants make the body's immune system react and start a response. This reaction can make a layer of tissue form around the device. This layer can make the signals worse. The device not work as well over time. Stopping the layer of tissue that forms is important for the device to work well in the body and keep working. Anti-fouling strategies are used to stop this layer forming so this section includes the word "anti-fouling" in that bigger way [62,63].

A main reason for this layer is the space between the device and the tissue near it. This space lets cells called fibroblasts move in and make collagen. Methods that make the device fit better around the body's curves have been made to fix this [64]. For example, Wu and their team made a layer that closes the space between the tissue and the device helping stop the thick layer from forming. Tests in animals showed less swelling and less collagen in the sticky places compared to places without the sticky layer, which showed a strong way to stop the thick layer.

Just using methods may not be enough for long-term use. The body's parts moving and stress can eventually pull the device away from the tissue [65]. Chemical ways can help by making the body's cells less active and lowering signs of inflammation. Li and their team added parts to the polymer called selenophene and cyclosulfone groups, which made the body's signals less active [66]. The selenophene parts took away some of the particles while the cyclosulfone parts stopped more of the bad reactions.

Stereochemical ways to make the device have also been found to help stop the layer. Hydrogels made with types of a chemical called polyserine had less thick layers than those made with just one type. They also had signs of inflammation and less swelling [67]. These results show that chemical and stereochemical ways can stop the layer and help the device work well with soft tissues over a long time.

8. Tissue adhesion

As mentioned before sticky materials help make a connection between the tissue and the device and stop the thick layer from forming which helps the device work well over time. They also keep the device in the place making the signals more reliable and the way the device connects with the tissue steadier. If the device moves away from the tissue, it can make the device stop working increase resistance and have signals, which can stop the device from working properly.

Physical ways to make materials sticky can be used with types of polymers. One simple way uses the way polymer chains twist together. High molecular weight polymers go into chains making a double layer that stays together unless a strong force is used [68]. When these polymers connect with the body's materials they make a sticky layer at the connection. Methods that copy how nature makes things stick can make a more reliable connection while keeping the material flexible. Ho and their team made a

design like the patterns on a frog or a geckos feet. These patterns make space for the connection to happen making the stickiness stronger. They used ways to make similar patterns on artificial materials [69]. Other work looked at how octopus suckers work, which use spaces to make a pull and stick better [70]. Scientists made a similar pull using materials that change when the temperature changes, like PNIPAM. Changes in size from temperature help the connection be strong but able to come off making a connection that can be taken off again with a pull of over 10 kPa [71].

Physical ways to make things sticky can be used with hydrogel setups but the connection is not strong enough. Chemical ways to make the bond stronger have been studied a lot [72]. Hydrogen bonds can form between amine, acid and alcohol groups. These groups can be added to the polymer part by attaching them [73]. On their own hydrogen bonds are not strong enough for lasting connections with body tissue. Making a connection by changing the material while it is in the body can help.

Yuk and their team made the connection between the hydrogel and the body stronger using EDC/NHS chemistry. The hydrogels with parts that react to body amines made bonds directly at the connection [74,75]. Adding parts that can hold onto metal made the connection better helping the device fit well under normal body conditions. Other ways to make a connection have been made. For example, hydrogels with parts that react to amines in the body can make a lasting connection with a pull of about 1 MPa and lasting a long time [76].

9. Biodegradability

Recent work has looked at ways to make materials that work long-term when they are inside the body. However, devices and their parts are still foreign so the body might still react while they are in. Devices and parts that break down can help lower these risks by disappearing after they have done their job [51, 52]. Things like polymers, stretchy materials and hydrogels are examples of materials that can work for a while and then break down on purpose.

Thin layers of materials that break down have been studied a lot as bases for devices that disappear. Silk fibroin is one example. This material from nature is safe. Has low issues with toxicity. Electronics can be made on a layer of silk and then moved to the body's surface making the device fit well [19]. After being in the body enzymes slowly break down the silk helping the parts of the device fit with the tissue. As the device gets thinner it fits better. The way silk breaks down is not easy to control, which limits how it can be used when timing is important. Materials made from chemicals, like PLGA can be adjusted easily. The time it takes for the material to break down can be controlled by changing the mix of parts. For instance, researchers made a device that helps with nerve stimulation using PLGA. The part that touches the nerve directly and breaks down over time during the treatment [77].

Degradable polymers can also create hydrogel networks. Combining elasticity with controlled biodegradation expands the range of uses for bioelectronics. One example is a copolymer based on poly(L-lactide-co-ε-caprolactone) (PLCL). Its lactide segments add stiffness while its caprolactone domains provide elasticity [78]. These properties give the material stretchability under external strain and accelerated in vitro tests confirmed its programmed biodegradability. Cha et al. Also reported a hydrogel with injectability, adhesion and stretchability. A double-network. Added functional groups enabled in situ gelation through four concurrent reactions. The resulting multifunctional hydrogel interface is suited to biomedical applications.

10. Multi-Functional Adaptive Bio interfaces for Wearable and Implantable Applications

Biological tissues. Change shape over time so soft HMIs need to perform several functions at once. Researchers are exploring a range of design strategies to meet this need [79–81]. For soft HMIs multifunctionality is vital. A reliable high-quality interface with moving perspiring skin must measure biopotentials, strain, temperature and chemical signals. It may also need to provide feedback, heat therapy or transdermal drug delivery. These functions must work alongside power management, wireless communication and lasting comfort. Combining them in one conformal platform can reduce motion artefacts remove interconnects and support closed-loop feedback during daily activity.

Recent advances have helped make this possible. They include shape-ultra-thin laminates [82, 83] and materials that resist swelling and drying while allowing water vapor to pass through helping skin to "breathe" [84, 85]. Self-healing conductive networks based on PEDOT:PSS, MXenes or liquid-metal microchannels can maintain interfacial impedance [86–88]. Other

developments include tissue-adhesive coatings [89, 90]; printed or stretchable radios [91]; triboelectric and thermoelectric energy harvesters [92,93]; and NFC or Bluetooth modules that support on-device analysis [94].

Implantable soft HMIs also need to combine functions. Sensing, electrical, chemical or mechanical stimulation, local drug release and secure telemetry can support closed-loop therapy. At the time the interface must remain stable and cause minimal disruption to nearby tissue over long periods. Anti-fibrotic and biodegradable designs can help achieve this. Examples include surfaces that mimic extracellular matrix or contain zwitterions, transient magnesium and silicon conductors and matrices made from silk, gelatin or hyaluronic acid. These materials can maintain stable tissue impedance and remove the need for device extraction [95,96]. Injectable and deployable designs can also reduce injury [97,98] while chemically bonded hydrogel-elastomer junctions help prevent delamination as organs move [99,100].

Other supporting technologies include energy storage [101] and ultrasound or NFC-based power delivery [102]. Microfluidic drug reservoirs can be combined with stimulation [103] while hydrogels compatible with photolithography enable patterned microelectrode fabrication [104]. Scalable additive manufacturing can also pattern sensors, actuators and interconnects together [105]. Together these developments are enabling HMIs that conform to tissue remain in place and sense interpret and act as integrated bio interfaces for wearable and implantable use.

11. Wearable Bioelectronics with a Multi-Functional Adaptive Interface

Combining stretchability, permeability and self-healing in one HMI remains difficult. The challenge largely stems from trade-offs in materials used at biotic interfaces. For example, ultra-thin breathable electrodes are hard to make self-healing. In materials strong interactions between fibers improve mechanical strength but can disrupt supramolecular dynamics. This may prevent the bond exchange needed for repair.

Zhu et al. Addressed this issue with a confinement method. It controls interactions at both fiber scales stabilizing dynamic hydrogen bonds within electro spun fibers [106]. The method produced a -thin neural-net-like nanofibrous membrane. It retained self-healing while preserving the open pores needed for skin breathability. When used in an epidermal electrode the membrane showed strong mechanical and electrical stability during long-term wear.

The net structure increased the effective contact area on rough moving skin. This allowed attachment with little interfacial energy and reduced irritation caused by pressure. Hierarchical confinement also maintained a low-modulus fiber surface that could settle into shallow skin creases. The electrode therefore stayed in contact during movement. It enabled time electrophysiological monitoring with high signal quality and little burden on the underlying tissue without harming skin health. The findings show that hierarchical confinement can balance self-healing with nanofiber stability supporting barely perceptible and biocompatible epidermal interfaces.

Sheng et al. Developed a self-healing hydrogel coating for materials [107]. They used a cross-linked double-network (DN) hydrogel made through a plasma-electrolysis process. Its dense network of hydrogen bonds supported repair while the hydrogel entered and coated the substrate's porous structure. First plasma electrolytic oxidation textured the substrate surface. The DN hydrogel then formed inside its pores.

The resulting soft HMI was assessed using impedance spectroscopy and polarization tests in chloride solutions. Self-healing tests measured the recovery of electrochemical performance. Compared with porous substrates the coated interfaces had much greater corrosion resistance. They also healed rapidly reaching about 86% efficiency within 45 minutes. Strong supramolecular interactions in the DN network were the cause. The study offers a scalable way to coat porous structures with conformal damage-tolerant hydrogel interfaces improving the durability of soft HMIs.

For term wearable HMI use, biocompatibility and antimicrobial protection matter as much as softness, breathability and self-healing. Xu et al. Reported an antimicrobial HMI based on liquid-metal (LM) conductors [108]. A phase-separation process produced LM-elastomer composites. In these materials a microcellular elastomer network held LM droplets in place limiting flow

and leakage. It also lowered the electrical percolation threshold reducing LM use without lowering conductivity. The researchers added ϵ -poly-L-lysine to provide spectrum antimicrobial activity.

The composites were compliant highly stretchable and conductive during deformation. They also allowed water vapor to pass through. Were compatible with magnetic resonance imaging. Integrated into skin-interfaced bioelectronics they supported monitoring of cardiac electrical and mechanical activity as well as electrical stimulation during movement. The study presents a manufacturable materials approach that limits LM leakage and adds built-in protection while maintaining mechanical and electrical performance. It advances LM composites for durable and hygienic epidermal bio interfaces.

Recently, Zhu et al. Developed a direct-writing method for erasable reconfigurable multifunctional on-skin HMIs. It addresses three limits of epidermal systems: complex pre-fabrication and transfer printing, fixed layouts that restrict customization and poor reuse after wear [109]. The team made a skin-adhered coating from conductive ink creating a substrate that can be written on and readily erased. The hydrophilic composite ink contained graphite, carbon black, polyvinylpyrrolidone (PVP K30) glycerol and water. PVP dispersed the carbon fillers, lowered surface tension for deposition and bound the fillers in place as the ink dried. Glycerol adjusted viscosity, kept the ink dispersed and improved adhesion and resistance to deformation after the solvent evaporated. With a ballpoint-style conductor users could draw circuit traces and sensor layouts onto the coated skin then erase or change them as needed. Water enabled the graphite and carbon network to reconnect within the PVP/glycerol matrix on a water-based acrylic emulsion substrate giving the system its self-healing property. The resulting circuits were ultrathin, breathable and conformal. Maintained stable signals during daily activities. They could also be. Rewritten repeatedly to change sensor layouts or repair damage. This work showed how customizable, multifunctional and reusable on-skin HMIs could be made at the point of care without transfer methods or adhesives.

12. Implantable Bioelectronics with Multi-Functional Adaptive Interface

Implantable HMIs require features such as biocompatibility, biodegradability, self-healing a modulus suited to target tissues and strong adhesion. These demands add to the challenges of material choice, device design and fabrication. Jang et al. Developed a stretchable and intrinsically self-healing conductor for an implantable HMI that combines sensing and therapy [110]. Their two-layer conductor comprised a self-healing elastomer (SH-PLCL) with disulphide exchange and hydrogen bonding and a self-healing conductive composite (SH-CC). The composite used PEDOT: PSS plasticized with P14[TFPI] to improve stretchability and polyethylene glycol/glycerol to aid self-healing and conductivity. The layers adhered strongly through interpenetration and bonds at the SH-PLCL/SH-CC interface. The team tested the implant in vivo on a mouse bladder. It combined strain sensing, electromyography recording and electrical stimulation in one device. After cuts electrical function recovered at room temperature in about two minutes. The conductor retained conductivity (about 10^3 S cm⁻¹) and stretchability (about 500%) through repeated damage while polymer interpenetration maintained strong adhesion between the layers. SH-PLCL also degraded in conditions. The self-healing implant bladder voiding efficiency and maintained stable signals during repeated organ movement. The study showed a material design that combines biodegradability and mechanical strength with therapeutic functions, in an implant.

Jung et al. Described an intrinsically stretchable organic field-effect transistor (sOFET) platform for implantable interfaces. It can do on-device logic while handling body movement and biofluids [111]. The platform has low-voltage OFETs with stretchable corrosion-resistant electrodes in active-matrix and logic circuits, including inverter, NOR and NAND circuits. These circuits work inside the body allowing local signal processing inside tissue of just passive sensing. The team mixed a high-mobility semiconducting polymer (DPPT-TT) with grade Bromo butyl rubber (BIIR). They then vulcanized the elastomer with sulfur, DPPT and stearic acid to make a nanofiber-percolated semiconductor inside a matrix. The material worked without cracks up to 100% strain. Kept stable mobility over 1,000 cycles. Dual-layer Ag/Au metallization made contacts that resisted sweat and stayed stable in artificial sweat for 72 hours. Active-matrix arrays and pseudo-CMOS logic were tested under strain and in water. Biocompatibility tests included in vitro tests with dermal fibroblasts and macrophages, antibacterial tests and a 30-day mouse study of subcutaneous implants. The study measured markers and fibrous capsule thickness. The sOFETs and circuits kept mobility and on/off ratios up to 50% strain and after 10,000 cycles. They also stayed stable in deionized water, saline and PBS. Implanted logic circuits kept their switching properties for days showing that elastomeric OFET logic can work inside living

tissue. This work provided a material design for OFET logic with tested biocompatibility in vitro and in vivo solving known problems of ion-gated OECTs including high off-currents and crosstalk.

Lee et al. Described a shape-morphing HMI that sticks to a wet cortex and supports closed-loop transcranial focused ultrasound (tFUS) neurostimulation [112]. A catechol-conjugated alginate hydrogel gave strong adhesion to the cortex. The team also made a self-healing polymer substrate for shape-morphing conformity and mechanical durability. A stretchable 16-channel ECoG array allowed high-fidelity sensing. Was connected to a pulse-controlled tFUS module for closed-loop use. In rodent models of epilepsy, the system found pre-seizure high-frequency oscillations (HFOs) and changed the ultrasound dose automatically to stop seizures. The cortex-adhered shape-morphing sensor kept artefact-resistant neural recordings during tFUS. It found pre-seizure HFOs in real time and allowed closed-loop seizure control with adaptive ultrasound dosing in awake animals. The study showed a materials-based approach to closed-loop ultrasound neuromodulation.

13. Bioelectrically Active Electronic Skins

Chronic wounds are becoming more common worldwide. Standard electrical stimulation systems use rigid electrodes and external power sources. They often are not flexible couple signals poorly. May harm nearby soft tissue [113,114]. These limits make it harder to control tissue conditions continuously and precisely [115]. Flexible electronics with biomimetic wearable materials offer new chances.

More evidence shows that the skins natural endogenous electric field (EF) is a factor in wound repair [116–118]. Electrical and optical signals along with physiological measures also help regulate cell migration, inflammation and angiogenesis as the wound microenvironment goes back to balance [119,120–122]. Electronic skin can create this environment offering a new way to help tissue regeneration [123].

13.1 Electronic Skin Based on Multi-Responsive Sustained Drug-Delivery Systems

Melanoma is an invasive malignant tumor linked with high rates and poor results [124]. Standard treatments, including chemotherapy, surgery and photodynamic therapy have limits. These include effectiveness, poor depth of penetration and risk of secondary wound infection [125–127]. Immunotherapy may offer a cure. Clinical response rates are still low [128]. In years nanomaterial-based drug delivery systems using smart stimulus-responsive technologies have developed rapidly [129,130]. They let drugs be released precisely and controlled in response to signals such as heat, pH, light or electricity. This can improve the availability and selectivity of anticancer drugs [131].

Building on this work Zheng's group [132] made a Mult responsive controlled-release electronic skin for drug delivery called PADM-MX-Ag-Si@Dox. The system uses porcine dermal matrix (PADM) as its base. Its structure includes MXene nanosheets, silver nanowires (AgNWs) and multi-responsive TSOHSiO₂@Dox microspheres. Unlike natural hydrogel dressings PADM has natural collagen macro- and nanofibers that form a dermis-like extracellular matrix (ECM) scaffold. This structure helps promote cell adhesion, angiogenesis and wound healing [133,134]. In the skin AgNWs and two-dimensional MXene coat highly adsorbent PADM-modified collagen nanotubes evenly forming a continuous conductive network. Compared with patches this design offers strong antibacterial properties and good biocompatibility. PADM-MX-Ag-Si@Dox also has a surface than PADM alone while keeping the characteristic ordered d-band structure of collagen fibers [135].

This structure gives PADM-MX-Ag-Si@Dox a tensile strength of about 22.76 MPa. It can handle tissue pulling during wound healing. Keep mechanical stability [136]. PADM's three-dimensional porous structure gives a base for microsphere attachment and tissue cell growth. It also helps spread TSOHSiO₂@Dox microspheres which can carry a high drug load. As a result, the electronic skin can release Dox in response to temperature, electrical stimulation.

In temperature-responsive tests, hydrophobic shrinkage of the P(NIPAM-co-AA) chains on the TSOHSiO₂ surface further helps Dox release. Under simulated responsive conditions deprotonation of -COOH groups increases intermolecular electrostatic repulsion. The TSOHSiO₂@Dox microspheres then. Release Dox. Zheng's group [132] found that the microspheres achieved a

controlled-release efficiency of about 47-55% at 37 °C and pH 6.8. This result shows their response to changing conditions and their ability to control drug release [137].

The charged TSOHSiO₂@Dox microspheres stick loosely to collagen nanofibers because the interfacial bonds are weak. Under electrical stimulation (ES) they detach and move toward the anode. This raises the electronic skins controlled-release efficiency to 52.42%. At the level ES increased the number of cells in DNA synthesis and post-synthesis phases compared to cells in a normal microenvironment. Forward and side scatter values also dropped significantly showing cell size. Together these findings show that a conductive environment made by ES can activate ion channels, reactive oxygen species (ROS) and growth factor expression. This can improve cell activity and potential for growth [138,139].

Zheng's group [132] also showed that PADM-MX-Ag-Si@Dox can track melanoma lesion movement and post-operative wound healing in time. By combining -responsive drug release with ES the electronic skin stopped more than 90% of melanoma recurrence and sped up wound healing. It offers a way for post-operative melanoma care and wound repair. Its main biological action comes from TSOHSiO₂@Dox, which acts as a unit. With ES this unit drives targeted drug release. Helps fibroblast migration toward the wound. The resulting physical and chemical environment supports angiogenesis and tissue repair. Future work will focus on translation and making greener smarter dressings. These advances could give affordable and environmentally friendly options for cancer treatment and post-operative care around the world [140,141].

13.2 Electronic Skin Based on Multifunctional Integrated Hydrogels

Chronic wound healing has become a global health problem. These wounds have a risk of infection heal slowly and are hard to monitor well [142]. Traditional dressings usually do one thing don't fit the mechanics of living tissue and can't provide real-time feedback in complex conditions. Functional hydrogel materials have biocompatibility and electroactivity [143,144]. Combined with stimulation therapy they have become a growing area of research for electronic skin patches [145]. Liu's [146] and Shin's [147] research groups made -modal responsive-release electronic skin systems by combining multi-hydrogel technologies with bioelectrically active materials.

Liu's group [146] made an antibacterial electronic skin patch based on a tissue engineering scaffold. It is made in layers from a PDMS/PTFE membrane, liquid metal E-GaIn and HQPS@MoS₂ hydrogel. Based on a nanogenerator (TENG) the patch can create its own power wirelessly through contact and separation. The PDMS/PTFE material also creates electric fields, which speed wound cell growth. Compared with PDMS membranes the PDMS/PTFE composite shows about a 1.4-fold increase. Its excellent interface compatibility gives the material mechanical strength. The -CF₂ groups in PTFE lower surface energy making PDMS/PTFE hydrophobic. This helps sensing in conditions and limits interference from bacterial regrowth, in sweat. Compared with films PDMS/PTFE produces 3.8 times the short-circuit current. This shows self-powering performance and stable bioelectric signal output through triboelectric sensing.

The HQPS@MoS₂ hydrogel has a pore size of about 32.9 μm. Its porous structure absorbs wound fluid while its photothermal conversion efficiency of 44.38% allows infrared (NIR) stimulation to make heat and start the production of ·OH radicals. These features give the hydrogel mechanical strength, uniform distribution and strong antibacterial activity. Its temperature and strain sensing functions also allow real-time wound monitoring. Multiple effective attachments help move signals to the wound creating a conductive path that supports angiogenesis and cell movement. In contact-separation mode the TENG produces a voltage of 7.8 V and a current of 97.5 nA without needing an external power source. This helps increase the expression of factors. When stretched a thinner E-GaIn layer reduces the distance that carriers travel and improves electron transport [148].

Shin's group [147] created an active electronic skin using several hydrogel materials. The base is a PHEA hydrogel matrix. A tough and highly adhesive PDA hydrogel helps with tissue attachment while a PEDOT: PSS hydrogel with electrochemical properties works as the working electrode. Ag foil hydrogels connect the parts. Compared to patches this hydrogel-based electronic skin has a lower Young's modulus and more water content. These features support drug delivery and isolate the wound surface impedance during electrical stimulation (ES) [149,150]. Compared to skin without an added electric field electrical stimulation therapy increased wound closure rates by about 15%. It also created skin appendages, thicker granulation tissue and

fewer inflammatory responses. Shin's group [147] also made a drug delivery method that combines iontophoresis with repulsion. It sends charged epidermal growth factor (EGF) from the hydrogel-based electronic skin to the wound. EGF can control cell growth, movement and development [151]. The group also used a bioimpedance measurement system with two electrodes at places allowing the electronic skin to track wound healing [147].

These systems use the properties of hydrogels to create a strong tissue-device connection that reacts to changing body conditions [152,153]. They also mix the healing effects of stimulation which helps cells grow and develop at the wound area [154] with sensors for real-time non-invasive checking. This way it improves the way chronic wounds are treated and supports a personalized treatment plan [155]. The first system is about warning through temperature and strain signals. The second one is about a treatment loop based on ion release and impedance mapping. Both research teams use hydrogels to control changing fields with electrical stimulation as the main treatment. The hydrogels' ability to conduct electricity and their compatibility with the body allow control of the immune response. The electronic skin system limits much inflammation and helps stop chronic inflammation. It also increases the release of growth factors. Improves blood flow in the wound providing oxygen and nutrients to the injured tissue. These benefits increase the speed and ability of tissue repair.

These multi-functional hydrogel electronic skin patches offer a way to manage chronic wounds. Integrated technologies have achieved healing rates over 80% faster and 95% effectiveness. Future designs might tackle complex wounds by combining better biocompatibility with programmable drug delivery systems [156,157].

13.3 Electronic Skin Based on Photoelectric Synergistic Stimulation

electronic skin systems being studied use a single type of stimulation like electrical stimulation. This limits how different effects can work together. Material design and understanding of how cells respond are still not complete [158–160]. Adding stimulation to the electroactive processes involved in wound healing has become an area of active research [161–163]. Liu's group [146] and Shin's group [147] combined stimulation with electronic skin for wound treatment and checking. Tian's group [164] and Wang's group [165] took an approach creating bioelectrically active electronic skin based on combined optoelectronic stimulation. By combining energy transfer with electrical signals this method can change the wound healing process and fill the gap between infection control and managing cell activity in current technologies [166,167].

To treat wounds that're hard to heal Tian's group [164] made a light-driven electronic skin, shown in Figure 5a. It has a p-type silicon film with a microcolumn structure and a near-infrared light unit. The stable film changes light into signals. The team changed the distance between the electrode film and light plate during tests. At a distance of 1 mm the photocurrent dropped by 50% showing that the films photoconversion has millimeter-level precision. Through PES effects it increases the level of calcium ions by 1.23 times and helps fibroblast movement between the microcolumns. Calcium ion channel levels are closely connected to cell contractility [168,169].

This discovery shows the potential of PES to help cells grow again. every PES-treated group had wound healing within two days. The control group, which had no PES healed 25% slower. After three days cell activity was 117% higher. These results confirm that combined light and electrical stimulation help wound-repair cell growth and movement more than either stimulus Tian's group [164] also used this skin on diabetic wounds. It reduced inflammation during the stage and made the inflammatory cycle shorter [170,171]. Tian's group [164] also noted that PES can help cell movement and wound repair by increasing mTOR pathway activity linked to mRNA translation. Calcium influx can also increase actomyosin contractility further helping these effects.

Wang's group [165] made a self-powered electronic skin with a three-layer design. It combines the effects of electric fields and photothermal activity. A Pd@Au nano frame acts as the interface and changes light into heat efficiently. Compared to single materials it heats faster raising the temperature by 35.5 °C in five minutes under 808 nm near-infrared light at 1 W/cm². The stimulated sensing layer uses a glucose oxidase (GOD) reaction controlled by thrombin (TB). TB is a protein that can make an intrinsic electric field. The transparent conductive layer has than 90% transmittance and is made of hexadecyltrimethylammonium bromide (CTAB)-functionalized multiwalled carbon nanotubes (C-MWCNTs) and thermally deposited polydimethylsiloxane

(PDMS). After curing the C-MWCNTs/PDMS layer can stretch along one axis by up to 550%. Its adhesion strength is 2 kPa, stretching and twisting have little effect on its output voltage. These features give the layer toughness and stable conductivity supporting real-time visual checking of wound changes [171].

Antimicrobial tests with *Escherichia coli* showed that the self-powered transparent electronic skin was 198% more effective with 0.59 V stimulation than without. Based on these results the team made a platform that combines electrical stimulation. Wireless devices. Send electrical signals and test results. Wang's group [165] also found that wounds covered by the self-powered electronic skin, which combines light-driven and electrical stimulation healed completely in seven days. This was half the 14 days needed for wounds without treatment. Both teams used -invasive interfaces to deliver controlled signals that mimic the skins natural electric signals [173,174]. These systems let people interact with the wound environment in time. Tian's group [164] focused on light-driven and calcium-cascade mechanisms to make responses to light and electricity [175]. Wang's group [165] focused on the combined effects of heating and electrical stimulation. Its conductive layer also collects data and tracks changes in real time.

Both teams used sensitive materials to turn external light into local electrical signals. This created a controlled electric field inside the electronic skin guiding epithelial cells and fibroblasts toward the wound center. The process helped with tissue shaping and building up the matrix. Optoelectronic couplers can also lower the levels of -inflammatory factors and keep internal electrical signals stable. This supports balance while limiting the damage caused by the stimulation. Both types of skin could move from bioelectrically active designs to real medical use. Combining responses and photoelectric effects with drug delivery systems could give more complete control and personalized diagnosis and treatment for each wound [153,176,177].

II. Conclusion

This review looks at progress in electronic skin for wound healing, including the advantages and uses of each method. It focuses on two types: biomimetic thermotherapy and bioelectrically active electronic skin. Thermotherapy-based designs want to improve wound healing by copying how the body controls heat. TPC-based electronic skins adjust their temperature and physical response while TRES-based systems link heat sensing with heat delivery in a loop.

Bioelectrically active electronic skins link signals with biological processes. They include systems for on-demand drug delivery hydrogel platforms that mix stimulation with other functions and tools that pair light and electrical stimulation. The review found that mixing stimulation with bioactive factors can speed up the growth of blood vessels, collagen and re-epithelialization in chronic wounds. Together these methods give a way to manage the wound environment.

These technologies can also bring social benefits. Self-powered systems don't need battery changes lowering energy costs over time.

Modular design connects bioelectronics with treatment by combining different parts in one system. This can almost eliminate the need for maintenance replacing materials and labor for treatment devices. Continuous electrical stimulation can speed up wound healing and tissue repair. Along with checking systems it can also reduce the physical isolation that people with limited movement feel. Some materials have parts that break down naturally into safe molecules. This can lower the impact of medical devices and support "ecological healing".

Though new electronic skin materials keep appearing their long-term compatibility with the body needs more study. This is especially important when electronic skin systems keep regulating heat or provide stimulation. Researchers must check if the material molecules cause inflammation at wound areas increase the chance of tissue forming around the device or change cell behavior. The harmful effects of products, from biodegradable materials also need to be tested.

Electronic skin is moving from lab models to products but making it big and engineering it properly is still tough. Most current wound healing systems use tiny manufacturing methods. These special ways don't yet let companies make a lot of them while keeping them working for long. Getting approval is another problem. Electronic skin products vary in how they feel and act and how they help wounds heal. This might make it hard to decide if they are devices or medicines making approval harder than for

regular bandages. Progress depends on engineering, testing in real situations and clear rules. These steps are needed to make sure electronic skin can be safely and properly used on a scale for checking and treating wounds.

The following areas are important:

- (1) Creating materials that last and work with the body. New materials have helped skin research but most work has been about improving what already exists and adding features. Not enough attention has been given to how these materials work with living tissue. Questions remain about metals left behind. If long-term contact with electronic skin materials could release harmful things. Future work should look at how electronic parts can work with tissue over time. Electrodes that break down slowly could be made, along with databases that track how active materials work in the body. These tools would help check and understand material safety.
- (2) Creating ways to put different parts together. Research has made sensors accurate and power sources better but putting everything together is still a challenge. For example, how light moves through materials limits how well some devices work. Systems that control temperature can change quickly. They need a lot of power making them hard to use in small wearables. Researchers could improve power use by combining energy from sources with smart storage. More work should make device designs better build AI databases for use and improve how energy is used for each user.
- (3) Making it easier to make a lot. Many new materials for skin are cheap to make. The main parts are still hard to design and make properly. For example, making electrode patterns and channels in gel is hard to do cheaply and in large amounts. Future tests should look at both cost and design when deciding if a product can be made on a scale. This would help make designs and balance use with good performance.
- (4) Looking again at how things work. Current technologies can. Fix wounds using physical effects, like light and heat. Most still use ways of doing this. Future work could use loops that use gels to respond to signals from the body. These systems could send fields when they sense certain signals helping with healing and drug delivery. This would create closed-loop systems that sense treat and give feedback.
- (5) Focusing on use in clinics. Researchers can use electronic skin samples to create standard animal models. They can also build a shared system that checks safety and new benefits while making the approval process better. Collaboration between schools, companies and hospitals would help train people in making materials putting parts together and studying diseases. This work can help bring electronic skin into real hospitals as modern treatments.

Wound healing is still a topic in medicine and electronic skin offers new ways to treat it on a big scale. This review looks at progress in heat therapy and active electronic skin. It checks what they can do and what they might be used for looks at what should be studied next. The findings aim to help work in this area.

This review has covered advances in adaptive HMI technologies for the third generation of bioelectronics. These systems are in two groups: ones that change with movement and those that change with body functions. Mechano-adaptive ways include shapes that can be changed systems that can be injected designs that stop swelling and materials that can fix themselves. Biophysiological approaches include parts that control how things pass through chemicals that stop scarring layers that stick to tissue and parts that break down. Examples of implantable devices show the possible use of these interfaces in real life. The review has also looked at the challenges. What needs to be studied to make strong long-lasting bioelectronic tools for real use.

Soft HMI systems have made progress but future interfaces need to do more complex things. Their reliability and how they work in the body are still problems. Living in the body can cause them to break down which might affect how they work over time. Losing signals and safety issues like term immune reactions and body reactions to foreign things also need attention. Research should use tests in labs and animals. These should include aging tests, long-term implanting tests against dirt and checks on how they work when moved a lot. Shared ways to check things will help compare HMIs fairly.

Getting these systems into hospitals and making them in big amounts depends on thinking about rules early. Device design should think about how to clean them with things like ethylene oxide and gamma rays. It should also look at making them in numbers

making them the same each time packaging and power. Following safety rules, including ISO 10993 is very important. Progress on reliability making things the same and rules will decide if adaptive HMIs can move beyond ideas and into hospitals.

Technical progress will need help from areas. Using AI to look at signals making systems that work on their copying parts of the body can help make interfaces that work with living systems. This work could lead to devices that break down after a set time systems that sense and act and parts that help control the body's reactions. These could let soft HMIs work better with tissues and support care real-time checking and changing treatments. Together these steps could help shape how people and machines work together in the future.

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