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Advances in biomimetic E-Skin: Materials, mechanisms, and human interfaces

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Abstract

Electronic skin (e-skin) is a thin, flexible electronic material that mimics the sensory capabilities of human skin by integrating sensors into stretchable substrates, thereby directly influencing its sensitivity and durability. It serves as a 'human-friendly interface,' providing a seamless connection between biological tissues and digital systems, enabling applications in non-invasive healthcare, intuitive robotics, and advanced prosthetics. The development of artificial skin has advanced significantly since its introduction in the 1980s. Artificial skin enables researchers to gain valuable insights into various biochemical and physiological reactions happening within the skin. The combination of natural and synthetic materials in developing artificial skin has tremendously improved the overall quality of artificial skin or skin models produced. E-skin represents our advancement and a futuristic approach to mimicking human skin. Different materials used to make the e-skin, which cater to a multitude of functions, provide it with flexibility and adaptability to address future problems. E-skin made with new materials, such as graphene, represents ongoing innovations aimed at improving its overall performance. The race to use thinner, more flexible materials would ultimately yield greater adaptability in the devices created. High-sensitivity sensors enhance e-skin's tactile sensing, giving the device a more 'human feel'. A flexible, ultrathin material paired with ultra-sensitive sensors embedded in the skin enables real-time monitoring of the subject, thereby improving the quality of e-skin results. With the current rate of development, we are very optimistic that artificial skin capable of fully mimicking human skin will be on the market in the coming years.

Keywords: Electronic skin (e-skin), artificial skin, human-machine interface, prosthetics, nanomaterials, healthcare diagnostics

Introduction

Electronic Skin (E-Skin) is a groundbreaking class of flexible, stretchable, and biocompatible sensors that mimic the tactile, temperature, and pressure-sensing capabilities of human skin. As a human-friendly interface, e-skin enables seamless, real-time, non-invasive, and comfortable on-body monitoring of physiological signals. Electronic textiles, also known as bright garments, smart clothing, smart textiles, or smart fabrics, are fabrics that enable the embedding of digital components such as batteries and lights (including small computers). Innovative fabrics designed by smart textiles, utilising advanced technologies, are beneficial to the end users. As reported by Pailles-Friedman of Pratt Institute, these fabrics perform better than conventional materials.

Smart textiles can be classified into two categories: aesthetic and performance-enhancing. Examples of smart aesthetic fabrics that can produce light and change colour. These fabrics are able to absorb the energy of their surroundings by capturing vibrations, sound, heat and respond accordingly. The integration of electronic devices with the fabric that provides power for lighting and colour change. The smart textiles with performance-enhancing properties

are intended for use in sports and military environments. Ultimately, these fabrics are helpful to regulate body temperature, minimise wind resistance and reduce muscle vibrations. These factors collectively support improving the physical performance.

In one of the studies from Cientifica Research, it was reported that the market scenario of textile-based wearable techniques highlighted key products and the technologies that support their development. These technologies are categorised into three different components as stated below:

Component one: First generation or passive smart textile, which is sensor-based apparel. This technique is presently used by many sports shoe makers such as Adidas, Nike and Under Armour.

Component two: Second generation or active smart textile products, these products with sensor-embedded techniques in the garments are presently used by a few companies, namely Samsung, Alphabet, Ralph Lauren, and Flex.

Component three: Third generation wearables or intelligent textiles, which are garments themselves that work

as sensors, avoiding strains and responding to temperature. The e-textiles may focus in upcoming industries like sports goods, products meant for wellbeing and medical devices. Similarly, the e-skin, also called electronic skin, enables the user to monitor motion, breathing, body temperature, and other medically relevant vital functions. E-skin is machine-washable, highly durable, and as comfortable as a typical shirt. Hence, e-skin has been considered an advanced, fourth-generation textile, or ultrasmart textile. In the biomedical field, artificial skin is known by several other names. In the field of electronics, it is called as electronic skin; researchers and scientists also refer to it as sensitive skin and also call it synthetic skin.

Evolution of e-Skin

- It was reported in the first science fiction works for examination as one of the concept to replace the organs mechanically was by Cyborg by Martin Caidin, published in 1971. This novel later inspired the popular television series *The Six Million Dollar Man* (1974), which centres on a man enhanced with bionic implants, including a mechanical arm and an artificial eye.
- During 1980s, George Lucas visualized an electronic skin in the Star Wars Saga a very famous scene shows that a medical robot fitting Luke Skywalker with an artificial hand capable with sensory preparation, illustrate with an early vision of e-skin concept.
- Again in the 1984, the movie *Terminator* was introduced humanoid robots, including a self-healing one.
- These depictions of e-skin taken place in real-life situations with the advanced research in microelectronics with the integration of science fiction into scientific reality.
- Clippinger *et al* (1974) concluded that sensory feedback from stimulating environment hand prostheses derived from myoelectric control system.
- Again in 1983, Hewlett-Packard (HP) introduced a personal computer (HP-150) with most advanced technologies as touchscreen and intuitive Interface which allowed users to use the screens just by touching and interact with the software.
- General Electric (1985) came out with the electronic skin by using the infrared sensors on a flexible sheet to cover a robotic arm.
- The work done by Jiang *et al* (1990) known as flexible sensor sheet to measure the tactile shear forces which is used to create silicon (Si) micro-electro-mechanical islands by using thin silicon.

Desirable properties for E-skin

Electronic skin (e-Skin) is engineered with characteristics similar to human skin to perceive tactile stimuli and deformation. It's able to adapt to different surfaces with the capacity to detect mechanical forces.

Biocompatibility and Biodegradability: e-skin applications are closely associated with biological systems, *in vitro* testing for devices.

Self-healing: The human body has the capacity to heal and repair the skin after mechanical damage naturally, whereas

this property still requires more research to be realised in e-skin. Bringing natural healing and repairing the human body's skin with artificial e-skin is challenging, yet it would be highly advantageous for practical use. The predominant strategies for incorporating self-healing properties into materials include materials loaded with healing agents and materials containing dynamic reversible bonds. The incorporation of healing-agent capsules was first demonstrated in self-healing and non-conducting polymers. However, for e-skin applications, an electrically active system is required.

Temperature sensitivity: Human skin's ability to sense temperature is a key function that helps to prevent mechanical injury and adapt to the surrounding environment. The majority of tactile sensors are temperature-sensitive; hence, their responses must be prioritised based on performance using a separate temperature sensor. Many groups are producing flexible electronic e-skins that can convey the difference between hot and cold pressure. RTD sensors, made of platinum or gold, are widely used because they are easy to use and compatible with standard electronics. The platinum sections are more accurate (0.03° resolution) over a wider range than other metals.

Self-Power: Providing a long-lasting power supply is a persistent challenge for mobile electronics. The human body is covered by a large area of skin, a major organ that stores energy. There are many promising technologies which have potential in generating of power, transmission and storage in stretchable systems. Sunlight is an abundant power source that can be effectively harvested using various devices with large surface areas.

Dielectric elastomer generators (DEGs) and piezoelectric generators are used to convert mechanical energy into electricity, with DEGs being promised for flexible "e-skin" applications because they are stretchable. A DEG is made of an elastomer film sandwiched between two electrodes, creating a variable capacitor that generates high-voltage power when stretched and relaxed. While DEGs offer high conversion efficiencies, their practical adoption has been hindered by complex electronics, though advancements in self-priming systems are reducing this overhead.

Supercapacitors are meant to store energy with double layers of charged species residing at the electrode-electrolyte interface and to provide very high power. Buckled CNT electrodes on pre-strained substrates have been used to make stretchable supercapacitors that can stretch up to 30%.

Key Characteristics of E-Skin

To integrate comfortably with the human body, e-skin is engineered with several critical properties

- **Flexibility & Stretchability:** Uses elastomers like PDMS or polyurethane (PU) to conform to body movements without damage.
- **Breathability:** Porous structures allow gas exchange, preventing skin irritation and ensuring comfort during long-term wear.
- **Self-Healing:** Inspired by human wounds, some materials can autonomously repair mechanical damage

to restore both structure and electrical function.

- **Biocompatibility & Biodegradability:** Often made from natural materials like chitosan or silk fibroin to ensure safety for medical implants and reduce electronic waste.
- **Self-Powered:** Can harvest energy from the environment via triboelectric or piezoelectric effects, eliminating the need for bulky batteries

Highly integrated electronic skin devices

As discussed above, various technologies have the potential to integrate mechanical sensor arrays with multiple functionalities. There are a number of advanced technologies which are described below based on their capabilities in the field of biomedical devices, robotics, and optoelectronics.

Biomedical Devices

The electrode arrays demonstrated to measure the electrical activity in heart and brain. These arrays which are compliance with mechanical arrays are essential to achieve and confirmed interactions with of irregular shaped organs

Raw materials for e-Skin: These can be classified as follows

- Degradable fibers are those which can be absorbed by the body within two to three months and include natural fibers like alginate, chitin, chitosan, collagen, and some protein fibres like casein
- Non-degradable fibers are those that take more than six months to degrade and be absorbed by the body. They include synthetic fibres such as polyamide, polyester, polypropylene and PTFE (Poly Tetra Fluoro Ethylene).
- Resorbable fibers are those which are fully biodegradable, produce no harmful degradation products and are entirely absorbed in the body. These include materials obtained from polymers such as Polydioxanone (PDS), Polyglycolic acid (PGA), and Poly Lactic Acid (PLA). It takes a few weeks for implants to be fully absorbed.

e-Skin Technologies

Bio-stamp technology: is used for high-performance silicon which stretches up to 200 per cent and also monitors temperature, hydration and strain with 360-degree proximity sensor.

Nano-wire-Sensitivity: large-area electronics by printing semiconducting nanowires onto plastics and paper.

- Nanowires have excellent electron mobility,
- Electromagnetic coupling technology,
- A flexible and transparent electronics sheet of about eight thousand transistors using vertical nanowires of zinc oxide.
- The transistor has the capacity to convert mechanical motion into signals that are electronically controlled.

Organic Light Emitting Diode: a conductive, pressure-sensitive rubber material, organic light-emitting diodes (OLEDs) and thin-film transistors made of semiconductor-enriched carbon nanotubes to build an array of pressure-sensing, light-emitting pixels and is fabricated on a silicon surface.

- The light responds to the hard surface under pressure.
- Semiconductor-based transistors integrated with

flexible silicon to stimulate human skin.

A microfluidic skin with a simple bilayer membrane design can produce a constant sweat density that mimics human skin texture and pore size, enabling rapid, repeatable testing for skin-wearable devices.

- The efficient bilayer design helps in providing pore density similar to sweat pores in skin and uniform flow from all pores at low flow rates associated with sweating.
- A simple gravity approach similar to an intravenous drip bag is used as a pumping mechanism to supply constant fluid at a very low flow rate for continuous perspiration stimulation.

3D skin equivalents made from IPSC-derived keratinocytes and fibroblasts: potential use in skin reconstruction, such as postsurgical skin treatment and wound healing.

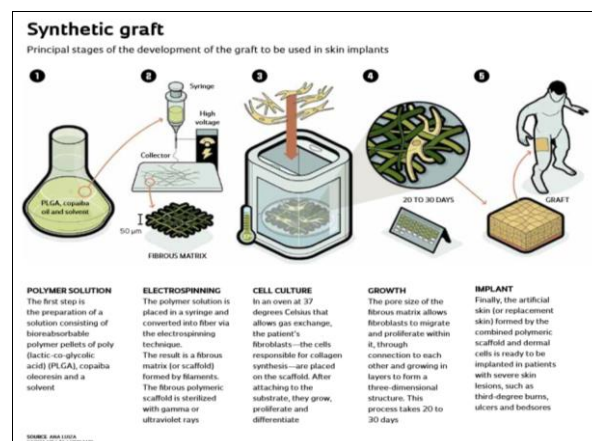
Dermal substitutes: commonly made from collagen or fibronectin that are impregnated with human fibroblast and/or keratinocytes to accelerate the wound healing process.

- An elastin-based scaffold was proposed as an alternative to a collagen-based scaffold for dermal substitute application since it has the potential to significantly improve the outcomes of severe burn injury treatment by reducing wound contraction and severe scarring and shortening the wound healing period.
- Most commonly used natural skin substitutes with allogenic cells

Core Sensing Technologies

E-skin utilises various mechanisms to convert external stimuli into electrical signals:

1. **Piezoresistive:** Changes in resistance due to pressure or strain; highly sensitive and widely used for joint and pulse monitoring.
2. **Capacitive:** Measures changes in charge storage; known for high linearity and used in fine tactile sensing.
3. **Piezoelectric/Triboelectric:** Generates voltage directly from mechanical stress or friction; ideal for dynamic sensations like vibrations and self-powered operation.
4. **Multi-functional:** Advanced systems can simultaneously detect temperature, humidity, and chemical markers (e.g., glucose or pH in sweat).



Transformative Applications

- **Personalised Healthcare:** Continuous monitoring of vital signs (heart rate, blood pressure, respiration) and real-time wound monitoring without bulky equipment.
- **Advanced Prosthetics:** Restores a sense of touch to amputees, providing feedback on texture, pressure, and temperature to improve manual dexterity.
- **Robotics:** Gives robots a human-like sense of touch, enabling safe interaction in shared workspaces and the handling of delicate objects.
- **Human-Machine Interfaces (HMI):** Enable gesture-based controls and seamless interaction with virtual and augmented reality.

Future Outlook: AI Integration

The next frontier for e-skin involves tight integration with Artificial Intelligence. Researchers are developing neuromorphic e-skin that generates brain-compatible signals, allowing direct communication between the device and the human nervous system. AI algorithms further enhance this by performing real-time data analysis for predictive health monitoring and complex pattern recognition.

Conclusion

- The technologically advanced electronic devices must be handy to carry with utmost usability. Researchers or scientists are able to develop artificial skin that is capable of tactile.
- Artificial skin is an advanced sophisticated technology which makes human life better.
- We can predict a patient's oncoming heart attack hours in advance. In future, even virtual screens may be placed on devices to monitor our body functions.
- To date, there is no artificial skin that could completely replace the actual human skin.
- However, with the recent progress shown, we are on the right track to produce a reliable and robust artificial skin/e-skin for general and specific usage.
- The current skin substitutes used for grafting are usually combined with autologous skin to produce better cosmetic and functional results.
- Efforts are being taken to reduce the recovery time and degree of pain in patient who undergoes skin grafting.
- Recent development is very positive as the healing time, functionality of the skin post-surgery and severity of scarring are greatly improved.
- E-skin represents our advancement and futuristic way of tackling the human skin mimicking problem.

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