Biocompatible Soft Conductor for Electric-tactile Haptic Interface

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Abstract

Purpose of the study: Haptic technology, which can qualitatively expand virtual or augmented reality experiences beyond the sensation of the ear and eye, is realized by electrical and mechanical stimulation of afferent nerves or mechanoreceptors. In this review, researchers highlight the biological basis for sensation and suggest the advanced direction in the electric tactile-based haptic system using low impedance materials.

Methodology: Conductive polymer called "Poly(3,4-ethylenedioxythiophene): poly(styrenesulfonate) (PEDOT:PSS)" was examined for chemical properties and biocompatibility.

Main Findings: Study of PEDOT:PSS shows the superior property in terms of deformability and electrical performance for developing the low-impedance, skin-like haptic interfaces.

Implications: To provide wear- comfort, skin-like technologies that impose a negligible physical burden on the user should be used. The mainstream of haptic technology involves the development of a system that could provide myriads of sensations to the skin through not only to the fingertips but also to some or all regions of the body.

Novelty: Researchers also provide the strategy to impart skin-like property as well as low impedance using hydrogel polymer which is desirable in wearable haptic systems.

INTRODUCTION

Bioelectronic materials for the haptic system have been researched for many years to achieve electrically and mechanically stable interfaces enabling recording or stimulating the neural interface and skin (Athukorala et al, 2021). To achieve these functions, material research is needed to translate current skin-haptic interfaces into a low-impedance technology in which stiff metallic electrodes are replaced by more biocompatible and soft electrodes. In other words, advancement in electrode architectures is needed to match the mechanical and electrical properties of wearable devices with those of skin. Therefore, several concepts and techniques from flexible and wearable electronics have been adapted to skin-like haptic interface applications.

Conductive polymers (CPs) such as PEDOT:PSS, Polyaniline (PANI), and Polypyrrole (PPy), which have both mechanical flexibility and high conductivity, have been promising materials for wearable electronics. These properties originate from the conjugated nature of their backbones and to subsequent display of polaron and bipolaron structure representing singly and doubly charged quasiparticles. Besides, CPs offer excellent properties to improve electrode/tissue interface. Wearable electrodes fabricated by CPs have extremely lower impedance than inorganic electrodes such as Au, Ag, Ni and Cu due to their combined ionic-electronic conductivity. (Athukorala et al, 2021).

In addition, CP-based electrode minimizes the mechanical mismatch between electrode/skin interface, allowing a long-lasting functional skin interface (Fan et al, 2019) with diminished biofouling due to its biocompatibility (Lu et al, 2019). When CP is coated on thin flexible films of polyimide or parylene, the thin and flexible electrodes have conformal contact with the curvilinear region of any body parts (Schander et al, 2016). However, it is still challenging to achieve both superior electrical performance and skin-like modulus simultaneously due to the relatively high modulus of CP compared to that of skin.

Hydrogel, which shows both high stretchability and low modulus property, have been researched for bioinspired materials. Lim et al. propose a skin-device interface with tissue-like features, formed by using an ultrathin type of a functionalized hydrogel. They showed the functionalized hydrogel film based on poly(acrylamide) (PAAm), which can form a stationary quasi-solid but moisturized interface between the wearable bioelectronic device and human skin (Lim et al, 2021). However, the intrinsic conductivity of hydrogel is very low to operate the entire wearable electronic system.

In this research, we have performed a systematic review of biocompatible functional materials for skin-like haptic interfaces. We have provided the advantages of conventional PEDOT:PSS polymeric material used as a low impedance electrical stimulator and hydrogel to lower the modulus of polymeric materials for minimizing the mechanical burden on the skin. For this review, we categorized the three materials as shown in below.

- PEDOT:PSS: conventional polymeric materials for low impedance electronics

- Hydrogel: Tissue-like low modulus materials for bioelectronics
- PEDOT:PSS hydrogel composite: Composite materials consisting of PEDOT:PSS and hydrogel.

PEDOT

Chemical basis

Poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT: PSS) is an organic conductor consisting of positively charged PEDOT imparting electrical conductivity and negatively charged insulating PSS. PSS polymer anions can stabilize polymer cations in water and some polar organic solvents. Currently, PEDOT:PSS aqueous solution is a commercially available product with different electrical properties, such as Clevios PH500, PH1000, Clevios PVP CH8000. The chemical structure and morphology of PEDOT:PSS are demonstrated in Figure 1.

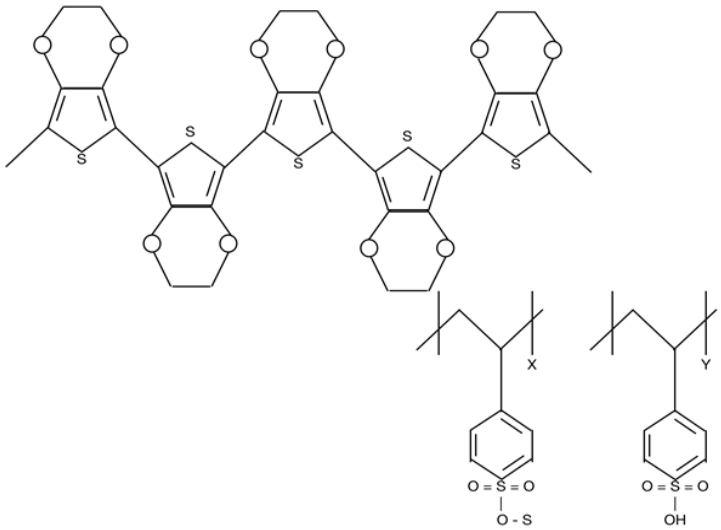

Figure 1: Chemical structure of PEDOT:PSS

The insoluble PEDOT short chain is well attached to the negative-charged PSS that has a long polymeric chain so that it can be steadily dispersed in water. The grain size of 30–50 nm is composed of numerous tangles, and each tangle is made of a single PSS chain with several PEDOT segments. PEDOT chains may interact with each other through p-orbital interactions in the core region. Moreover, hydrogen bonds are formed through HSO_3 groups between the PSS shells, which provides robust chemical bonding to each other.

To improve the electrical conductivity, secondary doping and post-treatment with acid have been researched by removing the excess insulating PSS, leading to phase separation, or inducing morphological re-arrangement. Polar solvents such as DMSO, ethylene glycol, and ionic liquids can largely increase the electrical conductivity of PEDOT:PSS films.

Biocompatibility

Generally, the term ‘‘biocompatibility’’ is defined not only by the lack of cytotoxicity of a biomaterial but also by the bio-functionality of the material that allows high-quality and compatible interfaces between biotic–abiotic interactions where the biomaterial is applied. The research of biocompatibility in biomaterial is important, especially in the field of a human-friendly electronic system such as a wearable haptic device which requires in vitro experiments to test the local and systemic effects of the material on the whole body. Compared with other metallic materials, PEDOT:PSS is a promising material for biomaterial due to its well-known biocompatibility.

However, the two components of PEDOT:PSS are limited due to not only the lack of functionality of PEDOT but also the low biocompatibility of PSS. To overcome this issue, much effort has been devoted to designing innovative poly(dioxythiophene) polymers containing different functional groups for improved biocompatibility. A demonstrated strategy to enhance biocompatibility and reduce cytotoxicity is the utilization of biomolecules as dopants. Thus, the incorporation of biopolymers could be the way to overcome the limitation of PEDOT:PSS dispersions for the skin-like haptic interface.

The strategy to synthesize PEDOT doped by biopolymers is electropolymerization of EDOT in the presence of biomolecules (heparin, hyaluronic acid, fibrinogen, gellan gum, carboxymethyl cellulose, xanthan gum, pectin and gellan gum). (Thaning et al, 2009) The functionalized PEDOT shows non-toxicity (Asplund et al, 2009) and the potential to serve as electrode interfaces for skins. Inspired by this strategy, different water-based PEDOT: biopolymer dispersions have been more recently synthesized by different groups using chemical polymerization. By using this technology, we could provide human-friendly haptic systems fabricated by biocompatible PEDOT electrodes on our bodies without any irritations.

HYDROGEL

Chemical basis

Another material to reduce the impedance of electrodes in wearable devices is a hydrogel. Hydrogel is a three-dimensional (3D) network of hydrophilic polymers that can swell in water and hold a large amount of water while maintaining the structure due to chemical or physical cross-linking of polymer chains (Figure 2). The ability to absorb large amounts of water or biological fluid in the body originates from the presence of hydrophilic groups in the hydrogel structure (Sharma, 2020). The hydrophilic functional groups in the main polymer chain of hydrogel include the hydroxyl groups (OH-), carboxyl (COOH-), amine (NH_2), and sulfate (SO_3H) (Fu et al, 2020).

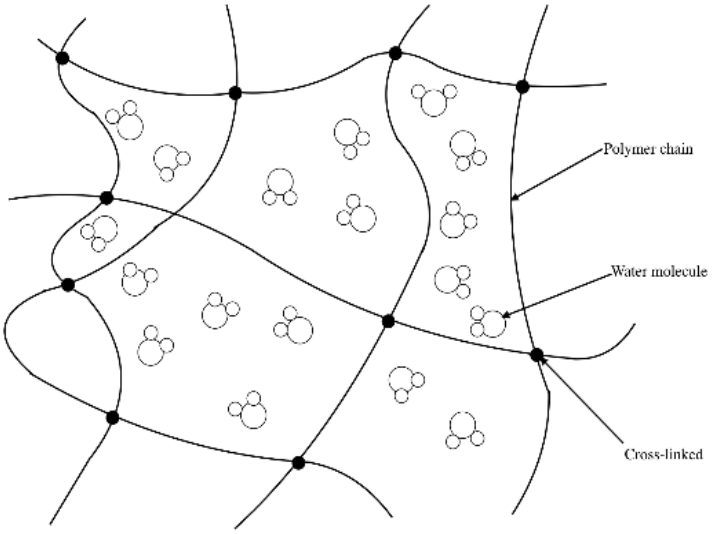

Figure 2: Schematic showing structure of the hydrogel

Hydrogel also possesses a degree of deformability very similar to living tissue due to its significant water content. The hydrogel could undergo a significant volume change or gel-sol phase transition in response to certain physical and chemical stimuli. The physical stimuli include temperature, electric fields, solvent composition, and pressure, while the chemical stimuli include pH, ions, and specific chemical compositions. However, conformational transitions are reversible in most cases; therefore, the hydrogels can recover their initial state after a reaction as soon as the trigger is removed. With this tissue-like material that contains softness, deformability, and chemically biocompatibility, skin-integrated haptic electrodes could provide wear-comfort, low impedance for stimulator and robustness under movements of the body.

Ionic conductivity

A key property of hydrogel is the ionic conductivity due to its porous network that allows the transport of water and small molecular solutes. As we mentioned above, hydrogel could undergo volume change as it absorbs the water or fluid due to its hydrophilicity. When the molecular solutes flow into the hydrogel, the conductivity of hydrogel is enhanced due to the increase in ionic conductivity. Since sweat is present on the skin most of the time, the hydrogel is very suitable to be applied on the wearable device. Sweat is also known as perspiration and consists of water with tiny amounts of other chemicals like ammonia, urea, salts, and sugar. These biomolecules could impart ionic conductivity to hydrogel by penetrating the polymer structure.

PEDOT/Hydrogel composite for haptic application

Conductive polymer-based hydrogel contains the characteristics of both hydrogel and conducting polymer, which allows a high-quality interface between electronic stimulator and skin. The structure of PEDOT/Hydrogel composite is illustrated in Figure 3. The polymer/hydrogel composite shows multidimensional characteristics such as the transport phenomenon of charges, ions, and molecules due to the intrinsic 3-dimensional microstructure in a conducting framework. Thus, the most intrinsic characteristic of this conducting hydrogel is the combination of electro-activity given by the conducting polymer and the ionic conductivity given by the aqueous media (Han et al, 2018).

It is easily fabricated into a thin film with various shapes using a mold. The major advantage of the composite is that any target design with biocompatibility and self-adhesive properties in the skin can be achieved via micro-patterning through the screen- or inkjet printing (Teo et al, 2019). The selection of electrode materials for an electric tactile-based haptic system depends on the trade-off between the homogeneity of current distribution applied to the skin and the conductivity of the electrodes. High conductivity brings a less homogeneous current distribution to the skin, while low conductivity can lead to high voltages at the stimulation electrode. Further optimization in the conductive hydrogel consisting of PEDOT:PSS and hydrophilic polymer network is needed to realize a desirable haptic system with light-weight and wear-comfortability in the future (Yang et al, 2020).

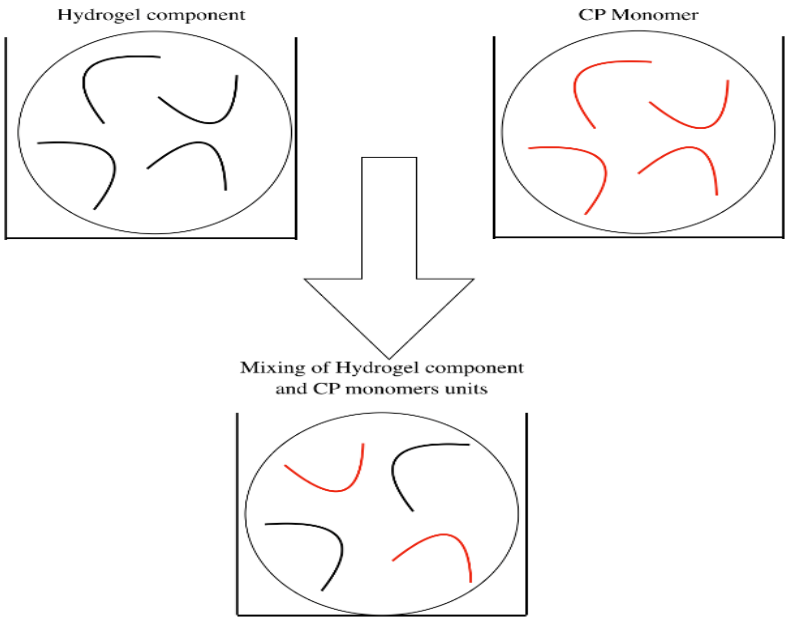

Figure 3: Schematic showing PEDOT/Hydrogel

CONCLUSION

Wearable haptic systems have been researched in many aspects of research such as materials, electronics, and mechanics. Besides visual and auditory senses, our experience could be expanded to all our bodies by using the sensory feedback of the haptic system. To bring the full experience of the haptic system, many researchers have searched for materials with high conductivity and high deformability. We review the two promising polymeric materials for electric tactile-based haptic systems. 1) PEDOT:PSS and 2) Hydrogel.

Among organic materials, PEDOT shows relatively stable performance to air and moisture and is also chemically and thermally stable. Moreover, its intrinsic flexibility allows haptic systems to be fabricated in wearable form. Hydrogel, which is a cross-linked polymeric network that contains a large volume of water within the porous structure, has long been used in biomedical applications. The polymeric network imparts properties of a solid to hydrogel as it can be easily molded and structured into various shapes, while the water content allows liquid-like characteristics.

PEDOT:PSS/Hydrogel composite, a mixture of the above two materials, is a promising material that provides a synergistic effect of both materials. In the haptic electronic system, hydrogel imparts mechanical softness and PEDOT:PSS provides a percolative conductive pathway in the composite matrix. With this material strategy, a mechanically soft electric-tactile-based haptic system could be developed in the future.

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