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Research Article

SELF-POWERED WEARABLE ELECTRICAL STIMULATOR USING TRIBOELECTRIC METHODS FOR HAPTIC INTERFACE

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Abstract

Recently, many wearable haptic systems have been researched in many groups. Tactile sensation offers important information in virtual reality and augmented reality systems. Typically, mechanical, electrical and thermal stimulations are applied on to skin. Therefore, these wearable stimulators must be light-weight, comfortable to wear, and reliable for long-term use to achieve full experience of tactile sensation. This report provides the device strategy of wearable haptic system using triboelectric nanogenerator to impart a self-powered, painless, and highly sensitive electro-tactile (ET) system for virtual tactile experiences. Furthermore, this report discusses details about a principle of triboelectric generation and each component of overall device including charge-generating layer, charge-trapping later, and charge-collecting layer. To show the potential of triboelectric-based haptic system for wearable device application, we explore the stretchable, skin-conformable materials which allow the wearable electronic system to be properly operated under dynamic environment of body. In addition, the mechanical and electrical properties of these materials under deformed condition will be examined.

Keywords: Haptic, Light-weight, Triboelectric, Self-power, Wearable electronic system.

INTRODUCTION

Virtual reality (VR) and augmented reality (AR) systems are becoming a sensational field because of their high accessibility, function, and universality. These systems combine both natural and interactive virtual environments materialized by haptic, audio, and visual feedback to construct the enhanced reality system. Further development of this technology in various applications, including immersive entertainment, remote control, and physical therapy, has the potential to influence multiple fields such as wearable electronics, bio-electronics. However, rigid form factor of current haptic devices has hindered compatibility and usability with dynamic movements of human. Although various soft materials have been studied to improve wearable haptic devices applicable to everyday life, devices composed of materials with much higher compatibility with the human body are needed to provide a much natural VR/AR experience. The triboelectric nanogenerator (TENG) (Bera, 2016) is a newly developed strategy to operate haptic system by harvesting electrical energy from mechanical movements (Yu *et al.,* 2019). Triboelectric generation for electrical system has been widely researched as energy harvesters for mechanical energy scavenging, ranging from natural energy such as wind (Bae *et al.,* 2013) and blue energy (Liu *et al.,* 2020) to the biomechanical energy of human body. Thanks to its exceptional output performance, wide material choices, good scalability, simple fabrication, and low cost, triboelectric generator has been highlighted as a next-generation haptic device system. Considering the kinetic energies generated from the daily lives of humans including hand motion and joint rotation, the nanogenerators can collect motion-induced energies enabling a fully self-powered system for wearable haptic interfaces. Basically, the haptic interfaces induced by TENG are related to electric-tactile stimulation. Electric-tactile stimulation is very promising technology to achieve large scale production of wearable haptic device with low- cost fabrication (Kim, 2022). The control of electrical charge transfer via triboelectric device could realize the electric tactile-based wearable haptic system. The research of applying the triboelectric principle to wearable haptic system begins from the understanding of triboelectric generation and developing the device into deformable form factor. In this article, we review potential applicability of triboelectric generator to wearable haptic system. First, we show the fundamental principles and types of triboelectric generation as well as important basic structure of devices. Secondly, we organize candidate materials to develop deformable triboelectric generator. Specifically, various soft materials will be discussed as they can provide long-term stability and superb performance in wearable electronic devices under various deformations. Moreover, we will examine the requirements and properties ofsoft materials for electrode, charge-generating layer, and charge-collecting layer.

In the future, the resolution of haptic stimulation will become a critical factor since there are many types of information. We present the future direction of wearable triboelectric devices in terms of fabrication and entire design of haptic system application with a discussion of current hindrances.

Triboelectric generator

Typically, the triboelectric nanogenerator has two basic operation modes: vertical contact-separation mode and in-plane sliding mode as shown in Figure 1. They have different characteristics and are suitable for different applications.

Vertical Contact-Separation Mode

The basic mechanism of the triboelectric generation is described as the periodic change of the potential difference

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induced by the repetitive contact, separation, and re-contact of the opposite triboelectric charges on the inner surfaces of the two sheets (Figure 1). When a mechanical stress is applied onto the device such as bending or pressing, the contact surfaces of the two sheets move closer toward each other and the charge transfer begins. Each side of the surfaces becomes positively charged and negatively charged, respectively. When the deformation is released, the two inner surfaces with opposite charges separate and generate an electric field in between sheets, inducing a potential difference across the top and bottom electrodes. With this electrical driving force, the electrons flow from one electrode to the other electrode. The power generated in this process continues until the electrical potentials of the two electrodes recover into same. When the two sheets are subsequently pressed towards each other again, the triboelectric-charge induced potential difference decreases to zero. Then, the transferred charges flow back through the external load, generating another current pulse in the opposite direction. When this periodic mechanical deformation occurs continuously, the alternating current (AC) signals is continuously generated, providing powers to the external system.

Sliding Mode

We demonstrate TENG that is designed based on the in-plane sliding between the two surfaces in lateral direction in Figure 1. With sliding friction, a repetitive change of contact area between two inner surfaces leads to current flow by charge-induced electrical field, creating a voltage drop in the flow of electrons. The mechanism of sliding-induced electrical generation is schematically depicted in Figure 1. In the original position, the two inner surfaces of sheets fully overlap and contact with each other. Because of the large difference in the capability to attract electrons between the two sheets, the triboelectrification allows one surface with net positive charges and the other with net negative charges. An induced-charges are located only in the surface layer of an insulator without any leakage out to external electrode for an extended period of time. The separation between the positively charged surface and negatively charged surface is negligible at this overlapping position. Thus, there is no potential drop across the two electrodes. When the top sheet with the positively charged starts to slide outward, the in-plane charge separation is initiated due to the decrease in contact surface area. The separated charges generate an electric field, inducing a higher potential at the top electrode. This potential difference can generate current flow from the top electrode to the bottom.

Material design for haptic application Electrode

Recently, stretchable electrodes have been researched in many research groups for emerging field of skin-inspired electronics, biocompatible electronics, and soft robots, as well as conformal human– machine interfaces (Jung *et al.,* 2021). In the future, wearable device system that are integrated into our clothes and accessories, attached to our skin, and even implanted in our bodies could be realized. To develop such wearable devices, stretchable electrode is a key component for operating entire system in dynamic movements of human body. The demand of stretchable and conducting electrode has led to extensive research in nanomaterials such as carbon nanotubes (CNTs) (Wang *et al.,* 2019), graphene sheets (Das *et al.,* 2018), metal nanowires (Zhang *et al.,* 2021), organic films (Cao *et al.,* 2014), and their composites (Park *et al.,* 2014). CNTs, the tube-shaped carbon materials, were first reported as flexible transparent electrodes and have since been extensively explored for flexible or stretchable electronics, including deformable energy storage devices and skin-like electronics. The alignment of spring-like CNTs has rendered simultaneous achievements of high stretch ability and high conductivity with high stain (Downes *et al.,* 2014). Unlike metal-based nanomaterials such as Ag, Cu, and Au nanowires, CNT networks, however, cannot exhibit high electrical conductivity, limiting their further applications in complex and large-scale wearable electronics. Currently, many studies on solution-processed metal (Ag, Cu, etc.) nanowires have been reported, leading to much easier and cheaper fabrication of metal-nanowire-based wearable haptic system (Wang *et al.,* 2021).

As a one-atom-thick 2-demensional material with excellent mechanical and electrical properties, graphene shows great potential for flexible or stretchable electronics (Kumar *et al.,* 2019).The electrodes made of graphene films show superior mechanical bendability, making graphene as a promising candidate for flexible touch pads. Graphene sheets can also be stretchable. Previous work has shown that graphene films could be grown in large-scale by chemical vapor deposition method (Muñoz *et al.,* 2013). The synthesized graphene film can be stretched up to 30%, and long-term stability of the film under repetitive cyclic stretching has been shown. Another widely used material is an organic film. Poly (3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) is a popular material that has deformability and conductivity (Mantione *et al.,* 2017). With a simple spin coating method, PEDOT: PSS films show a superior electrical conductivity. Thin PEDOT:PSS films are stretchable, and have been widely used in polymer-based light-emitting diodes (PLEDs) as well as organic solar cells. Recent advancement in these promising materials and various optimization strategies brings the realization of high-performance stretchable triboelectric device closer to everyday life in the future.

Charge-generating layer, charge-collecting layer

Almost all materials including wood, polymer, metal, and silk have triboelectric effects. According to the operating principle of TENG, all of those materials can be used as the friction layers of TENGs. However, not every pair can produce high output. In the material aspect, high output is strongly dependent on the polarity difference of charge-generating and -collecting materials. As shown in Figure 2. The closer the material is to the bottom of the sequence, the easier it is to obtain electrons with negative charge. In contrast, the closer the material is to the top of the sequence, the easier it is to obtain positive electricity, meaning losing of electron. Basically, proper selection of two materials is very important to obtain high output performance according to the application field. Therefore, material selection is the first step for the fabrication of TENGs. When we select a pair, the charge characteristics and the output characteristics of the TENG could be expected. To provide the deformability, rigid materials such as metallic components (Au, Cu) could be mixed with elastomer. Other polymeric materials could be used for flexible triboelectric layers.

Future direction

In thefuture, we anticipate that there will be a significant advancement in the wearable haptic system if the triboelectric technology to be improved in this field. In fact, the newly developed wearable triboelectric devices act as a complementary or even indispensable part of the energy field for self-powered electronics as well as deformable haptic system. To impart stretch ability with multifunctionality in wearable haptic system, deformable materials and its optimization process need to be established first. Also, the long-term stability in deformed condition and humid environment is an additional property required in next-generation wearable haptic system. If all the layers of triboelectric device could be realized in deformable form, intrinsically stretchable and self-powered haptic platform for next generation wearable haptic interfaces could be achieved.

Conclusion

Conventional haptic technology using rigid and bulky devices have many limitations in wearable applications such as low wear-comfort and easy failure under body movements. In this study, we address the principle of triboelectric generation and its potential of application to wearable haptic system. The triboelectric generator can enhance the virtual haptic interfaces using electrical tactile stimulation, while it is fabricated into deformable form factor. TENGs with various operation modes and structural designs have the potential to realize soft and stretchable haptic system, which is the most prominent feature of TENGs to make a breakthrough in current haptic technologies. Therefore, it is extremely valuable and challenging to further investigate new materials that exhibit both high triboelectric properties and compatibility with wearable applications. With a current speed of developments and researches in the fields of chemical, electrical, and material engineering, it is very promising that significant advancement in wearable haptic system is in the near future for practical use of haptic system in our daily lives.

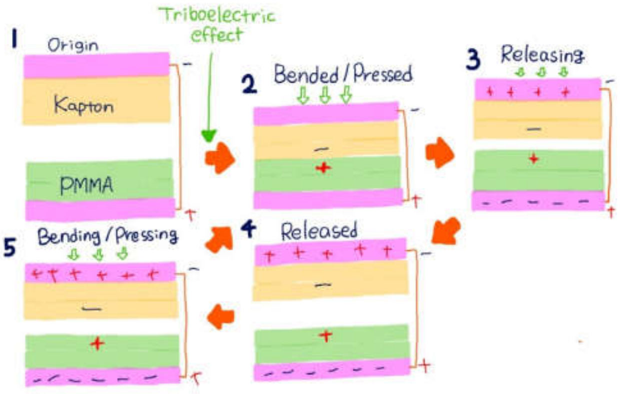

Figure 1. Principle of triboelectric in contact mode

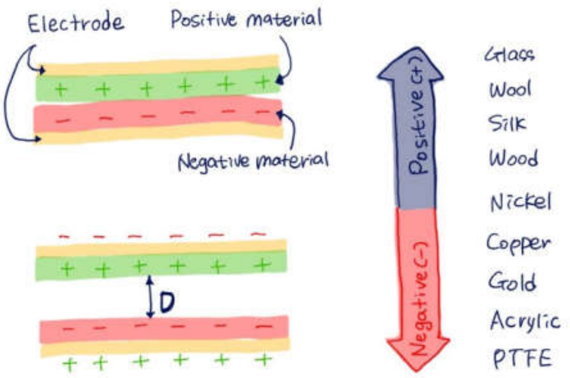

Figure 2. Charge affinity of different materials

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