# Wearable Haptic Interfaces and Systems

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**Abstract—**The past two decades have seen significant advances in how users interact with machines. Yet nowadays, people are increasingly paying attention to developing new control terminals and interfaces regarding communication between humans and robots, special equipment, or the virtual world. Wearable haptic interfaces offer more comfortable and realistic interactive experiences in human-machine touch and satisfy people's needs beyond simply controlling objects. They are now applied in various areas, including health, education, virtual reality, object detection, etc... The passage briefly introduces some familiar wearable haptic interfaces, including hand-worn, vest-worn, and foot-worn devices. And then the advantages and disadvantages of the mentioned wearable devices will also be discussed. This passage will provide an overview of the current technology in wearable haptic interfaces and help people understand the strengths and weaknesses of the devices for different body parts.

## 1 Introduction

Wearable haptic systems are wearable tools for human-computer interaction, and their appearance is a huge step forward. For example, A robot is controlled as an enslaved person in a remote scenario. A haptic interface feeds back the registered contact forces at the master side, enabling the user to perceive the remote environment [1]. However, they are usually not wearable and unportable. Undoubtedly, it does not meet the need for portability in everyday life.

Wearable haptic interfaces can communicate with human wearers while interacting with the environment they share in a natural yet private way [2]. Various devices have been developed called "Wearable" to achieve naturalness and privacy in human-computer interaction. Compared to traditional contact interfaces, wearable interfaces enhance the human-computer interaction experience, improving the ease of interaction while breaking down spatial constraints. This undoubtedly gives wearable haptic interfaces a vast potential for development. This also means that wearable haptic interfaces have a wide range of applications. Applications in clinical human diagnosis, health evaluation, health monitoring, virtual electronics, flexible touchscreens, flexible electronic skins, and even industrial robots have a lot of potentials.

To this end, several new devices have been developed called wearable devices. The first aspect is that it can be used in healthcare. Prosthetics, for example, can restore certain behavioral functions to patients, but haptic restoration has not yet been possible. The advent of haptic sensors may offer a new perspective on restoring haptic sensation in amputees. In 2015, researchers at Cleveland's Case Western Reserve University, Ohio, gave a prosthetic hand a sense of touch by attaching pressure sensors to the peripheral nerves of the arm. In 2018, a Stanford University team developed an almost entirely transparent and flexible sensor. The sensor can even clearly perceive the "touch" caused by a fly or a butterfly resting on its surface. The second aspect is that it can be used in portable electronic devices. In recent years, wearable haptic sensing devices have been developing rapidly with continuous breakthroughs and innovations in technologies related to flexible electronics. They can mimic the tactile function of human beings in direct contact with the external environment, enabling the detection of force signals, heat signals, moisture signals, etc... They are the nerve endings of the Internet of Things and the core components that assist humans in fully perceiving nature and themselves. In either application, the system is connected to the skin.

To this day, wearable haptic interfaces have not yet made their technological achievements available to society. Additionally, wearable technology's haptic stimuli are still only vibrations, with no way to simulate rich touch interactions. Toward a more realistic feeling of touching virtual and remote environments, researchers have historically focused on grounded haptic interfaces, such as the Sigma or Phantom devices, and glove-type haptic displays, such as the Cyber Grasp or the Rutgers Master. Although these devices provide compelling force sensations, they are complex and expensive [2]. However, this does not affect the vast potential of the wearable tactile interface and the broad market in the future.

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This article focuses on three important developments and applications of wearable haptic interfaces, including hand-worn haptic devices, vest-mounted tactile devices, and foot-worn tactile devices. First, the mechanism of hand-worn haptic devices is described. Second, how vest-mounted tactile devices work is described. Finally, how foot-worn tactile devices work is described. The characteristics and feasibility of the three technologies are compared, and the future of wearable haptic interfaces is predicted.

## 2 Hand-Worn Haptic Device

Nowadays, smart gloves are one of the most common hand-worn haptic devices and are often used as a new kind of human-machine interface (HMIs) that is widely applied in virtual reality since wearable glove-based HMIs. Compared to other types of traditional interfaces, they have the advantages of possessing multiple degrees of freedom control and relatively high accuracy. There has been much research on the design, fabrication, and computing of bright gloves to achieve a better motion-detecting ability and lower the cost of mass production. One of the most impressive results is the haptic-feedback smart glove with haptic-feedback using palm sliding sensors, piezoelectric mechanical stimulators, and triboelectric-based finger-bending sensors [3]. It consists of electric tactile sensors based on the elastomer, a piezoelectric transducer, and a piezoelectric robotic haptic simulator (Figure 1). A glove container (Figure 1i) is placed, housing the sensors and mechanical stimulators to detect motions from different dimensions and offer the user real-time haptic feedback. The finger-bending sensors can feel the movements of each finger bone from different angles, and the palm sensor can detect both the shear and normal force in eight directions (Figure 1, I to v). Different motions can generate other electric signals (Figure 1, ii, iv), thus allowing the device to distinguish between movements in different directions.

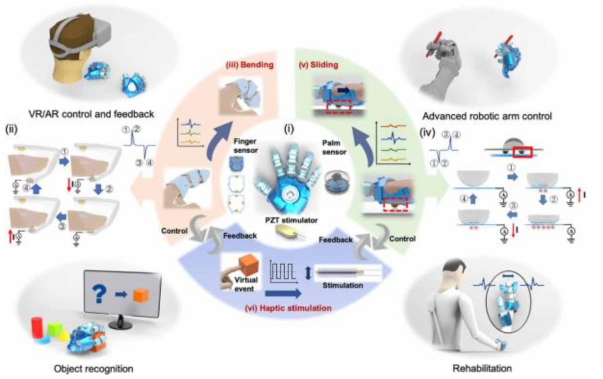


**Figure. 1.** Diverse applications of bright gloves in different areas. (i) Three central functional units [3].

The haptic-feedback smart glove has many possible applications. For instance, it can be used in VR/AR for advanced robots to perform complex tasks such as object recognition. Also, the proposed glove will help with the recovery of disabled patients through the close supervising of the rehabilitation activities by advanced joint manipulation, where the real-time impact event can also be immediately returned to the user thanks to piezoelectric haptic stimulation (Figure 1, vi) for improving our sensation and retaliating those weakened senses in indirect interaction [3].

The hand-worn haptic devices must be able to detect multiple motions while still allowing the flexibility of the hands of the users. One of the most important elements to achieve this goal is the clutch. Clutches are one of the most important elements for motion detection and suppression in haptic clothing, and electrostatic clutches are small and have a limited weight, making them especially suitable for wearable systems. Many reported wearable clutches have been invented, including a high density of force textile-based clutch [4]. It generates frictional shear stresses of about 20 N·cm at only 300 V, a stress level over ten times higher than almost any other clutches, and approximately 90 times stronger than textile-based electrostatic clutches. The fundamental principles of an electrostatic clutch are shown in Figure 2.

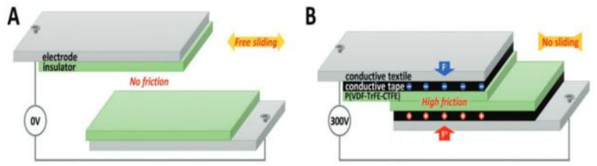


**Figure 2.** (A) With a voltage of 0 V applied between the electrodes, the electrostatic clutch is free to slide. (B) The blocking state where the textile electrostatic clutch has 300 V applied between the electrodes, pulling the upper side and the lower side to each other [4].

The high-force density textile-based clutch is highly flexible and light, so it is highly suitable for wearing and hand movement and can adapt to different body shapes. Also, the engaging and disengaging time of the clutch is relatively short, with the time of release ranging from 5 to 15 ms, which meets the basic requirements of a wearable haptic device. A unique material with very high permittivity was chosen to achieve a high frictional sheer stress.

## 3 Vest-Worn Haptic Device

Vest-worn haptic devices provide users with a sense of a virtual environment (VE) via tactile and thermal inputs. There are primarily two types of actuators in haptic vests: A vibratory tactile actuator that gives the user the impression of being in a virtual environment; a thermoelectric actuator: that simulates the temperature change in the VE to make the user experience more real [5]. The pain-free temperature ranges from 15 to 45°C, depending on the physical condition, and the thermal stimulation created will be in this range. A haptic vest can bring users the experience of a multimodal virtual environment consisting of video, audio, and haptic feedback, making the perception of the VE more realistic.

To better assess the benefits of tactile vests in VE, the researchers designed an experiment that divided participants into three groups: tactile experts, technical experts, and non-experts. The experimental scene is the VE of the railway station after the explosion. By allowing the subjects and the VE to have tactile interaction and temperature experience, the influence of tactile equipment on experience is evaluated. Most users agreed that the tactile vest helped better understand the VE, and thermal stimulation helped more than tactile stimulation because it was more similar to real sensations. Although some participants felt that the tactile vest was not beneficial to the virtual environment experience, this was due to the mismatch between the events in the VE and the tactile response and the inaccurate temperature of the back. This is also an area that needs improvement to make the tactile vest a better user experience. In general, a haptic vest can better help users experience the VE. With the help of a haptic vest, most of the events happening in the VE can be recognized by users.

Vest-worn haptic devices can be used in tactile interaction for kinesthetic learning systems. Tactile interaction for kinesthetic learning systems can be used in teaching in the medical field. It corrects the user's movements by analyzing the difference between the standard and the movements and providing vibratory tactile feedback to multiple joints. Students can learn new motor skills faster and more deeply through this system. People in recovery can also use it to achieve faster and better results. The system uses the intensity of tactile pulses at equal time intervals to provide feedback on the error of joint Angle. The larger the error, the stronger the tactile vibrations. In addition, superimposed hop sequences are used to transmit rotation errors.

Experiments showed that adding tactile feedback to exercise training improved learning rates by up to 23% and steady-state learning errors by up to 27% compared to bending joints. The subjects with tactile feedback showed higher levels of attention and corrected their movements at all times, while the issues without tactile feedback were left idle [6]. And the device does not reduce user comfort. We may someday be able to train users to take in this input to learn motor abilities subconsciously, eventually establishing a muscular reflex because our brains process motor learning differently from other conscious learning kinds.

## 4 Foot-Worn Haptic Device

It is well known that humans conduct signaling through the nervous system. Nerve signals, on the other hand, are essentially electric. Therefore, we can analyze the electrical signals to determine the electrical signals that match different neural signal types. And based on this, haptic sensors were invented. The skin is stimulated by electrical signals so that the nervous system receives and transmits shadowy information to the brain so that we can also have an immersive feeling when experiencing virtual reality projects.

Self-diagnosis function can analyze and compare the system's current situation with the previous case and self-diagnose the problems that occur due to changes in the environment and the design inside.

In the face of changing external environmental conditions, it can automatically adjust its structure and function in time and change its state accordingly. The textile information system always optimally modifies to the outside world and changes its state accordingly so that it always responds to external changes optimally [7].

This technology is used in robotics and prosthetic skin-to-skin devices, where tactile perception is crucial. Haptic perception detects various stimuli, such as bending, strain, temperature, pressure, shear, vibration, and sliding. Wearable devices, also known as electronic skin physical sensors, can detect vital signs such as blood pressure and respiratory rate. Physical activity and posture, such as how the body feels, can also be monitored. These can provide helpful information such as fitness, posture, gait abnormalities, or sudden twitching of the limbs. In the case of robots and prosthetics, tactile sensors will enable robots or amputees to detect the hallucinations in which they are located so that they can only mention to real people the general form of various abilities and perceive their surroundings. For robots, proprioception is essential to the robot's regular operation. Especially for soft robots, monitoring proprioception is even more critical because their shape is easily affected by external forces and thus deformed. At the same time, they usually have the characteristics of nonlinearity, hysteresis, and viscoelasticity, which makes it difficult for them to complete real-time monitoring of the senses in time. Of course, there are currently finished devices on the market. For example, the United States Patent and Trademark Office officially granted Apple a bright foot wearable accessories patent. As a VR game accessory, the new foot accessory can provide users with various foot feedback, such as temperature changes and tactile changes, etc., to make the game feel more real [8].

This patented accessory is constructed like a sock or shoe, with a cavity configured to receive the user’s foot. Haptic output devices may also include a foot platform with a flat outer surface on which the user can stand. Haptic output components include piezoelectric components, electroactive polymer components, electromagnetic actuators, and other haptic output components.

During operation, shear forces and regular forces can be generated on the inner surface of the foot-shaped support surface and the outer surface of the foot platform. These forces can give the user the feeling of resting or sliding on the tile's exterior or surfaces with surface irregularities. Frictional effects and other effects can also be created using tactile output devices.

## 5 Discussion

The hand-worn haptic device is employed frequently in the inventive human-machine interface of virtual reality applications because of its unique benefits of high accuracy and multi-degree freedom control. Bright gloves are one of them and have good motion-detecting capabilities at a reasonable price. It comprises a PZT piezoelectric haptic mechanical stimulator and an elastomer-based triboelectric haptic sensor. Real-time haptic feedback and multi-dimensional motion detection are possible with 3D printed gloves, finger bending sensors include many degrees of freedom for detecting the movement of each finger bone, and palm sensors can sense regular and shear forces in eight directions. Hand-worn haptic devices can see various activities while allowing the user's hand flexibility. Users can enjoy a multimodal virtual environment with video, audio, and haptic stimulation thanks to the vest-worn haptic device, making the perception of the virtual environment more realistic. However, the user's experience in the VE is greatly affected by mismatches between events in the VE and tactile responses, as well as inaccurate back temperatures. But overall, Vest-worn haptic devices help users better experience virtual environments. The Vest-worn haptic device can also be used for tactile interaction with kinesthetic learning systems to help students learn and rehabilitate patients. The system is harmless to the human body. The foot-worn haptic device can be used in robotics and prosthetics to monitor body movement and position as well as to detect stimuli including pressure, strain, temperature, shear, bending, vibration, and slide. It can reveal important details about your health, posture, strange gait patterns, or unexpected limb tremors. Robots or amputees can detect their physical environment for tasks like handling and manipulating everyday objects and interacting with others thanks to foot-worn haptic devices. However, the current technology has the problem of signal feedback delay and is still being tested and improved.

## 6 Conclusion

This article reviews the basic situation of wearable haptic interfaces and describes the basic sensing mechanisms of such sensors. It explains the device structure design and final device performance. The practical applications of these devices are also described in turn. Wearable haptic interface technology is widespread and applied to some aspects of life. Moreover, with the development of the times, some technologies will be improved, and it is believed that their application will become more extensive.

Wearable haptic interfaces have been widely used in virtual reality devices and bionic bodies. We will also be in constant contact with it in our future lives. This technology still has a lot of room for development and application in the future. He can be applied to medicine and all aspects of social life to enrich our daily lives. It can also give people with disabilities a new lease on life. Overall, this is a critical technology. Therefore, investment in research and development of this technology should be increased.

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All the authors contributed equally to this work and should be considered co-first authors.

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