

## ORIGINAL RESEARCH ARTICLE

# Research progress of wearable plantar pressure monitoring system

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### ABSTRACT

In order to rapidly promote the application of wearable plantar pressure monitoring system, the physiological structure of human foot, the source of plantar pressure and exercise step frequency are introduced. Based on the current research status of wearable plantar pressure monitoring systems, the fabrication materials and response principles of the fabric sensor-based integrated pressure monitoring socks are explored, the principle of selecting the features of the wearable plantar pressure monitoring system and its application in the field of the pressure monitoring system is explained. The principle of selecting the features of wearable plantar pressure monitoring system and its application in fall detection, foot disease diagnosis, and plantar pressure database are explained. Finally, we discussed the problems in the industrialization of wearable plantar pressure monitoring system at this stage. The problems of poor material performance and short wireless transmission distance in the industrialization of wearable plantar pressure monitoring systems are discussed, and a better integrated system based on biomechanics, textile materials and electronic communication is proposed. A better application prospect based on the cross-fusion integration of biomechanics, textile materials and electronic communication is proposed.

**Keywords:** wearable; plantar pressure; pressure monitoring; flexible pressure sensors

## 1. Introduction

Plantar pressure refers to the human body standing or in motion, the body weight acting on the ground through the foot, the ground will simultaneously produce a force of equal size and opposite direction on the sole of the foot, this force can be used to assess the function and fatigue of the human lower limbs, often applied in medical diagnosis, foot

disease assessment, disease severity determination and other fields<sup>[1–2]</sup>. Plantar pressure measurement systems such as pressure test plates and test benches, where the collected plantar pressure data are often used in motion measurements and disease diagnosis<sup>[3–4]</sup>. These traditional pressure measurement devices are large and inflexible and cannot meet the demand for real-time monitoring of plantar pressure. On the contrary, pressure monitoring socks and shoes are highly adaptable and have little space

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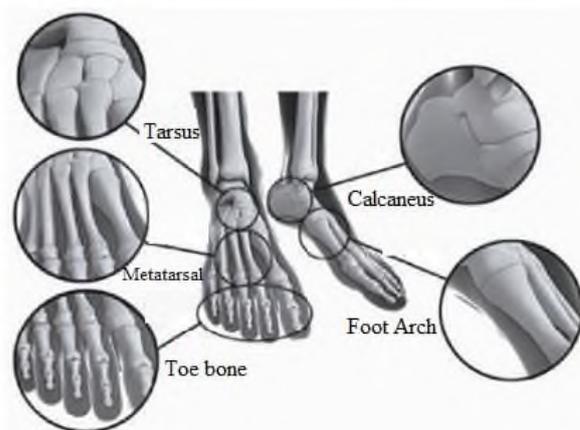
limitation, which can collect and analyze human plantar pressure information in real time and provide reliable data for gait research, footwear manufacturing, simulation robotics, and other fields. The development of such wearable plantar pressure monitoring systems covers several fields and requires research and analysis based on biomechanics, textiles, electronics, wireless transmission and other disciplines.

In this paper, we analyze the physiological structure of the human foot and the motion characteristics of the foot from the perspective of biomechanics, and explore the sensing elements and working principles related to plantar pressure monitoring socks and plantar pressure monitoring shoes. Finally, the research and application of wearable plantar pressure monitoring system is discussed, as well as the problems and development trend at this stage.

## 2. Human foot movement mechanics

### 2.1. Physiological structure of the human foot

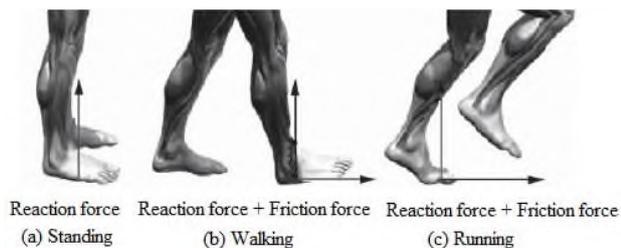
The human foot consists of 28 bones with different functions, 33 joints, and more than 130 ligaments, muscle groups, and the nervous system, making it a complex and independent physiological system<sup>[5]</sup>. According to the structure and function, the bones can be divided into heel, tarsus, metatarsus, phalanges, and arch, as shown in **Figure 1**. The heel bone is large and is the main pressure-bearing bone in the human body; the tarsus is short and controls the turning and twisting of the foot; the metatarsus is the main pressure-bearing bone and absorbs and cushions the impact of the ground on the bottom of the foot during movement; and the toe bone is short and flexible and is the key to regulating the body's balance<sup>[6]</sup>. The arch structure between the metatarsal and tarsal bones is the arch of the foot, which regulates body balance and has three major functions: cushioning, transition, and stirruping<sup>[7]</sup>.



**Figure 1.** Skeletal structure of human feet.

### 2.2. Plantar pressure comes

From the perspective of biomechanics, the force situation and movement law of the organism under the action of external and internal muscle forces can be explored to better analyze the causes and mechanisms of human plantar pressure. When standing, in the vertical direction, the ground exerts an upward reaction force on the sole of the foot, at which time the plantar pressure is uniformly distributed on the sole of the foot, as shown in **Figure 2(a)**. When walking, the body naturally leans forward, the contact between the sole of the foot and the ground is periodic, in addition to the vertical reaction force, there is a horizontal force and friction, together to assist the body forward, at this time the peak plantar pressure is concentrated in the metatarsal region, as shown in **Figure 2(b)**. When running, the feet alternately land on the ground, the plantar and toe bone area when the sole of the foot touches the ground pressure is the largest, as shown in **Figure 2(c)**. Regardless of the movement state of the human body, by measuring and analyzing the magnitude and distribution characteristics of plantar pressure, the function of the skeletal and muscular groups of the lower limbs can be assessed for the purpose of preventing lower limb strain injury.



**Figure 2.** Analysis diagram of human foot of force from different motion state.

### 2.3. Foot movement gait analysis

Gait frequency is the number of circulatory exchanges between the left and right legs per unit of time, and is an important object of study in the field of bio motor mechanics, which affects the circulatory changes in plantar pressure. Jinman<sup>[8]</sup> pointed out that the frequency of human standing is 0 Hz, the frequency of natural walking is 1.7 to 2.0 Hz, and the ultimate gait frequency can reach 5.0 Hz. When a person walks, the ground reaction force compresses the plantar regularly, and the sensor of wearable pressure monitoring system can receive the cyclic stress of the plantar and output the pressure signal at a certain frequency. The resilience of the material can directly affect the accuracy of the pressure data, therefore, when developing the wearable pressure monitoring system, the matching between the response frequency of the material and the human step frequency must be considered to ensure that the monitoring system can accurately collect the plantar pressure signal and avoid the signal hysteresis phenomenon.

## 3. Wearable plantar pressure monitoring system

The early plantar pressure measurement method is the footprint method, i.e., a person stands on rubber, sand and other materials and leaves a footprint, and the plantar pressure information is analyzed by the morphological characteristics of the footprint<sup>[9]</sup>. Currently, pressure monitoring socks and pressure monitoring shoes have realized the collection, processing and wireless transmission of plantar pressure data. Their signal acquisition modules are all composed of pressure sensors, and the

plantar pressure sensor is compressed by the foot when walking, so that the electrical signal is generated instantaneously, and the electrical signal rapidly decreases and tends to zero when the foot is raised. The electrical signal generated by the sensor is processed by noise reduction and other processes, and sent by the wireless transmission module to the terminal for visualization and numerical conversion processing<sup>[10]</sup>.

The main difference between pressure monitoring socks and pressure monitoring shoes is that the former is knitted using a one-piece forming process in which conductive yarns are interwoven with ordinary yarns to form an intelligent wearable monitoring system containing several pressure sensor modules. In the latter, the flexible pressure sensors are placed directly into the insole, and the signal acquisition module and signal processing and output module are connected through thin wires to make an integrated intelligent monitoring system. The pressure monitoring sock has a high accuracy of measurement and can respond quickly to changes in plantar pressure due to its better wrapping of the foot, while the pressure monitoring shoe is more functional and can be loaded with subsequent data processing and output modules without affecting wearing comfort, while achieving efficient data acquisition and transmission.

### 3.1. Pressure monitoring socks

Pressure monitoring socks are wearable pressure monitoring systems with certain mechanical properties and pressure response performance by integrating pressure sensor modules made of conductive fibers or yarns into the characteristic locations of the socks, combined with signal processing technology and wireless transmission technology. The fabric sensor is the key part of the pressure monitoring sock, which is woven by conductive fibers or yarns according to certain laws, including knitted fabric sensor and woven fabric sensor. Its sensitivity is related to the type of conductive fibers, the compounding method and the structure of the fabric.

### Conductive fibers for textiles

Conductive fibers are fibers with resistivity less than  $1 \times 10^7 \Omega \cdot \text{cm}$  under standard conditions (temperature of  $20^\circ \text{C}$ , relative humidity of 65%)<sup>[11]</sup>. According to the different conductive components, they can be divided into metal conductive fibers, carbon black conductive fibers and organic conductive fibers. Metal conductive fibers are made from metal directly drawn into fine wires or metal particles coated on the surface of polyester fibers, such as stainless-steel fibers, silver-plated fibers, etc. Drawing method of metal conductive fibers prepared by large mass, spinnability and poor dyeing; coating method to prepare the fiber softness, spinnability is good, but the coating fastness is poor, not resistant to friction and washing, so not widely used in the textile field<sup>[12]</sup>. Carbon black conductive fibers, including carbon fibers, carbon black coated fibers and carbon black composite fibers, have the advantages of high strength, good heat resistance, its electrical conductivity is better than stainless steel fibers, and can quickly dissipate the charge generated by mutual friction between yarns; however, due to its dark color, poor dispersion ability and other disadvantages, limiting its application in the field of textiles. Organic conductive fibers from conductive polymers directly spun into filaments or composite processing, common conductive polymers are polyacetylene, polyaniline, polypyrrole, etc. Conductive polymers are coated onto the surface of ordinary polyester fibers and made of composite conductive fibers with good electrical conductivity, excellent mechanical properties and stable chemical properties, which have good prospects for application in the field of functional textiles<sup>[13]</sup>.

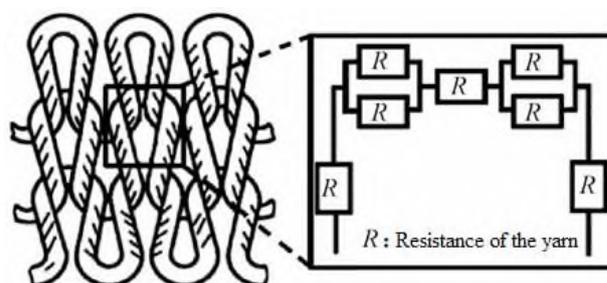
### Fabric sensors

Fabric sensor is a sensing element that weaves conductive fibers directly into a knitted or woven fabric, using the resilience of the fabric to respond to cyclic stress in different parts of the foot. When it is subjected to plantar compression, the relative position of the yarn is shifted, causing a change in sensor resistance or capacitance as a response to external stresses. The signal processing module converts,

reduces noise and amplifies the data collected by the sensor, and finally outputs the data to the PC for storage and display in combination with wireless transmission technology. Considering the conductive yarn as a wire, the conductive knitted fabric is like a complex parallel circuit, and when the coil in the fabric is deflected by the force, it causes a change in the resistance of the circuit, as shown in **Figure 3**<sup>[11]</sup>. Knitted fabric sensor resistance is calculated as:

$$R = \rho \frac{l}{A}$$

Where:  $R$  is the resistance of the conductive yarn,  $\Omega$ ;  $\rho$  is the resistivity of the conductive yarn (conductivity),  $\Omega \cdot \text{m}$ ;  $l$  is the length of the conductive yarn,  $\text{m}$ ;  $A$  is the cross-sectional area of the conductive yarn,  $\text{m}^2$ . conductive yarn resistivity is certain, its resistance is proportional to its length, and its cross-sectional area is inversely proportional.



**Figure 3.** Equivalent circuit diagram of knitted fabric unit coil

The pressure response principle of the woven fabric sensor differs from that of the knitted fabric sensor in that it is based on the capacitor principle to respond to changes in external stress, as shown in **Figure 4**. In the woven fabric sensor, the 2 opposing electrodes are composed of yarn, and the dielectric tissue between the 2 electrodes is composed of an outer insulating coating. When the fabric sensor is compressed by an external force, the spacing and relative area of the 2 electrodes change, causing a change in capacitance. The calculation formula for the capacitance of this type of sensor is:

$$C = \epsilon \frac{S}{d}$$

Where:  $C$  is the capacitance of the woven fabric sensor,  $\text{F}$ ;  $\epsilon$  is the dielectric constant of the dielectric tissue;  $S$  is the relative area between the 2 electrodes,

$m_2$ ;  $d$  is the distance between the 2 electrodes,  $m$ . When the dielectric constant of the dielectric tissue is certain, the capacitance of the woven fabric sensor is proportional to the relative area between the 2 electrodes and inversely proportional to the distance between the 2 electrodes.

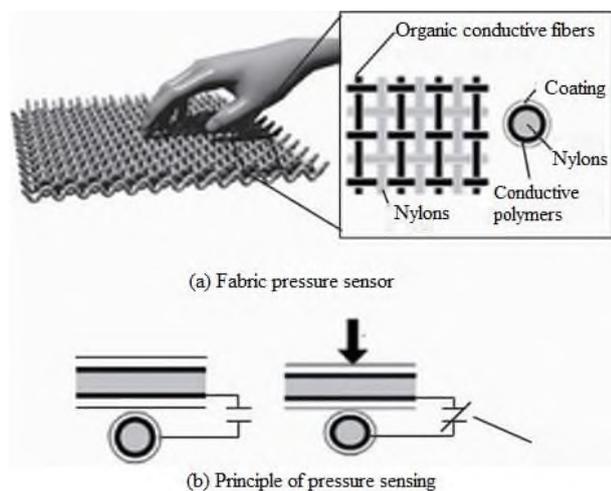


Figure 4. Schematic illustration of woven fabric pressure sensor.

Li et al.<sup>[14]</sup> prepared a pressure monitoring sock containing three knitted fabric sensors by one-piece forming process by using viscose conductive fibers

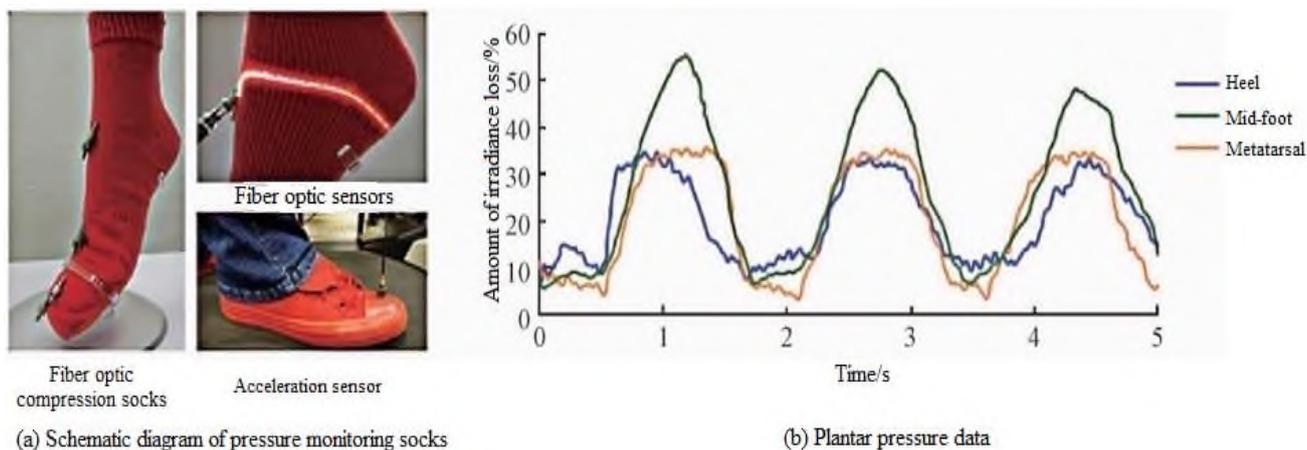


Figure 5. Pressure monitoring socks and pressure data.

### 3.2. Plantar pressure monitoring shoes

A plantar pressure monitoring shoe is a wearable monitoring system that integrates information acquisition module, signal processing and output module into the shoe body. It can rapidly collect and analyze the pressure data of human foot, and convert the pressure data into visual images or curves

containing stainless steel particles and nylon, and connected each sensor to the data processing equipment by conductive fibers. When the fabric sensor is subjected to a force, the fabric structure deflects and springs back, which in turn causes a change in the signal. On the contrary, woven fabric sensors have less resilience, are less sensitive than knitted fabric sensors, and suffer from signal hysteresis, making them unsuitable for application in pressure monitoring socks.

In addition, polymeric optical fibers can also be embedded into the characteristic parts of socks, combined with acceleration sensors to collect subjects' motion information and gait<sup>[15]</sup>, as shown in Figure 5. Although the fiber optic sensor is small in mass and responsive, it is difficult to control the response to external environmental factors such as temperature, pressure, and magnetic field during human movement, so the fiber optic sensor is still difficult to control in practical applications.

through the digital-to-analog conversion program, so as to analyze and evaluate the functions and force characteristics of human foot, and finally achieve the purpose of real-time collection and feedback of human gait information. The structure schematic and working principle of the foot pressure monitoring shoe are shown in Figure 6.

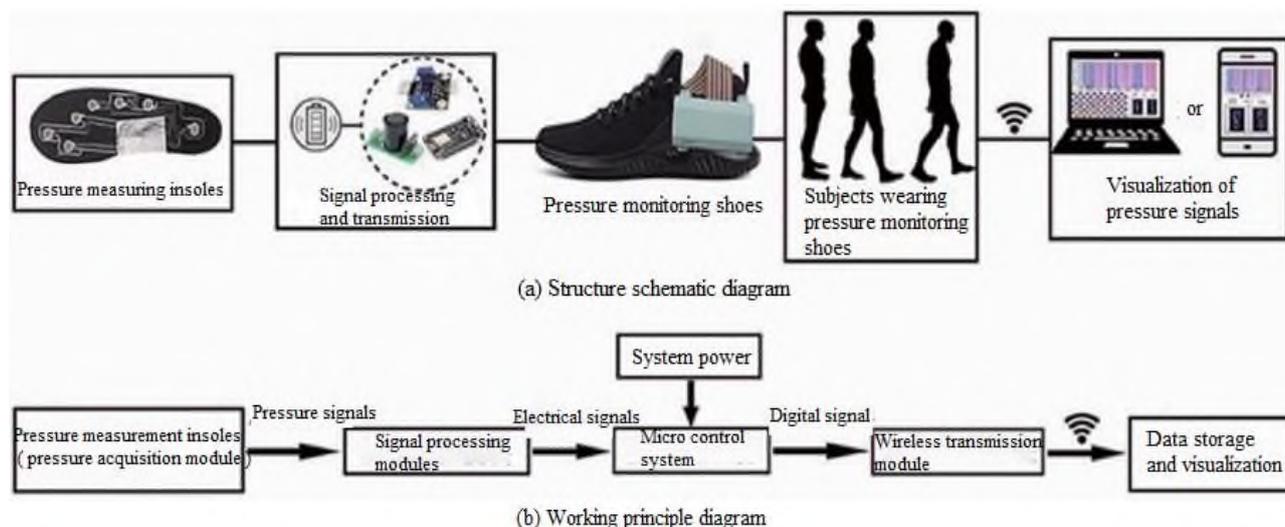


Figure 6. Structure diagram

### Information acquisition module

The information acquisition module realizes the acquisition of human plantar pressure signal by embedding the flexible pressure sensor into the insole. It is the key part of the wearable plantar pressure measurement system, and the sensors used should have good flexibility, ductility, repeatability and stability, and should not hinder human movement. Commonly used sensors include piezo-resistive flexible sensors, capacitive flexible sensors, and piezoelectric flexible sensors, which convert pressure signals into output electrical signals according to certain mathematical laws in response to changes in plantar pressure<sup>[16]</sup>, and the response principle of the sensors is shown in **Figure 7**.

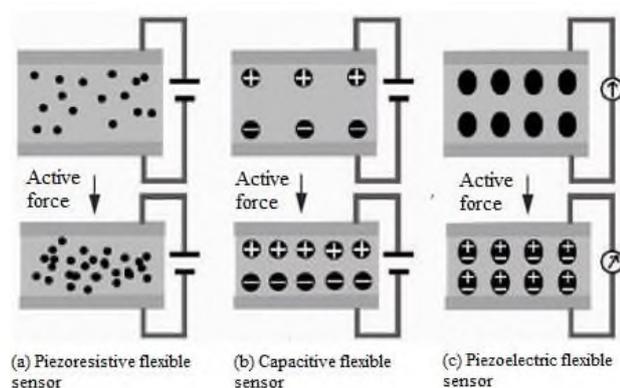


Figure 7. Schematic diagram of three flexible pressure sensors.

Piezo-resistive flexible sensors under force, the distance between the conductive particles in the elastic matrix becomes shorter and charge transfer

occurs, causing a change in material resistance, the resistance changes with the magnitude of the external force<sup>[17]</sup>. The piezoresistive material used in piezoresistive flexible sensors can be fibers, yarns or fabrics, so this type of sensor can be widely used in the field of wearable technology. However, these sensors need to be used in combination with signal conversion circuits to convert resistance into voltage, so they require high data processing equipment and the circuit design of the system is more complex. The composition of capacitive flexible sensors is like that of woven fabric sensors, both containing two opposing electrodes and a dielectric layer, the electrodes can be yarn, fabric, metal sheet or conductive film. Capacitive flexible sensor response speed, high sensitivity, is widely used in clothing touch technology (fabric keyboard); when the finger in the “fabric keyboard” on the tap, slide, the fabric sensor will generate an electrical signal in response to the “touch command”<sup>[18]</sup>. Piezoelectric flexible sensors subjected to force deformation, will instantly generate an electrical charge in response to external stress, the typical piezoelectric material is polyvinylidene fluoride (PVDF), the PVDF piezoelectric sensor embedded in the insole, can respond to changes in human movement underfoot pressure<sup>[19]</sup>. The piezoelectric flexible sensor has high sensitivity and wide response range, and it is also widely used in the field of cardiopulmonary detection, but its charge is proportional to the sensing area, and when the area is small, the electrical signal is weak, and a

circuit amplifier needs to be constructed to process it.

### ***Signal processing and output module***

The signal processing and output module is the key to obtain stable and accurate pressure digital signal for the plantar pressure monitoring system, which consists of three programs: signal processing, wireless transmission and data display.

The signal processing program includes signal conversion circuit, filter circuit and signal amplifier. Among them, the signal conversion circuit is applicable to the plantar pressure monitoring system of piezoresistive flexible sensor, which converts the resistance signal into voltage signal according to a certain law. The adjusted voltage signal is transmitted to the filter circuit, which suppresses the signal of high frequency by low-pass filtering and removes the noise and clutter in the data. The noise-reduced voltage signal is transmitted to the circuit amplifier with the purpose of amplifying the weak voltage signal in the same proportion according to a certain rule for subsequent analysis<sup>[20]</sup>. The multi-processed signal is transmitted to the microprocessor for numerical conversion, temporary storage and packing.

The wireless transmission procedure is implemented by wireless Bluetooth or Wi-Fi, and the wireless transmitting terminal sends the packaged data to the wireless receiving module of the host computer to complete the information transfer. The data received by the host computer is stored in a common database such as Microsoft Access or Microsoft SQL Server, and the data is uploaded and updated in real time through the wireless receiving module. Finally, the data display program visualizes the data stored in the database. Firstly, the data reading and writing program and the digital-to-analog conversion program are pre-designed in the LabVIEW platform, so that the data in the database can be transferred to the platform in real time<sup>[21]</sup>. Then the data is visualized by the digital-to-analog conversion program and presented in the form of graphs to achieve the purpose of real-time monitoring of plantar pressure.

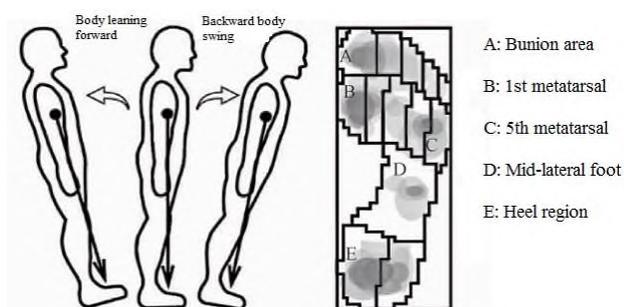
However, there are still some problems in the actual use of pressure monitoring shoes at this stage, such as the small range of pressure that can be responded to and the short wireless transmission distance of data; at the same time, because the human body presents complexity in the process of movement, the sensing module is not yet able to collect the irregular movements of sudden changes in plantar pressure such as bouncing and dancing, so the improvement of the performance of the pressure acquisition module and the realization of remote transmission of data are problem that needs to be solved.

## **4. Selection of feature locations for foot pressure measurement**

The pressure-bearing bones of the human foot vary under different sports conditions, therefore, when measuring plantar pressure, the plantar area should be divided to facilitate the selection of appropriate feature locations for the placement of pressure sensors. The number and location of sensors affect the accuracy of the data, such as the F-Scan and Pedar pressure test insoles, which have nearly 1,000 sensors embedded in each insole and collect accurate pressure data. However, when the number of sensors in a pressure monitoring system is too large, the system load is too high, leading to increased experimental costs and data redundancy. Therefore, it is important to explore the principles of selecting the location of plantar pressure features and using the least number of feature locations to obtain more comprehensive and accurate information.

In existing studies, the selection of plantar pressure feature locations is usually based on physiological anatomy or experimental experience, such as selecting multiple feature locations in the insole to place flexible pressure sensors, which are used to identify the human body for normal walking or weight loss walking; or dividing the plantar into several regions to investigate the gait characteristics of different people, such as patients with flat feet<sup>[22-23]</sup>. In daily life, foot movements are complex, and the changes of plantar pressure under different

movements must be considered when exploring human gait information. Lin et al.<sup>[24]</sup> put on plantar pressure measurement shoes and used the “inverted pendulum model” (under standing conditions, the body swings back and forth to the limit position) to measure the distribution of plantar pressure in subjects, as shown in **Figure 8**. The experiments showed that the main pressure-bearing areas were the midfoot, metatarsal, and the limit areas (bunion and heel); secondly, mathematical statistics and superposition were performed to select the characteristic locations of plantar pressure in existing studies, and the five areas with the highest correlation were: the bunion, the first metatarsal, the fifth metatarsal, the lateral midfoot, and the heel. Therefore, when measuring plantar pressure distribution, the bunion, metatarsal, mid-lateral, and heel regions are set as the characteristic locations to ensure the accuracy of the data and to obtain effective gait information with fewer characteristic locations.



**Figure 8.** Selection method and superposition processing of feature position.

Currently, there are few studies on the selection of plantar pressure characteristics, and there are two main problems in these studies: (1) the distribution of plantar pressure in different postures when the subject is standing only, without considering the complexity of human motion; (2) in the “inverted pendulum model” experiment, the forward and backward tilting movements are difficult to reach the experimental results were not accurate enough.

## 5. Application of plantar pressure monitoring system

### 5.1. Fall detection system

A study showed that 30% of elderly people (65 years old and above) in the United States have one fall per year, and 11.6% of the total accidents in Japan when elderly people are working in agriculture<sup>[25–26]</sup>, therefore, monitoring the behavior of elderly people can provide timely rescue for fall accidents and effectively reduce the casualty rate. By integrating flexible pressure sensors, axial accelerometers and other components into the sports shoe body, a wearable fall monitoring system that monitors the subject’s movement status in real time can be made. The monitoring system initiates an alarm when there is a sudden change in plantar pressure and acceleration, and if the wearer does not cancel the alarm within the specified time, the system will automatically request a third-party platform for timely rescue of the wearer<sup>[27]</sup>. Wearable monitoring system is a key research direction in the field of sports monitoring, but due to the complexity and variability of the wearing environment, the current functions such as wireless monitoring and data remote transmission can only be achieved in the laboratory with good results.

### 5.2. Diagnosis and treatment of foot disease

The prevalence of diabetes in the elderly continues to rise worldwide, with a prevalence of up to 20% in those aged 65–76 years or older, and 2011 data from the U.S. Department of Disease Control and Prevention show that about 8.3% of Americans have diabetes<sup>[28–29]</sup>. The plantar pressure distribution characteristics can effectively reflect the degree of foot ulcers in diabetic patients, and the use of pressure monitoring systems to determine the plantar pressure data of diabetic patients can provide scientific assessment of their stress conditions, which can provide reasonable treatment plans and take scientific and effective protective measures. The plantar pressure distribution characteristics of diabetic patients and healthy people when walking are different, and the main pressure-bearing area of the plantar of the former gradually shifts from the heel to the metatarsal, increasing the probability of ulcers in the metatarsal region<sup>[30]</sup>; therefore, pressure-relief insoles can be developed according to the plantar

pressure characteristics of diabetic patients to reduce the peak pressure and the incidence of plantar ulcers<sup>[31]</sup>.

### **5.3. Plantar pressure distribution characteristics database**

Gait is an individual-specific behavior and a highly distinguishable biological characteristic<sup>[32]</sup>, and its main parameter is the plantar pressure distribution characteristics, which can give feedback on the force characteristics and personalized features of the human foot<sup>[33]</sup>. A plantar pressure distribution characteristics database is a data processing method that collects a large amount of plantar pressure data, and stores and manages them. The wearable plantar pressure monitoring system can collect a large amount of plantar pressure information and establish a feature database to solve the problems of lack of pressure data, regional variability in pressure distribution features, and difficulties in sharing data resources. Gait feature recognition, as a biometric technology, can be applied in criminal investigation, where the unknown footprints are compared with the data in the database to analyze the individual characteristics of foot printers, which can improve the efficiency of investigation<sup>[34]</sup>. In addition, plantar pressure data can be applied in the research of human body posture correction<sup>[35]</sup>, disease treatment<sup>[36–37]</sup>, intelligent prosthesis<sup>[38]</sup>, and other fields.

## **6. Conclusions**

The wearable plantar pressure monitoring system is a fusion of plantar pressure measurement technology and textile and apparel field, which collects plantar pressure information through sensing elements and sends it to the host computer by combining signal processing technology and wireless transmission technology, and can provide real-time feedback on plantar pressure information. Therefore, wearable plantar pressure monitoring systems are widely used in human motion research, footwear manufacturing, intelligent robotics, disease monitoring and diagnosis. At the present stage, wearable plantar pressure monitoring system still has prob-

lems such as signal response lag, short material life, small pressure response range, and short wireless transmission distance, etc. Therefore, at this stage, the wearable plantar pressure monitoring system needs to be solved by enhancing the material performance and wireless transmission technology in order to promote its development in the direction of industrialization.

With the development of wearable technology, wearable pressure monitoring system can be applied not only in manufacturing and medical fields in the future, but also help the process of artificial intelligence and digitization of human body information, which has good application prospects.

## **Conflict of interest**

The authors declare no conflict of interest.

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