Flexible Stretchable Sensor Garments That Monitor Human Movement

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***Abstract*— In this paper, a flexible stretchable pressure sensor that can be combined with clothing is designed. Due to its excellent flexibility, it is no longer limited to conventional uses when combined with fabrics. This wearable flexible stretchable pressure sensor is easy to process and low in cost and can participate in human motion monitoring accurately, flexibly, and variably. The sensors show different performances when they are made of different flexible materials, microstructures, and processing technologies. They have ideal biocompatibility and adaptability and have considerable application prospects. Moreover, multiple sensors can be applied to various parts of the human body to measure the angle of the human body. Angle monitoring in the sagittal plane, coronal plane, and horizontal plane may also be realized in the future, In this report, the performance of the sensor integrated into the elastic tights was tested, and then the actual application and independence of the sensor clothing were demonstrated by measuring the angle of the hip joint in the sagittal plane. Finally, when the sensor clothing was worn, the synchronous gait measurement was carried out on the treadmill with the dynamic capture, and then the captured data was processed to obtain the human motion data. Through comparison with the dynamic capture system, To detect the initial actual performance of the sensor and characterize the defects in wearing measurement.**

I. INTRODUCTION

In recent years, flexible exoskeleton robots have been constantly explored and innovated by people. Based on integrating many disciplines, the flexible exoskeleton has been developed in the longer term. Compared with the rigid exoskeleton, a flexible exoskeleton assists people to move when carrying weight ensuring flexibility in complex environments [10]. Besides, the exoskeleton should recognize the movement status of people in the gait cycle and then perform the next step of control and adjustment, Therefore, wearers need to wear sensors to monitor the posture of the human body through sensors [2], which will more conveniently realize human-computer interaction.

General laboratories and other fixed places will adopt the visual human posture detection method. The dynamic capture system with high-precision cameras will capture the trajectory of human joints pasted with reflective marker points, and establish coordinates and human models according to the reflection points. This method not only needs to be recalibrated for each measurement. The movement pattern is also limited. At present, [9] MEMS acceleration sensor is mainly used. However, due to errors in accuracy and reliability, the sensor can not achieve a good human-machine interaction experience. The inertial measurement unit (IMU) based on MEMS [15] technology can measure motion angle and acceleration and is also used for human posture monitoring. However, the scene is relatively fixed in the process of use, and errors will continue to occur, Both filtering and external sensor fusion is needed to eliminate the integral drift. There is also an electronic goniometer that can measure the angle of the joint. Two rotating arms are tied to the upper and lower ends of the coronal plane of the joint, and then the potentiometer is arranged at the joint. However, the goniometer belongs to a rigid measuring device, which has defects in measuring accuracy. Similarly, the optical fiber that directly measures the body displacement also has accuracy problems [3].

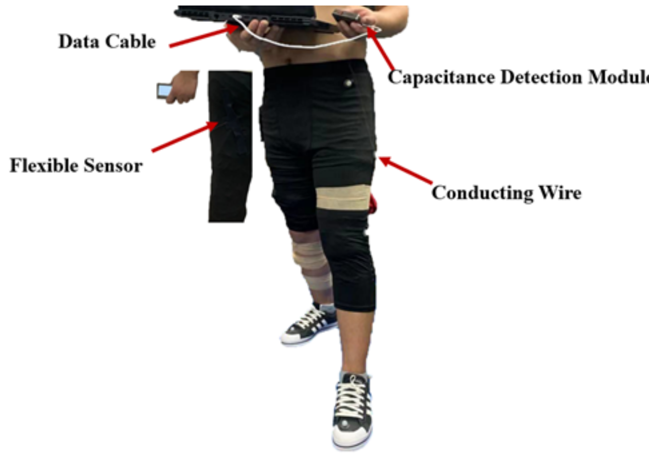

Fig. 1. Flexible stretchable sensor clothing for measuring the angle of lower limb joints, which is attached by Velcro to flexibly adjust the position.

A new type of nondifferential mechanism is used to measure the bending curvature of the super elastic soft microfluidic thin film [17]. This sensor can directly sense the curvature on the bending plane, thus eliminating the restrictions imposed by the strain gauge coefficient and the sensor thickness. Perhaps, in order to make a more sensitive and flexible sensor, it is necessary to integrate the nondifferential curvature sensor on the elastomer made of different materials. Although there are many common sense and innovations of flexible sensors, they lack robustness

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and systematicness in motion. In this work, we prepared and demonstrated a high-performance flexible stretchable mechanical sensor, which is made of SEBS (linear triblock copolymer with polystyrene as the end segment and ethylene butene copolymer obtained by hydrogenation of polybutadiene as the intermediate elastic block) elastic substrate and flexible stretchable electrode material, It has a good linear response, stable strain cycling, and the stretching degree can basically meet the normal movement. The second part will introduce the working principle and the manufacturing process of the sensor. The third part is about the composition and application of the sensor set and the performance evaluation of the sensor. The last part is the application evaluation of sensor clothing [12].

II. SENSOR DESCRIPTION

A. *Working principle of flexible sensor*

The flexible sensor mainly converts external deformation into electrical signals. The core is the piezoelectric element that can generate the piezoelectric effect. When the piezoelectric material is subjected to the external load, it will generate deformation. The deformation of the dielectric will cause the internal positive and negative charges to shift, that is, the polarization phenomenon. The positive and negative ions will be separated to both ends, thereby generating electrical signal changes.

According to the working mechanism, the traditional sensors are piezoelectric, resistive, capacitive, and triboelectric. In contrast, the resistance sensor will generate heat due to resistance change during measurement, which is sensitive to temperature and has general accuracy; Piezoelectric sensors can only measure static pressure signals and have a high-frequency response. They should be used together with charge amplifiers. In general, capacitive sensors are easy to realize, simple to operate and have low requirements on process equipment in the process of processing and design. At the same time, they perform well in performance. The linearity under pure stretching is better than that of resistive sensors, for example, they show better linearity under stretching, In general, it is not easy to produce signal drift, high response repeatability, and low energy consumption in the process, which is more suitable for application on the changeable human body. The theoretical model of the capacitive flexible stretchable pressure sensor is shown in Fig.2. It is composed of two layers of flexible conductive materials and an elastic base in the middle. When the element is stimulated by external pressure, the charge changes, and thus the capacitance changes. The capacitance changes are affected by the area s of the upper and lower layers of electrodes and the dielectric layer[1], the distance d between the plates, and the relative dielectric constant of the dielectric layer r. Capacitance space absolute dielectric constant 0. If the field side effect of the capacitor plate is ignored, the capacitance calculation formula can be expressed:

$$C_0 = \varepsilon_0 \varepsilon_r \frac{A}{d} (1)$$

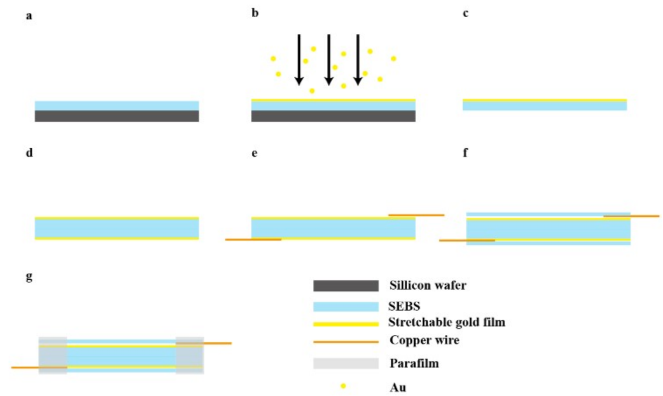

Fig. 2. Schematic of the fabrication processes. a) Spin coating of SEBS on a silicon wafer, b) Deposition of the gold film by magnetic sputtering, c) Taking the electrode off the silicon wafer and cutting it into slices, d) Combination of two pieces from back-to-back by self-adhesion of SEBS to form the capacitance, e) Connect copper wires to both sides of the capacitance, f) Encapsulation of the capacitance sensor by SEBS insulation layers, g) Encapsulation of the capacitance sensor by parafilm layers.

The change of capacitance value is mainly determined by the distance between the plates and the dielectric constant. The characteristics of flexible electrodes and elastic substrates of different materials are important factors affecting the capacitance value[1]. Therefore, capacitive flexible sensors with different energy can be fabricated by designing different sizes and applying different flexible conductive materials and elastic substrates.

B. *Sensor fabrication*

The flexible stretchable sensor is light, transparent, and easy to attach to the skin. Unlike the traditional sensor, the elastic substrate can not use hard and brittle materials such as glass and ceramics, but high molecular organic polymer materials such as graphene, polydimethylsiloxane (PDMS), polyethylene film (PET), polyimide (PI), polyurethane (PU). Among many flexible materials, SEBS is finally selected as the flexible substrate. This new thermoplastic elastomer does not contain unsaturated double bonds, has good stability, oxidation resistance, and aging resistance, and also has excellent mechanical properties such as plasticity and high elasticity. The flexible electrode materials and backing generally include metal films, ionic conductors, metal nanowires, ITO, pet, and experimental sections.

To fabricate the stretchable strain sensor [8] [13], firstly, a clean silicon wafer was evaporated with a monolayer of 1H, 1H, 2H, and 2H perfluoro-octyl-trichlorosilane (Sigma Aldrich) to remove the layer at the end of fabrication. Then the Styrene Ethylene Butylene Styrene (SEBS) was diluted in toluene with a weight concentration of 15% and then dropped onto a silicon wafer manually. Subsequently, the SEBS was cured at 25 °C for 24 h. As a result, a SEBS coating with 100 m thickness was prepared. A magnetic sputtering system (JS4S-75G, China) was adopted to deposit a gold film of 25 nm thickness. The stretchable gold film electrodes were obtained after peeling off the mask at the end of the sputtering process. Then the stretchable electrodes were cropped into slices of proper sizes. After that two pieces of the stretchable electrode were combined together by attachment from the back-to-back side taking advantage of the characteristic of self-adhesion of SEBS to compose a capacitance sensor. Later on, copper wires were connected to two ends of the sensor. Finally, the sensor was encapsulated with a SEBS layer and parafilm to keep it insulating and robust. The fabrication processes are illustrated in Figure 3.

The stretchable sensor is made of a stretchable gold film deposited on the elastic SEBS substrate. The mechanical properties of the sensors are characterized by stretching measurements in a universal mechanical tester shown in Figure 3. The sensor has a maximum tensile rate of more than 100%. The capacitance of the stretchable sensor as a function of the strain is shown in Figure 4.The curve has high linearity and no hysteresis (different from the resistance strain sensor), which is very desirable for sensor applications. Besides, the sensor has cyclic stability of more than 5000 strain cycles. Figure 5 illustrates the capacitance strain curve after extended cycles, which demonstrated its stability and linearity.

III. SENSOR APPLICATION

A. Sensor performance evaluation

The fabricated SEBS elastic stretchable strain sensor is sewn up with flexible textile materials and is mainly divided into four parts. The effective sensing area is the sensor itself; The protection area is a certain area around the sensor, which is used to prevent the sensor from being worn during the deformation process; The electrode area is the part where the wire and the electrode are directly connected. The connection area is the guarantee for the transmission of electric signals and cannot be in contact with the outside world; The outermost part is the suture area. The round hair surface of the Velcro is sewn around, and the bristle surface is sewn at the corresponding joints. The flexible sensor that mainly detects the joints of the lower limbs of the human body is integrated into a pair of stretchable tight pants by sewing Velcro. Both sides of the Velcro are sewn on the flexible sensor and the pants respectively. The elastic cloth is used as the substrate and can be integrated into the clothing to achieve a fully flexible and elastic state [11]. It can be used normally even in the case of long-term movement and sweating, and the sensors of corresponding specifications can be customized according to different people and joints[10], Of course, the sensor position can also be flexibly adjusted to keep the relative position between the sensor and the joint in a stretched state, so as to ensure the accuracy of measurement and facilitate movement when wearing the exoskeleton.

At present, the sensors in the lower limbs are mainly distributed in the hip joint [1], knee joint, and ankle joint. The sensors in the hip joint are located under the gluteus maximus and the biceps femoris at both ends of the back of the thigh, which are roughly parallel to the semitendinosus. The knee joint sensor is located in the front knee, vertically attached between the rectus femoris and the tibialis anterior muscle, covering the knee bone. At present, there are two

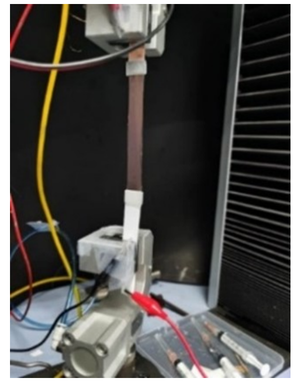

Fig. 3. The stretchable capacitance sensor being stretched by a mechanical

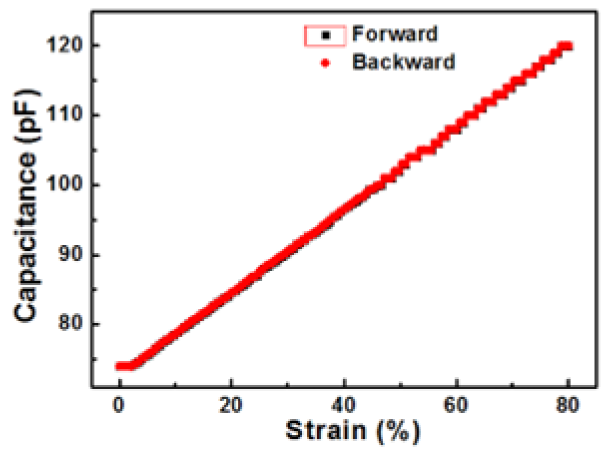

Fig. 4. The capacitance of the stretchable sensor as a function of the strain for a single stretch, showing high linearity and no hysteresis.

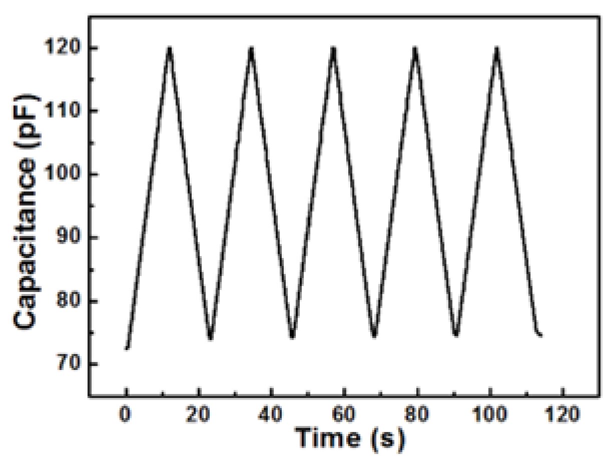

Fig. 5. The capacitance of the stretchable sensor as a function of the strain during extended cyclic tests.

kinds of ankle joint sensors. The first one is attached to the back of the foot and the bottom of the lower leg, and the second one is connected between the heel and the Achilles tendon [6].

In the process of human movement, the sagittal motion of the hip joint can be similar to the pendulum motion [4]. If the joint point is regarded as the origin, the distance from the point to the sensor is equivalent to the radius. When the joint moves, the angle changes. The angle The arc length L calculated by the change and radius R is similar to the deformation of the sensor. When the sensor is deformed [1], the capacitance changes [5]. Therefore, the change in the joint angle can be characterized by the change in the capacitance value. The stretching length of the sensor is approximated by an arc to calculate the relationship between the angle and the capacitance.

The fabricated flexible tension sensor can be used for both static force and dynamic force measurement. Before use, it can be appropriately pre-stretched to eliminate internal stress. During use, sharp objects should be avoided to avoid damage to the sensor. Meanwhile, the stress should be kept as uniform as possible to avoid sudden stress causing sensor fracture.

The performance characteristics of the sensor shall be tested before use. Firstly, its linearity shall be tested [7]. Under the condition of uniform tension, whether the capacitance change is also linear growth shall be tested. The sensor shall be vertically fixed on the connecting piece of the fixed base and platform. The initial length of the sensor is 48mm. Before stretching, the sensor shall be pre-stretched to the just tensioned state, and the sensor can be stretched to about 200%, that is, 96mm, Therefore, during the stretching process, the smaller measuring range is 4mm each time, and the stretching is performed for 12 times in total. The stretching is performed in the vertical direction by moving the workbench. After each stretch, pause for 3 seconds for recording. In order to make the results universal and reduce the chance, the above steps are repeated for multiple sensors.

After that, the constant speed tensile cycle test is carried out. After periodic stretching, the strain response curve of the capacitance value with time is observed. It can be preliminarily concluded that the capacitance strain curve of the sensor has ideal linearity and basically no hysteresis phenomenon. However, when the sensor undergoes obvious irregular deformation beyond the stretchable area (100%), the capacitance value of the sensor does not continue to increase linearly, and the capacitance value changes very little or even does not increase. Moreover, when the stretching degree is too large, irreversible damage may be caused to the sensor. After the rebound, even if the sensor is uniformly stretched within the strain range, it will not show a good linear response as before, After a sufficient number of cycles, the cycle stability of the sensor is stable at more than 5000 strain cycles, and there will not be too much difference due to different joints. It has good compatibility, but it is inevitable to need a greater extent of stretching in the face of intense exercise.

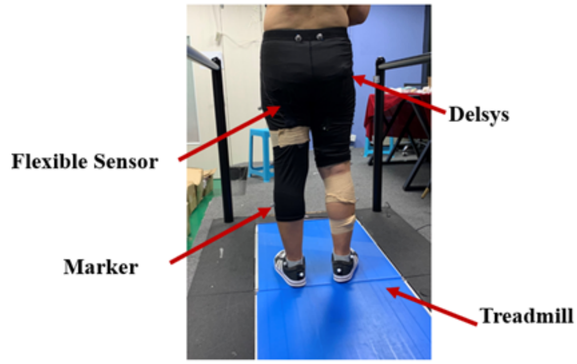

Fig. 6. Wearing sensor clothing to measure hip joint angle synchronously with Vicon on a treadmill.

B. Experimental process

The flexible pressure sensor has obvious advantages when it is used for irregular movement of the joint surfaces of the lower limbs [16] [14], such as hips, knees, and ankles. It does not need to be bound to a certain wearing mode. When it is closely fitted with the skin and can strain in real-time with the joint movement, it can accurately change the capacitance to reflect the movement posture, and the feedback of the angle is more intuitive and practical.

In order to prove the practical applicability of the flexible stretchable pressure sensor clothing, under the condition of wearing the sensor clothing, the gait experiment is carried out with the optical motion capture system. Based on the established body marker positions and several infrared cameras, the infrared reflective marker points are pasted at the waist, knee, ankle joint, heel, and toe of the lower limbs. The camera can collect the coordinates of the marker points in the three-dimensional space, The motion speed, acceleration, and the angle between the links formed between the points can be calculated through the coordinates, that is, the joint angle. The data acquisition of the sensor is transmitted to the capacitance detection module with the LCD screen through the wire. The module has the characteristics of high accuracy, large range, and multi-channel. Although each module can only connect three channels, it can use multiple channels at the same time to increase the number of detectable joints. Before each measurement, reset the capacitance value of the corresponding channel, and set the baud rate, transmission frequency, and transmission mode to DEC10, In the capacitance time curve display interface, the upper and lower limits of the capacitance change curve display can be changed according to the demand, and the channel can be freely selected.

In the experiment, after the dynamic capture system is arranged, the sensor clothing is worn, and the left hip joint is taken as an example for gait walking. Therefore, the two methods of measuring the joint angle of the human body are started synchronously after the start of the experiment, and the obtained joint angle is consistent with the gait cycle, so a comparison can be made. At the beginning of the experiment, walk on the treadmill at the normal walking speed of 1.3m/s.

First, measure three static postures. At the beginning of the gait, the left foot starts to leave the ground (the sensor starts to stretch), standing, and at the end of a gait, each of the three static postures stops for 5 seconds to measure static data. Since the sensor is linear, the capacitance value can be used to calibrate the angle and fit the functional relationship between the two. Then walk with a gait of about 1.1 seconds as a cycle, walk about five gaits at a time, and complete five walks.

Process the angle measurement data of Vicon's left hip joint and calculate the measured angle of the sensor according to the capacitance angle function, and then fit the gait curves of the two modes for comparison.

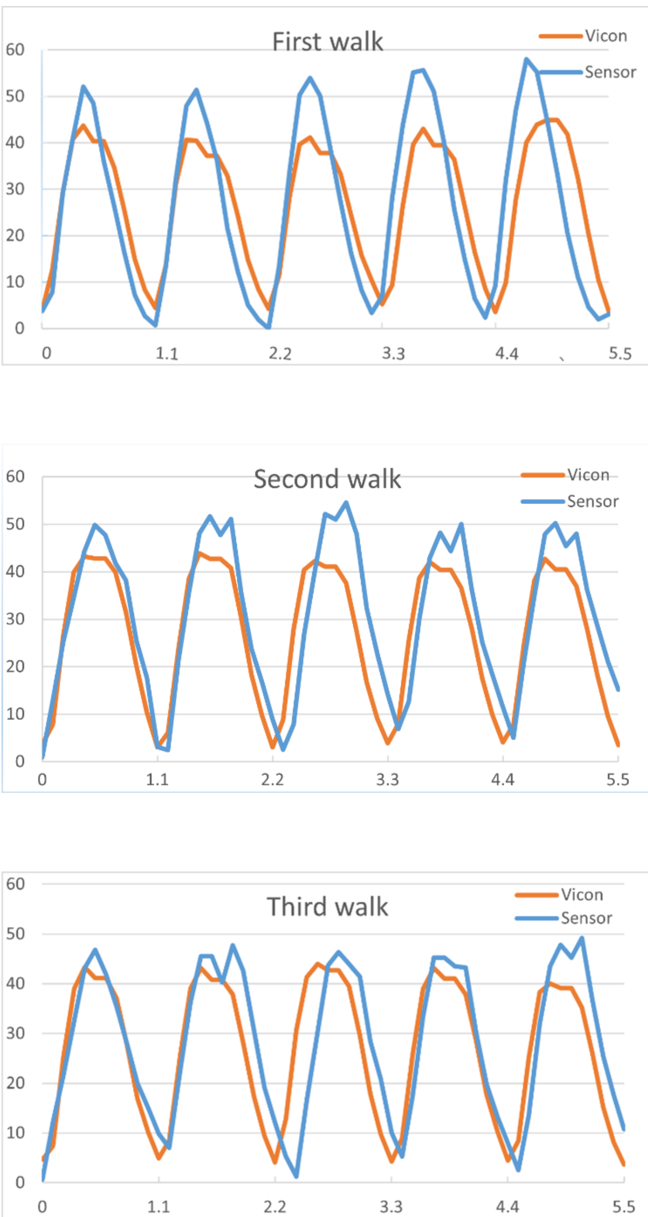

Fig. 7. Evaluating the synchronization of sensor clothing and Vicon. They are the angle time curves of the first three walks. Each walk has about five gaits, and each gait is 1.1 seconds.

IV. Result

Wear a flexible sensor package to walk under the measurement of Vicon. No matter how many times you walk, the maximum value of the sensor is obviously larger than the dynamic capture measurement value as a whole, and the difference is about 10 °, and the measurement angle lags many times. It is very likely that the sensor and hip joint slip and the sensor is loose due to the long walking time or the large walking amplitude, and the angle is converted through a function, Therefore, the dynamic change of the sensor also causes the instability of the static value in the calibration process. The detection value of the three-time walking sensor and the synchronization of the dynamic capture are high, the measurement difference is maintained within 15 °, and the measurement range is relatively real-time, with a wide range and good synchronization. At the same time, the sensor will not affect the normal walking of people during the stretching process.

After walking 5 times, the measurement range of the sensor set is significantly reduced. There is a certain difference between the gait at the beginning and the gait at the end of the walking process, and the coincidence degree in the middle is the highest, as shown in Fig. 8. Through dynamic capture, it can be seen that the angle curves of the five walking processes are highly consistent, that is, the walking is stable, so the difference of about 10 ° is basically caused by the instability of the sensor, but it also shows the practical application of joint angle monitoring, as well as good periodicity and stable cycle durability.

V. CONCLUSIONS

In this report, we propose a flexible measurement clothing equipped with flexible sensors, which aims to collect the human body's motion data while maintaining excellent elasticity and following the human body's movement to generate the corresponding deformation and fit the human musculoskeletal model obtained from the data collected by the sensors and muscle activation sensors with the original human body model, so as to determine the human's motion state, whether to walk naturally or carry forward with the load. And adjust the exoskeleton accordingly to realize human-computer interaction.

With the specific application of flexible sensors to human posture detection, flexible wearable devices are more and more used in biomedicine, sports, medical health, human-computer interaction, and other fields. Flexible sensors basically solve the difficulty of wearing traditional rigid wearable sensors, and basically do not hinder the natural movement of the human body, with good integration and matching. As an intelligent auxiliary device, the flexible exoskeleton designed by imitating the physiological structure of the human body can be worn on the human body and provide auxiliary means for some patients with mobility difficulties and other industry load-bearing personnel. For military industrial personnel and Army soldiers, it is of great significance to improve the physical endurance and bearing capacity during combat through external forces to complete tasks efficiently, This requires the flexible sensor to adapt to the exoskeleton and fit the human body shape as much as possible, without adding additional volume, so as not to cause obstacles and reflect flexibility and reliability.

During the experiment, the disadvantages of the sensor are also gradually discovered. How to design the sensor in the face of a more complex environment, how to make a more reasonable layout in the face of the irregular structure of the human body, and whether to design a sensor similar to the joint in order to solve the slip phenomenon during the movement, whether its sensitivity and usability can be guaranteed after long-term use, and whether the use range of the sensor will be expanded in the future work, Solve its performance and adaptability, and play a more independent and multi-degree of freedom role in the body.

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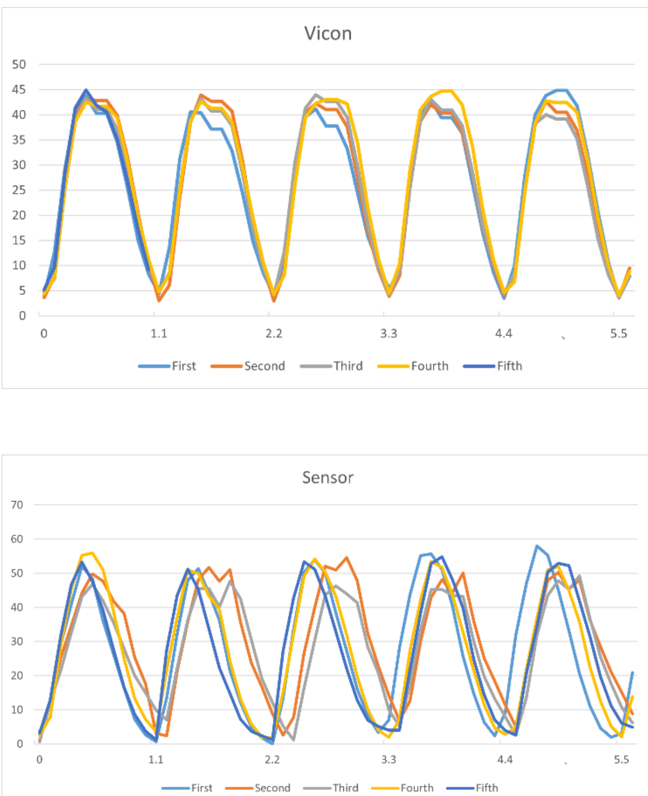

Fig. 8. Joint angle time curve of five walks of Vicon and sensor. The gait walking of Vicon and sensor were compared respectively.

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