2019 IEEE 4th International Conference on Advanced
Robotics and Mechatronics (ICARM)

A Novel Control Method of A Soft Exosuit with Plantar Pressure Sensors

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***Abstract*—Soft Exosuit is a kind of Lower-limb wearable robots to augment and assist the wearer's performance. Recently, our team developed a cable-driven wearable robot named *SIAT Soft Exosuit* (SSEX) which can transmit assistive force to wearer's body. Natural gait feature extraction is the key to control a Soft Exosuit. In this paper, we propose a method to obtain the gait feature by plantar pressure sensors which measure the force load on a shoe insole. The system can detect the gait event accurately and reliably in real time which is the onset time of assistance for hip extension. Then we use IMUs to get the hip joint angle during hip extension which can help us calculate the variation of cable length and motor position profile. There are also two load cells in our system to make a feedback and get us desired assistant force. To achieve a desired active force, the control system adapt a way based on learning iterative control.**

I. Introduction

An increasing number of wearable robotic devices of lower limb have appeared over the past decade. This kind of robots have applied on many occasions: assisting human walking to save energy [1] [2] [3], increasing load-carrying ability of human [4] [5] [6], helping patient to recover [7] [8] [9], etc. Most of the exoskeletons have rigid structures to transmit force to the ground. Some of them are even capable of carrying the paralysis to move. However, the rigid structures will interfere with the natural gait of the human body if the joints of exoskeleton are misaligned with biological joints or degrees of freedom are limited to support. Though many researchers improve the structure of exoskeletons to be lighter and explore better ways of human-machine interaction. Still, the traditional exoskeletons are still facing plenty of challenges. In the recent years, researchers begin to develop soft wearable robot which is composed of soft textiles, soft sensors and soft actuator. There is a soft exosuit that purposes to assist knee extension with soft-inflatable actuators [10]. Cable-driven system is used in soft exosuit to transmit force through the cables [11] [12] [13]. Compared with the traditional exoskeletons, the soft exosuit has numbers of advantages. Unlike traditional exoskeletons which have rigid structure, the soft exosuits are more comfortable to wear. Also, the soft exosuits is able to generate an assistive force during walking while not interfering with the normal gait.

Since the soft exosuit is mainly comprised of textiles, it doesn't limit the degree of freedom of joints and the human body's complex biomechanics. On the other hand, it is hard to control the soft exosuit to output a suitable assistance at biological joints. To support human body better, it is necessary to detect the gait event in real time. Camera-based system is one of the gait analysis systems, which can provide high accuracy. However, they are relatively expensive, and gait analysis will be limited to laboratory [14] [15]. A way to analyze gait is using the inertial measurement units (IMUs); The IMUs are relatively cheap, compact and lightweight. They are easy to be mounted on lower limb to measure the angle of joints [16] [17].

However, for accurate gait event detection, lower limb should attach at least six IMUs and the algorithms of using multiple IMUs is complicated [18] [19]. And when wearers want to use the system of IMUs, they must calibrate the postures of body which the IMUs correspond to. Our approach to analyze gait applies two kinds of sensors, plantar pressure sensors and IMUs.

The plantar pressure sensor are two insoles with six Force Sensitive Resistors (FSRs) each. There are certain gait events which are very difficult to be detected using only two IMUs during human walking. The plantar pressure sensors could identify different gait events especially those force-related ones such as heel strike (HS), foot flat (FF) and toe off (TO) which are very important phase in gait cycle. In an effort to deliver a stable assistance, two load cells are mounted on the soft exosuit to detect the assistive force. And the system adapts a learning iterative control strategy to adjust the assistance step by step.

II. System Overview

The soft exosuit in this paper is shown in Fig. 1, which is named by *SIAT Soft Exosuit* (SSEX). This suit is a composition of actuator system, battery, sensors and bands. And it is designed to assist human hip extension.

To deliver the assistive force from the thigh to the pelvis area and to attach sensors, the warps are necessary. The band is constructed with a woven textile with tough webbing. It insets to anchor to the wearer's thigh and closes with Velcro tabs, fitting a wide range of thigh shapes.

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(a) Walking with SIAT Soft Exosuit.

(b) System overview with components labeled.

Fig. 1. SIAT Soft Exosuit.

The sensors are an important part of the soft exosuit. Plantar pressure sensors, Inertial measurement units (IMUs) and load cells are used to gather real-time information from the wearer and the soft exosuit.

The plantar pressure sensors are mounted at the insoles. As shown in Fig. 2, the plantar pressure sensor consist of six Force Sensitive Resistors (FSRs). The FSRs are soft sensors and the shape of FSRs are flat which will not cause any discomfort. So they are fit to contact with foot plantar. The plantar pressure sensors are easy to carry and efficient to detect gait events. There are three FSRs placed underneath the heel and the front of foot respectively. So that we can detect events related to force changing. The response time of FSRs is less than 1 ms. So the plantar pressure sensors are used to detect the gait events in our system.

The IMUs we used to detect human posture is Perception Neuron (Beijing Noitom Technology Ltd., Beijing, China). Perception Neuron is a high performance motion capture system based on IMUs which can capture the human motion smoothly and naturally. On each leg, one IMU is mounted on the front of the thigh. The function of the IMUs are to obtain angular displacement during walking. Also, the load cells are used to measure the force on the hip extension load path. They are mounted at the back of thighconnecting the Bowden cable.

Fig. 2. Plantar pressure sensors.

III. Method

The soft exosuit is designed to help human walk and save their energy as much as possible. So it is necessary to detect key gait events, human posture and real assistive force. To detect gait accurately, our approach is to fuse the signals of plantar pressure sensors and IMUs. We use signal of plantar pressure sensors as a trigger to tell the timing of starting assistance and IMUs and load cells to tell how much we should assist.

A. Gait event detection

Most of energy is consumed from swing phase to stance phase for one leg during walking. Therefore, we decide to support the process of the hip extension. In order to support hip extension in time we have to detect gait event accurately. Human walking has a pattern [20]. The division of gait cycle is shown in Fig. 3 [20]. As shown in Fig. 3, the process of hip extension begins at mid stance and ends at terminal stance. Therefore, the mid stance is defined as the onset timing of assistance, the terminal stance is defined as the end timing of assistance. In the mid stance, one foot is standing on the ground, the other foot lifts to swing phase. In the terminal stance, one foot is still standing on the ground, the other foot strikes the ground. That is to say, there are two gait events to detect which are toe off (TO) and heel strike (HS).

It is considerable difficult to detect TO and HS by using IMUs which are mounted on shoes [21]. Therefore, our

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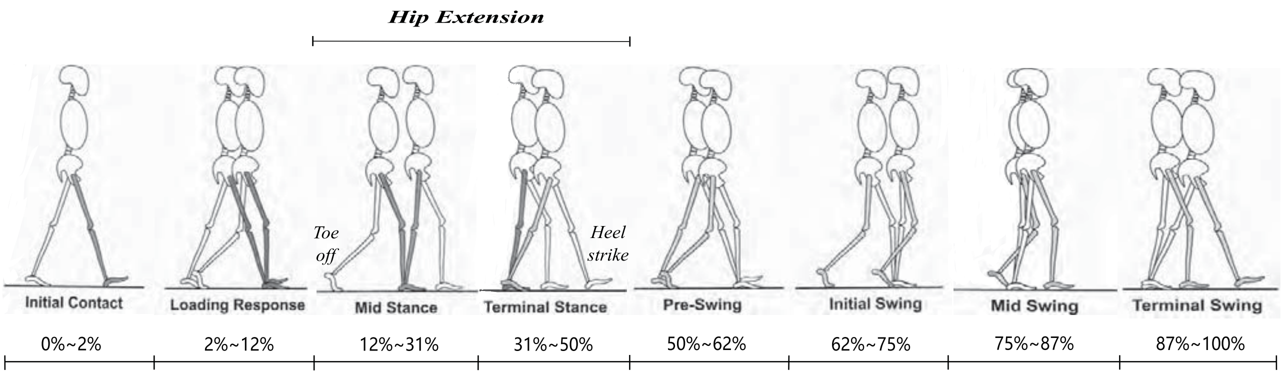

Fig. 3. Phases of gait with important events labeled.

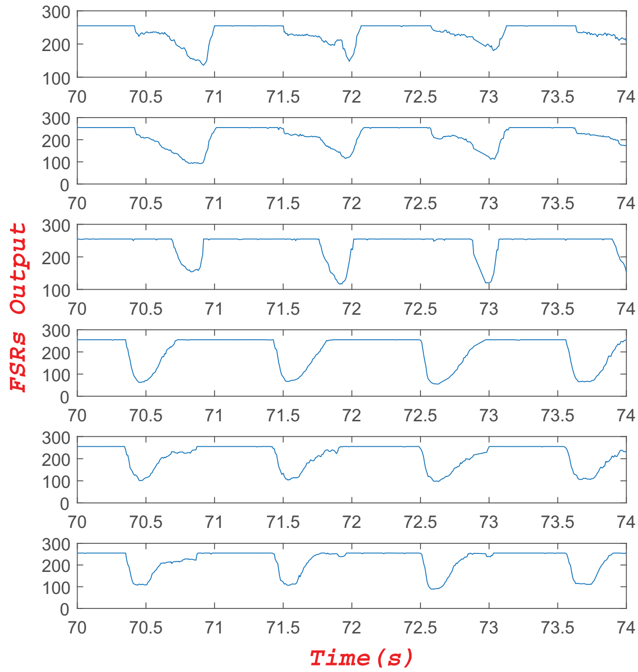

Fig. 4. Outputs of all FSRs.

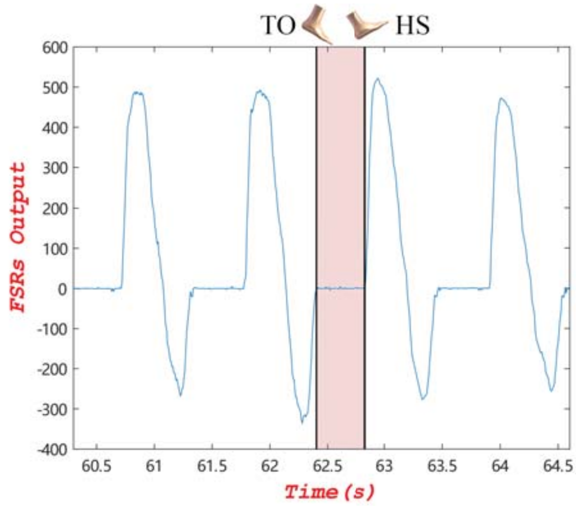

Fig. 5. Outputs of FSRs after calculation.

approach is using the plantar pressure sensors to do this. The plantar pressure sensors have features of low latency and long life time. Their response time of the plantar pressure sensor we use in our exosuit is less than 1 ms with repeatability of over 10 million times. There are six FSRs on one insole (shown in Fig. 2).

We believe there are more and better features in foot pressure trajectory than in joint angle trajectory. Because foot pressure can better reflect the force-related events and also has more obvious turning points which are easy to detect. To testify this idea, we made an experiment.

In the experiment, the subject walked naturally on a treadmill. The subject wore both foot pressure sensors and Perception Neuron (IMU-based detector) to identify differences between these two gait event detection methods. The speed of walking is 5 km/h for each subject and sampling frequency of plantar pressure sensors is 120 Hz.

The output data of subject one is shown in Fig. 4. One can observe the curves in Fig. 4 has an obvious pattern. Still it is difficult to distinguish heel strike and toe off events. So we use a function as follows:

$$S = FR_1 + FR_2 + FR_3 - FR_4 - FR_5 - FR_6 \qquad (1)$$

where FR_1, FR_2 and FR_3 are the outputs of FSRs in front of the plantar, FR_4, FR_5 and FR_6 are the outputs of FSRs underneath the heel, S is the output through the calculation. This function aims to find the center of pressure.

As shown in Fig. 5, by applying this function to data processing, we can get a very nice curve which represents the difference between pressure in tiptoe area and heel area. This method is simple but powerful. Processed data indicate how and when the center of foot pressure moves clearly. It also distinguishes events such as heel strike and toe off easier and faster.

This processing method has many other benefits. First, it can adapt to different walking habit. Different people has different habit of walking, which may cause some particular FSRs' value to be abnormally high. This method adds all

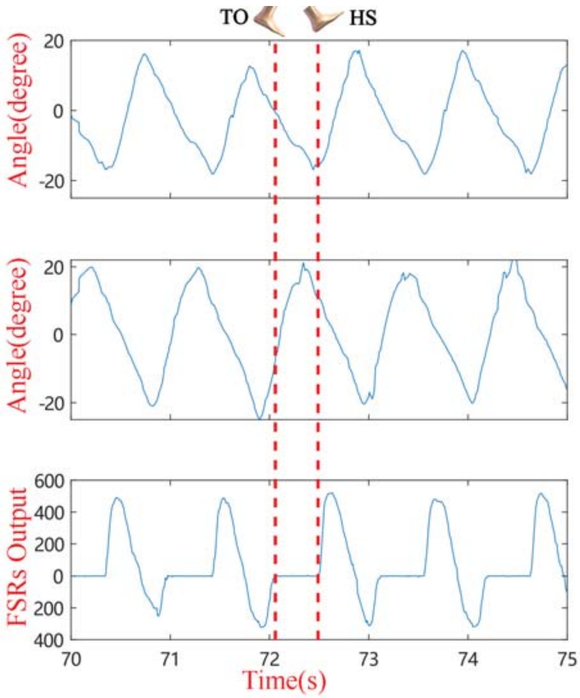

Fig. 6. Comparison of IMUs outputs and FSRs output during walking.

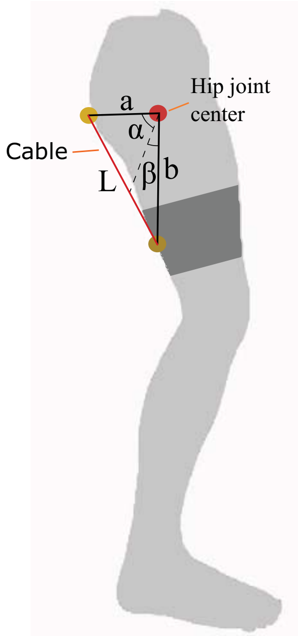

Fig. 7. Body geometry.

the tiptoe FSRs' value all together to prevent one particular FSR from generating an abnormally high value while others remain relatively low. By adding them all together, the pressure value will continuously be close to the wearer's body weight. Second, it can adapt to different people. The most obvious difference between two people here for foot pressure sensors is their body weight. If we focus only on the absolute value rather than the relative difference between pressure on tiptoe area and heel area, it will be very hard for us to detect a certain event because a new subject's weight and foot pressure trajectory can be totally different. However, the relative difference between pressure on tiptoe area and heel area is sufficiently close among all the subjects. Third, it is capable of filtering the noise automatically. There are some noises interfering with the real pressure value. Such as the vibration when foot strikes the tough ground, the vibration can influence the entire foot which will make the pressure signal to be messy. But by subtracting the tiptoe pressure from the heel pressure, part of the noise will be eliminated automatically and the curve will be more smooth by doing this.

Then we put the processed curve data and IMU data together to compare which way is better here to detect gait event and the timing of transmitting or ending assistive force. We can see from Fig. 6 that both Plantar pressure and IMU data have a good periodicity. However, it is obvious that there are too little events to be detected in the IMU curve. Except for the peak and trough of IMU curve, there is no more events can be detected easily. Unfortunately, the starting time of hip extension is between peak and trough point of IMU curve, which means this point is hard to detect just like other points between peak and trough point of IMU curve. However, in the curve of plantar pressure, there are apparently more turning points and more events to be detected. When the toe of the other foot is off the ground, the gluteus maximum begins to contract and push the body to move forward. So the plantar pressure center moves from the heel to the toe and finally pressure value becomes zero which represents the toe is off the ground. The *zero cross* event is the starting time of hip extension. It is also highly feasible to detect in the plantar pressure curve.

B. Position-Force Control

Even though timing of transmitting and ending assistive force are acquired at this point. However, to assist human body better, the information is just not enough. We should also know the angle of hip joint and the cable length to do accurate position control. Our way to do this is by measuring the hip angle during hip extension. By attaching IMUs on wearer's thigh and measuring the angle variation, Perception Neuron can do this accurately. Then we use body geometry to calculate the length of Bowden cable and the position of motor at the same time. When plantar pressure sensor detects the toe off event, the IMU-based hip angle measuring should be started. And when plantar pressure sensor detects the heel off event, the IMU-based hip angle measuring for one gait cycle is done.

The body geometry we use is shown in Fig. 7. The person in this figure is at a mid-stance [20], which is the start time of hip extension assistance. By using the formula shown below we can calculate the cable length which corresponds to motor position.

$$L = \sqrt{a^2 + b^2 - 2abcos(\alpha + \beta)} \tag{2}$$

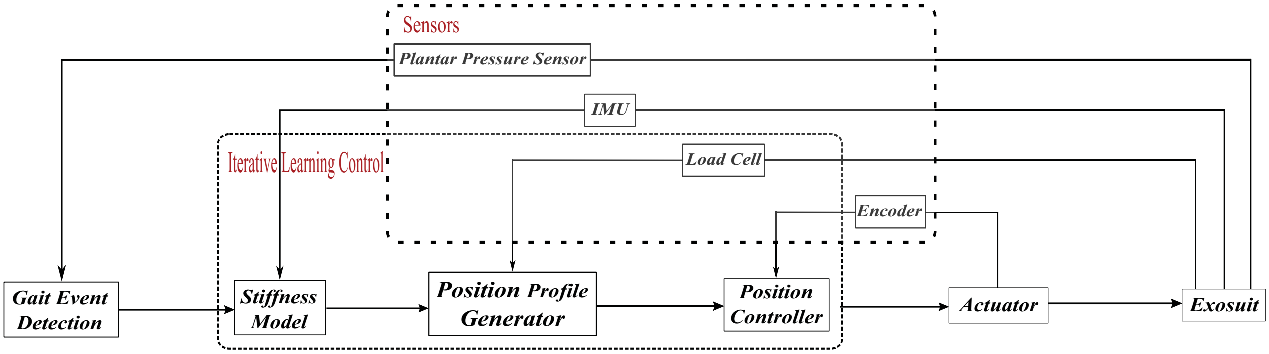

Fig. 8. Control diagram of the soft exosuit.

where L is the length of cable, a is the distance between the hip joint center and the cable connection point on the hip, b is the distance between the hip joint center and the cable fixing point on the thigh bands, α is the initial angle with standing on the ground. β is the hip joint angle during walking.

It is obviously not accurate by calculating cable length simply by using body geometry. Since calculating cable length simply by using body geometry fails to guarantee accuracy. This method can only help our motor rotate to a approximate angle. In order to give our hip joint a satisfied assistance, we should monitor the force level at the assistance point by using a load cell. The load cell will feedback the force level to help the position controller better the fine tuning. The real assistive force value will be compared with the expected force level. If the assistive force over performs, the controller will make sure there will be shorter cable length next cycle. And if the assistive force is insufficient, the controller will make sure there will be longer cable length next cycle. We use iterative learning control based method here to achieve this. That is to say we try to modify the cable length a bit in one gait cycle, then after enough gait cycles the force level be stable and the position controller will have a better performance over cycles. The control diagram is shown in Fig. 8.

IV. Performance

In order to testify the accuracy of the gait event detection, experiments were performed and data of objects walking with speed of 5km/h were collected with the frequency of 120 Hz, using plantar sensor and motion capture system (noitom).

As indicated in the figure, but these data show periodically pattern and match crests with maximum angles of hip joint and troughs with minimum angle of hip joint. The posture of coincides with initial contact of gait cycle at this time. Hence, stride time could be defined as time from one maximum angle of hip joint to the next one. Eight phases are derived from one gait cycle [20]. The hip extension is composed of the mid stance and the terminal stance. So the onset time of hip extension (toe off) is 12% GC, the end time of hip extension (heel stride) is 50% GC. To verify the precision of toe off and heel strike, stride time were retrieved to calculate the percentage of toe off and heel stride in GC.

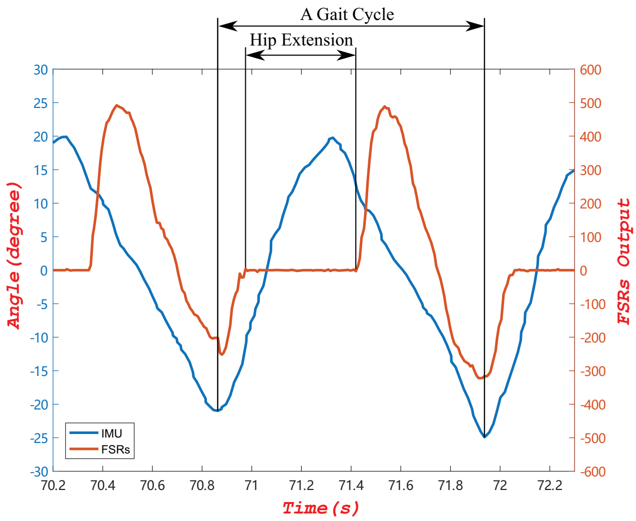

Fig. 9. Accuracy of the gait event detection with Plantar Pressure Sensors.

By the previous definition, we can distinguish the TO and HS from the curve of the plantar pressure sensors. We can see from the Fig. 9, the TO detected by the plantar pressure sensor is about 12% GC, the HS detected by the plantar pressure sensor is about 50% GC.

Five volunteers were recruited to participate in this experiment, and the experiment results are presented in table I. All of the five volunteers are young healthy adults including one woman. We can see from this table that by applying our method we can detect the starting and ending of hip assistance within 3% GC. Generally, 1% GC equals to about 10 ms in normal walking speed. So our detection method performs fairly good and useful in practice.

V. Conclusion

This paper has presented the framework of the control method applied in *SIAT Soft Exosuit*, which includes the assistance time estimation method based on plantar pressure sensors. The advantage of plantar pressure sensors to detect the starting or ending time of assistance is analyzed. And the

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TABLE I
THE TIME OF TO AND HS FOR DIFFERENT TESTING SUBJECTS

Subject	TO(%)		HS(%)	
	$Timing$	$Error$	$Timing$	$Error$
1	11.23	-0.77	51.56	1.56
2	10.51	-0.49	50.32	0.32
3	10.82	-1.18	50.68	0.68
4	11.83	-0.17	52.02	2.02
5	11.38	-0.62	51.66	1.66

position-force control method we use to assist human body accurately is introduced. The experiment result shows our system has a good event detection ability by using plantar pressure based method. Also, the hip joint can get timely and accurate assistive force by using the proposed control method and the SSEX platform.

ACKNOWLEDGMENT

This work is supported by the NSFC-Shenzhen Robotics Research Center Project (U1613219); Shenzhen Overseas Innovation and Entrepreneurship Research Program (KQJSCX20170731164301774) and Shenzhen Technology Project (JSGG20160301160759264). The authors would like to thank Noitom Corporation for providing excellent motion capture systems.

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