Flexible, wireless, multifunctional integrated electronic system for daily wearable gait detection

Weijie Liu, Shihang Wang, Jinyu Li, Deqing Mei and Yancheng Wang*, Member, IEEE

Abstract—With the rapid development of Internet of Things and Artificial Intelligence, long-term and wearable gait detection is of great significance for healthcare, rehabilitation, and sports training. However, current wearable gait detection devices are generally less flexible and only a small number of gait features can be detected, which limits their practical applications. Herein, we proposed a novel flexible, wireless, and multifunctional electronic system with proximity and contact pressure sensing capabilities for daily wearable gait monitoring. The system mainly consists of two types of sensing modulus: proximity sensing units for the detection of periodic swing of legs and contact pressure sensing units for swing force sensing of the knee during walking, along with a wireless acquisition module and an APP for data visualization. In addition, the hardware of the system is lightweight and fully-flexible for comfortable wearing on the knees. Benefiting from the above advantages, our system can realize the detection of more gait characteristics related to spatial changes such as stride length, spatial posture of legs, besides the step characteristics, while maintaining the flexibility of the device. It verifies the application potential of flexible integrated electronic system for daily wearable gait monitoring.

Keywords—Wearable electronics; Gait detection; Proximity sensing; Pressure sensing; Flexible sensors.

I. INTRODUCTION

AIT can be regarded as the manner or style of walking, which is a fundamental aspect of human movement [1]. JIt involves the intricate coordination of various body parts and muscles, resulting in a unique pattern of each individual movement. The detection of gait characteristics can provide a wealth of information to reflect an individual's physiological and biomechanical status, such as gait patterns can be indicative of underlying neurodegenerative diseases and musculoskeletal disorders [2]. Thus, gait detection and analysis are widely used in the fields of rehabilitation, sports performance evaluation [3], and biomechanics [4]. By analyzing gait patterns, researchers and clinicians can gain a better understanding of human's functional limitations, identify abnormalities or asymmetries, and develop targeted interventions to improve mobility and prevent injuries [5].

There are several methods have been proposed for gait pattern detection and characteristics analysis [6], such as using visual capture system and pressure platforms [7]. Pasinetti et al. [8] presented a marker-less motion capture system using commercial cameras and force platform to evaluate the upper limb stress of subjects. The camera system captured and dissects body movements, analyzing gait features through 2D images. The pressure platform gauged gait characteristics by discerning pressure changes in feet. Although these methods can provide accurate and detailed analysis [1], they are often expensive and require specialized expertise to operate. Additionally, those equipment would be bulky and cumbersome [9-10], which limits their practical daily usage. Several efforts have been applied for developing the lightweight and wearable device for gait detection [11-12]. Various motion sensors, such as accelerometer [13], gyroscope [14], are strategically utilized and placed on the shins, feet and waist, to accurately measure the gait parameters during walking. However, these sensors usually arranged in multiple locations on the body for detection purposes and are basically rigid, thus would be not suitable for daily and long-term wearing. The thin and flexible electronic devices that can be conformally attached to various parts of body and provide an almost seamless wearing experience, making them promising candidate for future development of wearable gait detection devices.

With rapid development of flexible electronics, especially flexible pressure sensors and strain sensors [15-16], several studies have begun to utilize flexible sensors for wearable gait detection [17]. For example, Lee et al. [18] developed a wearable triboelectric nanogenerator-based device for gait analysis. Two flexible triboelectric sensors were equipped in insole and a 98.4% identification accuracy for five different human movements was achieved. The utilized flexible sensors could significantly enhance the wearing experience. However, the integration level of these devices remains relatively weak considering the practical purposes. And current detection methods mainly rely on flexible pressure or strain sensors to detect contact information in areas such as the soles of the feet and wrists for gait detection. These methods can only extract limited gait features, primarily focusing on step detection, which restricts their practical usage. Therefore, there is an urgent need for further research aimed at new gait detection method and flexible integrated device suitable for daily wearable gait analysis.

In this study, we proposed a novel flexible integrated electronic system based on the combined perception of contactless proximity and contact pressure at the knee for daily wearable gait monitoring. It consists of an interdigital proximity sensing module, a porous SR/graphene pressure sensing module, a wireless acquisition module and a data visualization APP. The hardware of the system is lightweight and fully-flexible for comfortable wearing on the knees. By analyzing the waveform characteristics of the signals and conducting experimental verification, the system can realize the detection of more gait characteristics related to spatial changes such as stride length, spatial posture of legs, besides the step characteristics, while maintaining the flexibility of the device.

II. DESIGN OF INTEGRATED ELECTRONIC SYSTEM

A. System Overview

The knee joint is pivotal in walking, moving spatially as the legs swing. Varied walking modes induce corresponding changes in both knees. The movement patterns of the knees encapsulate substantial gait characteristic data. Moreover, during walking, the knees endure less load compared to the soles of feet, rendering them an ideal location for the placement of flexible sensors. To enable comprehensive daily monitoring of multiple gait characteristic parameters while ensure device comfort, we proposed a flexible, wireless, multifunctional integrated electronic system with both proximity and pressure sensing capabilities. As shown in Fig. 1, the integrated electronic system is worn onto the knee, which continuously collect gait data and transmit wireless trough Bluetooth. Then users can receive and view graphical gait data through smartphones to real time access their health status.



Fig. 1. Conceptual schematic of flexible, wireless, multifunctional integrated electronic system for daily wearable gait detection.

As depicted in Fig. 2(a), the system comprises four modulus: a proximity sensing module, a contact pressure sensing module, a wireless acquisition module for real-time gait signal collection, and an APP named as GaitMonitor for data visualization. During walking, the periodic swinging motion of the legs alters the spatial position and distance between them. The flexible capacitive proximity sensing module positioned on the inner side of the knee generates a fringe electric field between the legs. The periodic leg swinging disrupts this fringe electric field, consequently influencing the capacitance of the proximity sensing module. Analyzing the sensor signals allows for extraction of gaitspecific parameters. Concurrently, as the knees undergo periodic swinging during walking, monitoring the swing strength via flexible pressure sensor enables extraction of additional kinetic gait features. This approach reveals more spatial feature information compared to the methods solely relying on flexible sensors with contact sensing characteristics placed on the soles of feet. To improve comprehension of the system's functions and principles, detailed system design specifications will be described separately at the hardware and software levels.

B. System Hardware Design

The architecture and information flow of the entire system are illustrated in Fig. 2(b), the sensing modules continuously monitor pressure and distance information during walking movement, while the signal acquisition platform ensures realtime data collection, wirelessly transmitting the data to the mobile phone receiver via the BLE chip. Both the pressure sensing and proximity sensing modules are connected to the acquisition module through a reinforced flexible printed circuit (FPC) interface, and all three modules are encased in Polydimethylsiloxane (PDMS) for enhanced wearability.



Fig. 2. (a) Structural diagram of flexible, wireless, multifunctional integrated electronic system. (b) The architecture diagram of integrated electronic system

Proximity sensing module: As in Fig. 3(a), the proximity sensing module consists of a 3×3 interdigital capacitor array,

which operates on the electric field principle to detect distance information. When energized, two electrode plates of the interdigital capacitor accumulate charge. This not only generates an electric field between the plates but also induces a fringe electric field in the surrounding space. Proximity of external objects disrupts the fringe electric field to varying degrees, contingent upon the closeness and material composition, and the interdigital capacitor experiences a reduction in capacitance value. We have demonstrated that the interdigital electrode structure has a stronger fringe electric field and can achieve more sensitive proximity detection in our previous work [19]. To accommodate the loading area at the knee, the inter-finger spacing of interdigital electrodes is set at 1.0 mm, interdigital length is 11 mm, and the spacing between units is 10 mm. A reinforced FPC gold finger is designed at the end of electrodes, which is connected to the acquisition circuit through FPC interface.



Fig. 3. (a) Proximity sensing module and interdigital capacitor array. (b) Pressure sensing module and pressure sensing principle. (c) Signal acquisition module. (d) Schematic diagram of the acquisition circuit of piezoresistive array

Pressure sensing module: The pressure sensing module has 4×4 pressure sensing units, and each unit consists of three layers: upper electrode layer, central pressure-sensitive material layer, and bottom electrode layer. Considering the requirements of wearability, both upper and bottom electrode layer substrates are made of flexible Polyimide (PI) substrates, and copper electrodes are patterned on the PI substrate through photolithography and etching processes. As shown in Fig. 3(b), the pressure-sensitive material is our previous proposed porous SR/graphene composite material [20]. It has closed pores with an average pore diameter of about 300 µm. The conductive path is destroyed under pressure, causing the resistance of the material to change. The pressure can be obtained based on the changes in resistance. To improve pressure sensitivity, the sensitive material profile is designed into a truncated-pyramid shape [20]. The sensing module is also designed with a

reinforced FPC gold finger for better connecting to the acquisition circuit.

Wireless signal acquisition module: Considering the wearability and lightweight device, the signal acquisition module is designed as a flexible printed circuit board (FPCB) with an overall size of 52 mm \times 47 mm. As shown in Fig. 3(c), the entire circuit is powered by a 3.7V lithium battery, and the voltage is converted to 3.3V through a DC-DC regulator (PW2051) to meet the voltage requirement of other circuit modules such as MCU (STM32F103RCT6) and Bluetooth module (WH-BLE106). In order to collect the capacitance signal of proximity sensing module, the MCU controls two 3 to 1 channel MUXs (TS5A3359DCUR) to select the sensing unit. converter The capacitance-to-digital (AD7150BRMZ) measures the capacitance value of the selected sensing unit through square wave excitation, and then transmits the measurement results to the MCU through the IIC communication protocol. As shown in Fig. 3(d), the resistance signal of pressure sensing module is measured through the principle of voltage division. The MCU controls a 4 to 1 channel MUXs (ADG704BRMZ) to select the row electrode of the sensing array, and then reads the output voltage of the target column in the voltage following module (AD8619ARZ) through the ADCs. The resistance value can be obtained by comparing with standard voltage (3.3V). After receiving the data from the sensing modules, the serial port of STM32 communicates with the BLE module for wirelessly transmitting the data to mobile phone. The sampling frequency of acquisition module is 320 Hz, which meets the acquisition frequency requirements in the daily gait detection process.



Fig. 4. (a) Schematic diagram of the UI interface of the GaitMonitor APP. (b) Operation logic diagram of gait monitoring APP.

C. System Software Design

In order to help user record and evaluate health status of their walking gait at any time, a smartphone app that can receive and visualize gait data in real-time is crucial. As in Fig. 4, we have developed a smartphone app adapted to the wearable integrated electronic device using the MIT App Inventor. The gait monitoring APP is divided into two levels: front-end UI and back-end logic. The front-end is used for twoway interaction with users, and back-end processes various data and algorithms. The front-end UI interface of the APP is shown in Fig. 4(a), which mainly includes the sensor signal visualization area and various functional interaction buttons. As shown in Fig. 4(b), the operational sequence of the entire APP is as follows: 1) Upon powering on the wearable integrated electronic system, gait signals are collected during walking and transmitted wirelessly via low-power Bluetooth. 2) Subsequently, the user accesses the gait monitoring APP, searches for nearby low-power Bluetooth devices, establishes a Bluetooth connection, and begins to receive Bluetooth data. 3) Within the application, the user can select the sensor unit data for viewing, which is then visualized in real-time on the screen. Additionally, users have the option to save the data to a cloud server for subsequent processing and analysis.

III. EXPERIMENTAL SETUP AND PROCEDURE

Following the design and manufacturing processes at both hardware and software levels, a flexible, wireless, multifunctional integrated electronic system has been developed. To evaluate its performance, we affixed the system to the knee and conducted gait monitoring experiments during daily walking, as depicted in Fig. 5(a).



Fig. 5. (a) Wearing diagram of flexible integrated electronic system. (b) Experimental diagram of corridor walking.

The evaluation focused on identifying gait parameters, extracting gait features. Initially, a flat corridor walking test was employed to investigate proximity and pressure signal characteristics during walking, as illustrated in Fig. 5(b). Signal waveforms were utilized to discern the gait phase within the walking cycle. Subsequent experiments involved comparison of various gait parameters to study quantitative feature extraction methods. The gait features for exploration primarily encompass walking speed, step length, knee pressure during walking, and leg spatial posture. These features are essential for health monitoring and athletic training.

IV. RESULTS AND EVALUATION

A. Identification of gait cycle parameters

Upon detection of gait signals during walking, the acquisition of gait characteristics becomes imperative. Therefore, the first step involves identifying gait cycle parameters, primarily explored through the waveform changes of the proximity signal. Given the uniformity in waveform

change trends across the sensing array, it is deemed appropriate to utilize the waveform of a single unit for gait cycle analysis. Commencing with the left foot forward and right foot rearward as the starting point, a comprehensive walking cycle comprises the stance stage (left foot grounded, right foot swinging) and the swing stage (left foot swinging, right foot grounded), as shown in Fig. 6(a). Examination of the spatial knee distance alterations within these stages reveals that, during the stance phase, the knee distance gradually diminishes from the maximum position (Heel-strike) to a minimum (Mid-stance), subsequently increasing from this nadir to another maximum position (Terminal stance). Conversely, during the swing phase, the distance progressively diminishes from Terminal stance to an equivalent minimum (Mid-swing), then gradually expands from this minimum back to initial maximum position.



Fig. 6. (a) Schematic diagram of four key points in a gait cycle. (b) The detailed view of proximity signal diagram during walking.

The detailed view of proximity waveform for the sensor unit during walking is presented in Fig. 6(b). The proximity signal exhibits periodic waveform variations, featuring primary and secondary wave peaks, as well as primary and secondary wave troughs serving as distinctive points of reference. The pattern of the progression between adjacent primary wave peaks shows a decrease-increase-decrease-increase sequence. Remarkably, this pattern aligns precisely with the earlier analysis of knee distance alterations in the stance and swing stages. Consequently, the primary and secondary wave peaks correspond respectively to the Heel-strike and Terminal-stance nodes, representing the phases within the gait cycle where the knee distance is greatest. Similarly, the primary and secondary wave troughs respectively align with the Mid-stance and Midswing nodes, reflecting the phases in the gait cycle characterized by the smallest distance between the knees. Notably, there exists a discernible difference in signal

amplitude between the primary and secondary wave peaks, as well as between the primary and secondary wave troughs. This divergence predominantly arises from asymmetry in the spatial posture of the experimenter's legs during the Stance and Swing stages of walking, resulting in disparate external interference for the sensor across these two stages. Furthermore, this difference can also furnish a critical reference index for assessing the health of walking posture.

B. Extraction of gait features

Upon identifying gait cycle parameters, the method for quantitatively extracting gait features during walking can be further explored. Among these features, step count stands out as the most vital and fundamental. In scenarios necessitating quantitative training or rehabilitation, subjects are often required to walk a set number of steps within a specified time, with their health condition assessed based on physiological indicators post-walking. Accurate detection of walking steps is pivotal for wearable gait detection systems. Leveraging the previous analysis using the proximity signal to identify each phase of the gait cycle, we can proceed to extract step features. The transition from one signal peak to an adjacent peak signifies the subject's movement from the Heel-strike phase to the Terminal-stance phase (or vice versa), thereby enabling step count determination by tallying the number of signal peaks. Simultaneously, the walking speed can be evaluated based on the time interval (T) between two adjacent peaks, while Fig. 7(a) displays signals of varying walking speeds. Using the slow-walking process as the reference interval T, we observed a decrease in the average time interval between adjacent peaks from T to 0.6T during normal walking and further to 0.3T during fast walking. Additionally, quantitative step pace was determined by counting the number of steps completed within a sample period. For instance, 0.0973 during slow walking, 0.1778 during normal walking, and 0.2933 during fast walking. These values provide a means to quantify walking speed.



Fig. 7. (a) Proximity signal comparison diagram under different walking speeds. (b) Proximity signal comparison diagram in different stride distances.

While stride distance represents another key gait feature, current wearable gait detection equipment lacks the capability to extract stride features. Within the gait cycle, Heel-strike and Terminal-stance denote nodes reflecting the greatest knee distance, while Mid-stance and Mid-swing represent nodes with the smallest knee distance. Accordingly, evaluating the size of a step involves assessing the difference in signal amplitude between these two nodes ($C_{H(T)}$ - C_M). A larger disparity corresponds to a longer step, while a smaller disparity indicates a shorter step. Fig. 7(b) displays demonstrable signals of varying stride distances, the quantitative stride distance is 0.03125, 0.08621 and 0.15130 respectively in the three stages, illustrating the increasing difference in peak and trough of the proximity signal as the experimenter progresses from small to large step distances.



Fig. 8. (a) Proximity signal diagram under different leg postures. (b) Average Proximity signal diagram under different leg postures.

Furthermore, the spatial posture of the legs during walking serves as a crucial indicator for health assessment. To explore the leg posture evaluation method, a comparative experiment was conducted involving toe-in, toe-out, and normal walking postures within a corridor, as depicted in Fig. 8(a). Differences in trough amplitude were observed among the posture signals. Notably, the average proximity signal can more clearly reveal these differences, as shown in Fig. 8(b). The average amplitude level of average signal ($C_{average}$) can evaluate the spatial posture of the legs during walking, and the average amplitude level is 1.0789, 1.0833 and 1.0856 respectively in three stages. The inner toe-in posture exhibited the lowest trough amplitude level, while the outer toe-out posture displayed the highest amplitude level. Meanwhile, the average pressure signal from the knee sensing array was utilized to detect instances of sprain during flat staircase ambulation, as shown in Fig. 9. Each step prompted an increase in resistance of the piezoresistive sensor module, with regular voltage fluctuations from 0.81 V to 0.91 V observed during normal walking. In the event of sprain, the contact between the user's knee and the sensor may slip, leading to a sudden decline to 0.7879 V in the sensor signal. Monitoring sprains aids in evaluating walking health and preempting disease occurrence.



Fig.9. Pressure signal diagram of sprain monitoring during walking.

V. CONCLUSION

Daily wearable gait analysis emerges as a pivotal facet for enhancing medical health, rehabilitation, and sports training. The creation of lightweight, flexible, and wearable gait detection device to monitor gait data during daily activities is essential for effectively analyzing body movement parameters and overall health status. Present detection methodologies predominantly lean on the utilization of flexible pressure or strain sensors to capture contact data from regions like the soles of the feet and wrists for gait evaluation, thereby enabling only a limited extraction of essential gait characteristics. These inherent deficiencies considerably impede their real-world utility. In this article, a flexible, wireless, multifunctional integrated electronics system is developed for wearable daily gait monitoring, which can fit comfortably on the knee and transmit gait signals wirelessly. The system detects the periodic swing of legs through proximity sensing principle and the swing force of the knee through the pressure sensing principle during walking. By analyzing the waveform characteristics of the signals and conducting experimental verification, the system can realize the identification of gait cycle and the extraction of gait characteristics such as gait steps, step pace, the pressure changes at the knee, stride distance, spatial posture of the legs. In general, the developed method and designs provide new solutions for daily wearable gait detection. It has the potential to push forward the development of wearable gait detection and further access to wearable personal healthcare.

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