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A Wearable Walking Monitoring System for Gait Analysis

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***Abstract*— In this paper, both hardware and software design to develop a wearable walking monitoring system for gait analysis are presented. For hardware, the mechanism proposed is adaptive to different individuals to wear, and the portability of the design makes it easy to perform outdoor experiments. Four force sensors and two angle displacement sensors were used to measure plantar force distribution and the angles of hip and knee joints. For software design, a novel algorithm was developed to detect different gait phases and the four gait periods during the stance phase. Furthermore, the center of ground contact force was calculated based on the relationships of the force sensors. The results were compared with the *VICON* motion capture system and a force plate for validation. Experiments showed the behavior of the joint angles are similar to *VICON* system, and the average error in foot strike time is less than 90 ms.**

I. Introduction

Walking involves a series of complex movements associated with human lower extremity. Over the last few decades, much research has focused on gait analysis. From visual inspection, sensor technology, to motion capture system, various studies have led to different applications.

Based on the continuous nature of the walking gait cycle, research in biomechanics had divided it into two phases: stance phase and swing phase, to indicate whether or not the foot was in contact with the ground. To identify them, stance phase and swing phase are separated by two specific gait events, initial contact (IC) and toe-off (TO). Furthermore, stance phase is subdivided into four periods: loading response (LR), mid-stance (MS), terminal stance (TS), and pre-swing (PS); swing phase is subdivided into initial swing, mid-swing and terminal swing [1], [2].

The current gold standard that is the most reliable in performing gait analysis is believed to be the combination of motion capture system and force plate system, which is able to provide both kinematic and kinetic information in spatial coordination, such as the *VICON* motion capture system and the *Kistler* force plate system. Among them, the motion capture system is marker-based, requiring the subject to be placed with numerous markers on the body. It often takes more than an hour to place the markers on the subject. In addition, the force plate is mounted on the floor and is needed to be stepped by the subject correctly to obtain good results. As a result, the subject needed to be trained for the experiment, and the experiment could only be done in the professional motion laboratory that has trained operators and is able to afford the expensive equipment.

Due to the reasons stated above, many studies tried to seek alternative solutions to the in-door and costly limitation of the standard system. With the development of sensor technology, many kinds of sensors, such as accelerometers, gyroscopes, force-sensitive-resistor (FSR), electromyography (EMG) sensors, or combinations of the above, are used to build portable and wearable systems to conduct gait research [3]-[7]. Greene *et al.* developed a body-worn gait analysis system with gyroscopes, which was able to detect IC and TO via the proposed algorithm [4]. The result was compared with the force plate, with minor resulting error. However, since gyroscopes were the sole measurement tool of the system, it could only provide kinematic information. To obtain both kinematic and kinetic information, several hybrid systems were proposed. Senanayake *et al.* used gyroscopes and FSRs with fuzzy logic to develop a gait phase detection system [5]. Although their gait phase detection algorithm was acceptable, the validation of the accuracy remained dubious. The system developed did not compare with standard systems. On the other hand, the errors reported were calculated from the difference between the statistical data, which indicated the average duration of each gait period, and the data obtained from the system. Another hybrid system that Bamberg *et al.* developed was the "GaitShoe" system, which was able to provide detailed plantar information, and was validated by comparison to professional systems with healthy and Parkinsonian gait [6]. Nevertheless, with the absence of knee and hip joint angles, the system cannot be implemented in other applications, such as designing the lower extremity exoskeleton or biped robots, whose joints kinematics are important information [8], [9].

This paper proposes a wearable gait monitoring system. With a combination of four *Flexiforce* sensors and two *Burster* angle displacement sensors, the system is able to acquire both kinematic and kinetic information on gait cycle in the sagittal plane. *Flexiforce* sensors have been proved to provide better linearity, repeatability and time drift than FSRs [10]. The *Burster* angle displacement sensor is a high resolution potentiometer which can be used immediately and does not need calibration like a gyroscope sensor does. For software

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design, a novel algorithm was developed to detect the two gait phases and to segment the four gait periods during stance phase. Furthermore, the center of ground contact force was calculated based on the relationships among the four *Flexiforce* sensors. Finally, the experimental results were compared with the *VICON* motion capture system and force plate for validation.

II. Methods

A. Sensor Configuration and Hardware Design

Four *Flexiforce* sensors were used to measure plantar force distribution. These sensors were located on the 1st metatarsal head (Meta1), 4th metatarsal head (Meta4), hallux and heel, based on the biomechanical considerations [1]. As shown in Fig. 1, the sensors were placed on a shoe, and the placement could be modified to match different subjects.

Two *Burster* potentiometers were used to measure the knee's and hip's angles. In order to obtain accurate temporal information and angle displacement, it is crucial to place the sensors right beside the joints. A mechanism was designed for this express purpose. As shown in Fig. 2, the potentiometers were integrated into the mechanism; the length can be changed for subjects with different lengths of thighs and shanks. Velcro was used to affix the mechanism to the body and the combination was robust since the Velcro was for medical use. Wires were also integrated into the mechanism to prevent interference during walking. The total weight of the hardware system, including the circuits and a backpack, is 2.5 kg.

B. Data Acquisition

A 4-channel circuit was made to achieve amplification of the signals from the *Flexiforce* sensors, and a 2-channel circuit was made to measure the divided voltage of the potentiometers. A USB data acquisition (DAQ) device (NI-USB-6210), manufactured by National Instruments (NI), with 16-bit resolution was used to transmitted all the data to the host laptop in 1000 Hz sampling rate. The LabVIEW software, which is also manufactured by NI, was used to acquire data via the DAQ device. The circuits, DAQ device and laptop were all carried by the subject in backpack during the experiment. After the trial, the data were uploaded to the internet immediately, and could be downloaded by any other computer to perform offline analysis.

Before performing the algorithm for gait analysis, the raw signals acquired from the DAQ device were first filtered by the second order inverse Chebshev filter. The cutoff frequency was set as 60 Hz after the observation of the result from fast Fourier transform (FFT). To verify the performance of the filter, the signal-to-noise ratio (SNR) was calculated as follows:

$$SNR=10\cdot \log\sqrt{\frac{(\sigma_{Signal})^2}{(\sigma_{Base})^2}} \tag{1}$$

where σ_{Base} is the standard deviation of the signals during the initial period of the experiment. During the initial period, the subject was asked to stand still for 10 seconds. Similarly, σ_{signal} is the standard deviation of the signals during the walking period.

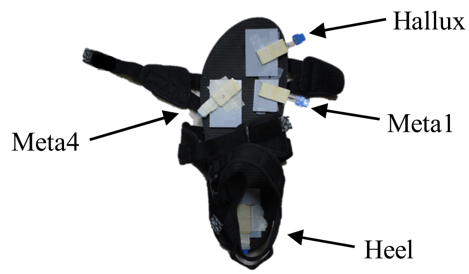

Fig. 1 Placement of the four *Flexiforce* sensors.

Fig. 2 The designed mechanism for potentiometers. The length of the mechanism is adjustable, and the wires are well integrated into the mechanism.

C. Gait Analysis

For the gait analysis, a novel algorithm was developed to detect IC and TO in order to separate stance phase and swing phase. After the gait phases were detected, the program would further segment the four gait periods during the stance phase, including LR, MS, TS and PS. From the statistical result, the maximum knee flexion angle during swing phase is 50 to 70 degrees [11]. Therefore, the intersection points of the horizontal 40 degree line and the data of knee that have positive slopes were chosen as the initial threshold points to perform the algorithm.

The timing of heel strike was used for IC detection; it was a local minimum that could be found by (2), where $H(n)$ is the data from the *Flexiforce* sensor placed on heel, and n begins at the initial threshold point mentioned above:

$$\text{IC}=\begin{cases} 1 & \text{if } H(n)-H(n-1)<0 \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

For TO, the procedure is similar, as shown in (3), where $T(n)$ is the data from the *Flexiforce* sensor placed on hallux:

$$\text{TO}=\begin{cases} 1 & \text{if } T(n)-T(n-1)>0 \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

Since IC and TO were determined, the four periods: LR, MS, TS and PS could be segmented inside the stance phase. The criterion to separate LR and MS is the moment that Meta1 hits the ground. For MS and TS, the criterion is the moment that the heel is above the ground, meeting its local minimum value.

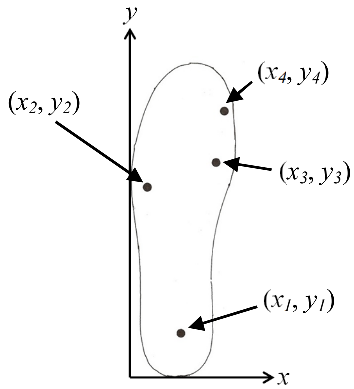

Fig. 3 To calculate C_{GCF}, the positions of the *Flexiforce* sensors are formatted to the Cartesian coordinate system.

Finally, the criterion of TS and PS is the time when hip joint extends to its maximum value during stance phase [2]. Since these aspects are all about finding local extreme value, the procedure can be done by modifying either (2) or (3). Besides gait phase detection and segmentation, the center of ground contact force was also calculated by (4):

$$C_{GCF}(x, y) = \frac{\Sigma (x_i\,,\ y_i) F_i}{\Sigma F_i} \tag{4}$$

In (4), F_i is the amplitude of the i^{th} sensor, and x_i, y_i is the real position measured in the Cartesian coordinate system, as shown in Fig. 3. The MATLAB software was used to develop the algorithms, and the codes were merged into LabVIEW to develop complete software.

III. Result and Discussion

A. Experimental Setup

The gait of two healthy subjects (males, 21 and 22 years old) were measured and analyzed. The experiments were started as soon as the subjects triggered the remote controller. During the experiment, each subject was guided by computer voice that was generated by the laptop in the backpack. The program would ask the subject to stand still for 10 seconds, and walk for 10 seconds.

B. Gait Phase Detection and Stance Phase Segmentation

After the inverse Chebshev filter was applied, the amplitudes of the *Flexiforce* sensors were decreased since the raw data have low SNRs. In addition, all of the signals had time shift. However, on average, the filter improved the SNRs of force sensors from 6.95 dB to 10.15 dB. Although suffering from time shift and decrease in amplitude, the temporal relationships of the data remained the same; therefore they would not influence the results of the gait analysis.

As mentioned in the previous section, the first step to perform gait analysis is to detect IC and TO. A sample from the results is shown in Fig. 4, where the solid line indicates the heel signal, and the dash line represents the hallux signal. After the gait phases were detected, the gait periods during the stance phase were detected, as shown in Fig. 5 for the same sample in Fig. 4, in addition to the signals of Meta1 and Meta4. Both hip and knee angles from the same sample are shown in Fig. 6.

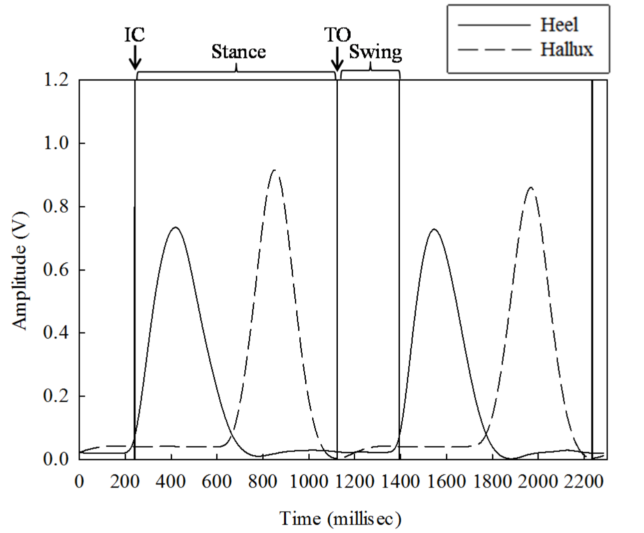

Fig. 4 IC and TO were detected to separate the stance and swing phases.

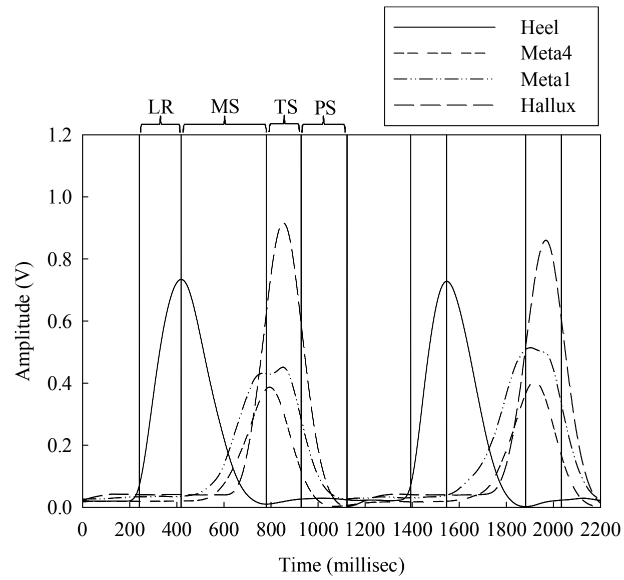

Fig. 5 Segmentation of gait periods during the stance phase.

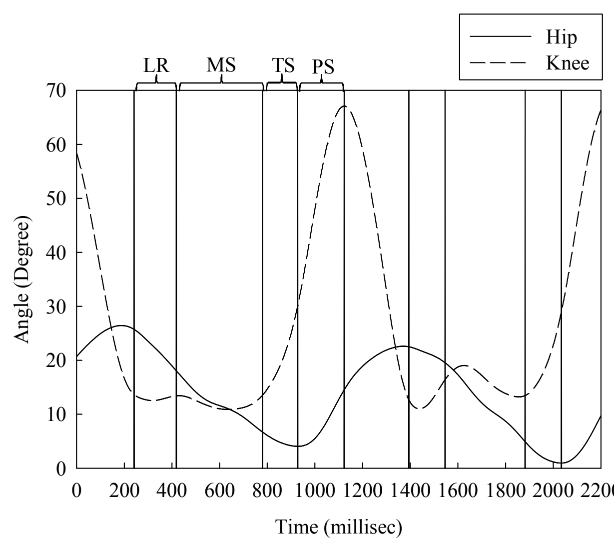

Fig. 6 Angles of hip joint and knee joint.

C. *Center of Ground Contact Force*

The trajectory of the change in the center for the ground contact force was plotted in Fig. 7. The timing information of IC and TO was used to determine the required region, that is, the starting and the ending time of the stance phase. It can be seen in Fig. 7 that the trajectory started from the position that is near the heel and ended at the position near to hallux.

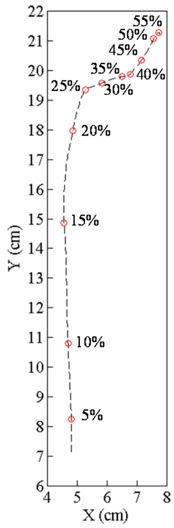

Fig. 7 Calculation of center of ground contact force. Each circle corresponds to a percentage of the gait cycle.

D. *Validation with VICON and Force Plate*

To validate the result, one subject was asked to simultaneously undertake the experiment with the purposed system and *VICON* motion capture system and force plate for five trials. The errors are reported in Table I, which shows the temporal differences in specific events and the errors in joint angles between the two systems.

As shown in Table I., the temporal error of foot strike is less than 90 ms in average; while the timing of joints to reach their maximum angle shared a similar level of error in lag. It is believed to be the misalignment of the potentiometers to the joints that caused the delay. However, the overall characteristics of the waveforms are similar.

TABLE I. ERRORS COMPARED WITH STANDARD SYSTEM

Trial number	Foot strike time	Max of knee flexion	Max angle of knee flexion	Max of hip extension	Max angle of hip extension
1	105.0 ms	45.7 ms	0.02°	90.7 ms	17.37°
2	79.0 ms	128.0 ms	1.26°	187.7 ms	17.07°
3	92.2 ms	119.3 ms	1.21°	166.0 ms	17.07°
4	72.8 ms	29.0 ms	3.37°	84.3 ms	16.15°
5	79.7 ms	37.0 ms	0.82°	89.0 ms	17.68°
Mean	85.8 ms	71.8 ms	1.34°	123.5 ms	17.07°
Standard Deviation	12.9 ms	47.8 ms	1.24°	49.3 ms	0.57°

IV. CONCLUSION

This paper proposed both hardware and software design of a gait analysis system. The system proposed is able to perform gait analysis base on the algorithm developed. However, since the force sensors can only measure single points, it is unlikely to accurately carry out detail kinetic analysis, such as moment and power consumption of the joints, which need accurate resultant plantar force to accomplish. Moreover, since only four sensors were used to measure plantar force, the calculation of the center of ground contact force may result in great error if one of the sensors is misplaced. For potentiometers, although the designed mechanism will not easily become misaligned once it is fixed, for the error countdown to milliseconds, a minor shift from the potentiometers to the joints will cause errors.

The results compared between the proposed system with the *VICON* system and the force plate indicated the similar behavior. In addition, the low cost, wearable, portable, and easy-to-use features of the system make it suitable to perform outdoor experiments, and the potential for developing advanced lower extremity exoskeleton.

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REFERENCES

[1] M. Nordin, and V. H. Frankel, *Basic biomechanics of the musculoskeletal system*. 3rd ed. Baltimore, MD: Lippincott Williams and Wilkins, 2001, ch. 9,17.

[2] M. W. White, *An introduction to gait analysis*. 4th ed. Boulevard, PA: Elsevier, 2007, ch. 2.

[3] S. S. Nair, R. M. French, D. Laroche, and E. Thomas, "The application of machine learning algorithms to the analysis of electromyographic patterns from arthritic patients," *IEEE Trans. Neural Syst. Reh. En*., vol. 18, pp. 174-184, April 2010.

[4] B. R. Greene, D. McGrath, L. J. O'Donovan, R. O'Neill, A. Burns, and B. Caulfield, "Adaptive estimation of temporal gait parameters using body-worn gyroscopes," *IEEE Int. Conf. Eng. Med. Biol. Soc.*, pp. 1296-1299. Aug.-Sept. 2010.

[5] C. M. Senanayake, and S. M. N. A. Senanayake, "Computational intelligent gait-phase detection system to identify pathological gait," *IEEE Trans. Inf. Technol. Biomed*. vol. 14, pp. 1173-1179, Sept. 2010.

[6] S. Bamberg, A. Y. Benbasat, D. M. Scarborough, D. E. Krebs, and J. A. Paradiso, "Gait analysis using a shoe-integrated wireless sensor system," *IEEE Trans. Inf. Technol. Biomed*. vol. 12, pp. 413-423, July 2008.

[7] I. P. I. Pappas, M. R. Popovic, T. Keller, V. Dietz, and M. Morari, "A reliable gait phase detection system," *IEEE Trans. Neural Syst. Reh. En*., vol. 9, pp.113-125, June 2001.

[8] A. M. Dollar, and H. Herr, "Lower extremity exoskeletons and active orthoses: challenges and state-of-the-art," *IEEE Trans. Robot.* vol. 24, pp.144-158, Feb. 2008.

[9] S. S. Ha, J. H. Yu, Y. J. Han, and H. S. Hahn, "Natural gait generation of biped robot based on analysis of human's gait," presented at the 2008 Int. Conf. Smart Manuf. Appl., Seoul.

[10] F. Vecchi, C. Freschi, S. Micera, A. M. Sabatini, P. Dario, and R. Sacchetti, "Experimental evaluation of two commercial force sensors for applications in biomechanics and motor control," presented at the 2000 Int. Conf. Funct. Elect. Stimulation Soc., Denmark.

[11] C. Kirtley, Clinical gait analysis: theory and practice. 1st ed. Boulevard, PA: Elsevier, 2006, ch. 2.