Proceedings of the 29th Annual International
Conference of the IEEE EMBS
Cité Internationale, Lyon, France
August 23-26, 2007.

Wearable Accelerometer System for Measuring the Temporal Parameters of Gait

Jung-Ah Lee, Sang-Hyun Cho, Jeong-Whan Lee, Kang-Hwi Lee, Heui-Kyung Yang

Abstract— **A small and wireless accelerometer system was developed for the estimation of temporal gait parameters. The new system was built using two 3-axis accelerometers. Measurement's accuracy was assessed using as a criterion standard provided by foot switches. To assess the consistency of this system, estimates of heel contact and toe off time based on accelerometers and those based on footswitches were compared for 20 steps from 8 individual healthy subjects. Accelerometers and footswitches had high consistency in the temporal gait parameters. The stance, swing, single support, and double support time of gait cycle revealed ICCs values of 0.95, 0.93, 0.86, and 0.75 on the right and 0.96, 0.86, 0.93, 0.84 on the left, respectively. Therefore, this system proved to be a reliable tool for identification of temporal gait parameters.**

I. Introduction

Gait analysis techniques have been used in clinical research to investigate the features of normal or abnormal gait, to quantify subsequent improvement after the lower-extremity operation, and to assess balance and mobility monitoring [1]. Objective measures of the motion analysis are necessary for better management of rehabilitation. Measurements of temporal parameters of gait are used for the evaluation of lower-extremity disorders and for the quantification of their subsequent improvement after therapeutic exercise [2]. Various instruments have been developed to assist in the study of human gait. Motion analysis systems and force plates contain kinematics and kinetics in 3 planes to spatiotemporal measures of gait analysis, but their cost and intricate setting have limited those to use them for large trials and daily life [3]. Foot switches or pressure sensors attached to the sole are used temporal parameters [4, 5]. These techniques provide unsatisfactory results for abnormal walking and sensor attachment. Inexpensive and miniature accelerometer sensors have been used in a clinical setting [6]. Accelerometer is typically lightweight and wearable which facilitate unencumbered movement of the subject. And it can be used to detect simple temporal features of gait, such as the stride time. A uniaxial accelerometer to identify each heel strike was used by Evans et al. [7]. They demonstrated the possibility of detecting steps and stride time from trunk acceleration. Temporal parameters were measured using two accelerometers attached on thigh by Aminian et al. [8]. According to Zijlstra and Hof, a basic pattern of trunk acceleration with fixed relationships to spatio-temporal gait parameters could be expected during walking [9]. Still, however, a portable and wireless acceleration data acquisition system to measure acceleration signals during walking and a gait analysis algorithm which can estimate temporal parameters has not been introduced. Also, a possibility to identify the main peaks of output signal such as heel strike and toe off from two accelerometers attached on each ankle compared with the standard reference based on footswitches has not been proposed.

In this study, we have developed a small, wireless, and portable 3D- acceleration data acquisition system to measure acceleration signal during walking and a gait analysis algorithm which can estimate temporal parameters of gait. We have also assessed its consistency by comparing its temporal parameters of gait with those of footswitches.

II. Methods

A. subject

The eight subjects (five men, three women) volunteered to participate in the validation study. Their average weight of the subjects 65 kg (range 48-85 kg), and their average height of the subjects was 166 cm (range 154-176 cm). Subjects with lower limb abnormalities, previous lower limb surgery, and low back pain as well as with neurological or surgical abnormalities on clinical examination were excluded from this study. Procedures were approved by the Human Investigation Committee of the Institution and all subjects signed informed consent from before participation.

B. Implementation of accelerometer system

Small and wireless system was built using 3-axis accelerometer (MMA7260, Freescale, TX). The sensitivity of accelerometer is calibrated by rotating device with variable

Manuscript received May 2, 2006. This work was supported by Yonsei University Research Fund of 2006.

Jugn-Ah Lee is with the Rehabilitation Therapy Department, Yonsei University, Wonju, 220-710, Korea (Corresponding author: 82-33-760-2498; fax: 82-33-760-2496; e-mail: leejungah@hotmail.com).

Sang-Hyun Cho is with the Rehabilitation Therapy Department, Yonsei University, Wonju, 220-710, Korea (e-mail: fastcloud@yonsei.ac.kr).

Jeong-Whan Lee is with the Biomedical Engineering Department, Konkuk University, Chungju, 380-701, Korea (e-mail: jwlee95@kku.ac.kr).

Kang-Hwi Lee is with the Biomedical Engineering Department, Konkuk University, Chungju, 380-701, Korea (e-mail: kku99lkh@kku.ac.kr).

Heui-Kyung Yang is with the information & Telecommunication Engineering Department, Cheongju University, Cheongju, 360-764, Korea (e-mail: danmie@paran.com)

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speed, and measured to calibrate the accelerometer signals in gravitational constant g(= 9.8 m/s^2) as a unit. With the advantages of small-package size (6mm x 6mm x 1.45mm; QFN-16) and low power consumption, the system could be powered by a small Li-Ion cell battery. In order to detect heel strike and toe off time of ankle, small and sensitive pressure sensors (foot switch/ IESF-R-5L, CUI Inc., OR) were connected to the proposed system and located in one's shoes. So, we could observe contact time of heel and toe, also, acceleration of ankle at the same time. Overall specifications of the developed system are summarized in Table 1.

TABLE 1. SPECIFICATION OF SYSTEM

		Specification
Degree of Freedom (DOF)		3
Accelerometer (MMA7260, Freescale)		3-axis (800 mV/g)
Foot switch		2 (heel & toe)
Pressure Sensor (IESF-R-5L, CUI)		Flexible PCB (Max. Load 4kg)
A/D converter (embedded with MSP430F149)	Resolution	12 bits
	Sampling rate	50Hz
Wireless Comm. (nRF2401, Nordic, Norway)	Carrier Freq.	2.4 GHz
	Modulation	GFSK
	Date Tx/Rx rate	1Mbps (Shock-Burst)
Power	Battery-powered	Li-Ion cell (3.7V 1200 mAhr)
Physical Characteristics	Size (W x H x D)	25x160x25,mm
	Weight	50 g
Current consumption		< 5 mA at 3.3V
Max distance		15 m
Max operating time		24 h

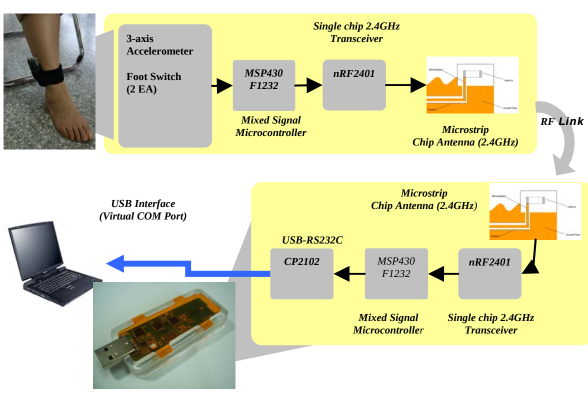

Fig. 1. System configuration of Accelerometer.

Fig. 2 The Accelerometers and Footswitches System.

C. *Data sampling*

Both the accelerometer data and foot switch data from the pair of ankle devices were A/D converted and transmitted wirelessly to the PC-side receiver at the rate of 61 Hz. The Acknowledge 3.7.3 program (BIOPAC, USA) read-in the data to determine its frequency domain and apply low pass filter (cut-off at 5Hz). Then the program merged the three-dimensional acceleration data into a "vector sum"; a = $\sqrt{(a_x^2 + a_y^2 + a_z^2)}$. From the accelerometer data of each subject, stable 20 consecutive steps were selected for the gait analysis.

D. *Gait analysis*

Accelerometer system was attached to the lateral side of the both ankles. Two footswitch sensors were placed inside each sole of a foot, under the heel and the first metatarsal. This way, the moments of heel strike and toe-off were directly detected. The subjects walked over a 5 meter-straight corridor for 5 minutes. They were instructed to walk at their preferred speed while monitored wirelessly by the accelerometer. Then from the data for the 20 consecutive steps, prominently repeating peaks of accelerometer data were marked to calculate the temporal parameters of gait cycle. The Acqknowledge 3.7.3 program was used for the visual peak detection while comparing it with simultaneous footswitch data, and the following gait parameters were determined for the each gait cycle: stance time, swing time, single support time, and double support time. From the 20 values for the each parameter in a single leg, statistical mean and standard deviation were calculated and used for the further statistical test.

E. *Statistical Analysis*

For the consistency study, the ICCs (Intraclass correlation coefficients) were used for each gait parameter. The ICCs value less than 0.75 were considered as 'poor to moderate', greater than 0.75 as 'good', and bigger than 0.90 as 'excellent' [10].

III. Results

A typical example of ankle acceleration during gait cycles was plotted in Fig 3. The results showed that the temporal parameters detected by the footswitches and those from the accelerometers matched well. The average temporal parameters of gait cycles were presented in Table 2. The mean duration of the right and left stance, swing, single support, and double support phases showed the differences in the accelerometers and footswitches for 20 steps (Table 2). Temporal gait parameters measured with our system revealed high ICCs (Table 3). The ICCs of the stance time was greater than those of the swing, single support, and double support time.

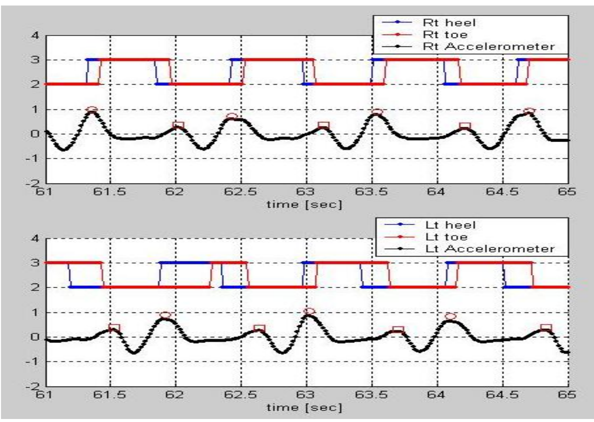

Fig. 3 Filtered ankle vector sum acceleration compared with output of footswitch over three strides.

TABLE 2. PARAMETERS VISUALLY CALCULATED USING THE ACCELEROMETERS PLACED ON EACH ANKLE ACCELEROMETER AND FOOTSWITCH PLACED UNDER EACH SOLE OF FOOT

Ankle	Footswitches (s)				Accelerometers (s)			
	ST	SW	SI	DS	ST	SW	SI	DS
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Right	0.67 (0.03)	0.45 (0.02)	0.43 (0.02)	0.25 (0.03)	0.68 (0.04)	0.44 (0.03)	0.40 (0.03)	0.28 (0.03)
Left	0.70 (0.03)	0.43 (0.02)	0.45 (0.02)	0.25 (0.03)	0.72 (0.04)	0.40 (0.03)	0.44 (0.03)	0.28 (0.03)

ST= stance time; SW= swing time; SS=single limb support time; DS=double-limb support time

TABLE 3. CONSISTENCY COMPARISON OF INTRACLASS CORRELATION COEFFICIENTS (ICC) OF VARIATION FOR ACCELEROMETERS AND FOOTSWITCHES PARAMETERS FOR HEALTHY SUBJECTS

Ankle	Variable	ICC(3, k)	95% Confidence interval	*P*
Right	ST	0.950	0.798~0.992	0.000
	SW	0.932	0.661~0.986	0.001
	SS	0.861	0.307~0.972	0.009
	DS	0.746	-0.267~0.949	0.045
Left	ST	0.956	0.780~0.991	0.000
	SW	0.861	0.307~0.972	0.009
	SS	0.932	0.661~0.986	0.001
	DS	0.837	0.186~0.967	0.014

ICCs=intraclass correlation coefficients; ST= stance time; SW= swing time; SS=single limb support time; DS=double-limb support time.

IV. Discussion

The purpose of this study was to develop and to verify a novel, portable, and wireless accelerometer system for gait analysis. To verify the accelerometers, footswitches were selected as standard criteria because footswitches have been generally used to measure the beginning and end of walking [11]. The result of the study showed that two peaks of acceleration for each gait cycle from the accelerometers could be found in normal gait. The first accelerometer peak meaning heel contact and the second peak meaning toe off matched well with footswitch actions, thus showing that gait phases were related to main peaks of acceleration. This result supported the study by Saremi et al. [12], which showed gait phases were related to main peaks of acceleration. In addition, the temporal parameters of gait from footswitches and those from the accelerometers were consistent enough that our accelerometer system could be used as a valuable tool for gait analysis (Table 3).

This paper has focused on the pattern of vector sum obtained from the $a = \sqrt{(a_x^2 + a_y^2 + a_z^2)}$. The signals from accelerometers can provide a useful information for gait analysis not in each of vertical, anterior-posterior, and medio-lateral axis but in the sum of three vectors. Acceleration is significantly influenced by the direction. But it is may be not in one direction but in the sum of three direction. Walking is a natural locomotion and can be influenced by three directions.

In addition, the signals from the accelerometers on the ankle showed a higher consistency. This may be due to the activity of both ankles during forward progression. Walking is a distal lower-extremity performance which is primarily controlled by the ankle and foot.

ICCs were used to analyze the consistency in the temporal parameters of gait from footswitches and that of the accelerometers. The high ICCs for temporal measures suggested that it could become a valuable tool for measuring phases of a gait cycle. Like other reliability coefficients, the ICC ranges from 0.00 to 1.00 [13]. It is calculated using variance estimates obtained through an analysis of variance. Therefore, it reflects both degree of correspondence and agreement among ratings.

The acceleration signal shape from our study was different from other studies, suggesting that the accelerometer position could affect the signal shape. The influence difference from the different accelerometer position on the body could be considered in the further studies.

The limitations of this study were accelerometer signal analysis by visual inspection and small number of subjects. Besides, for the visual inspection, only 20 steps from each subject were selected by the examiner. Therefore, for generalization of our findings, further study is warranted with large number of subjects and automatic signal analysis program. Maybe due to the visual peak detection, our accelerometer and foot switch showed a few inconsistencies in measurement of each phases in a gait cycle. In order to resolve the limitation, the automatic peak detection and phase measurement program is under development in our laboratory.

Despite this limitation, our wearable acceleration measurement system was proved to be a valuable tool to calculate temporal parameters of gait. The 3D acceleration measurement system is inexpensive and comfortable to wear, and it can partially replace or complement the complex and expensive motion analysis.

In this study, portable and wireless accelerometer system was developed and its validity for calculating temporal gait parameters was confirmed. The main peaks of the acceleration data for heel strike and toe off could be accurately determined. This system was found to be a highly consistent tool to measure gait detection in healthy subjects in daily life for functional gait analysis. The system demonstrated the feasibility for being used for mass trials and functional gait monitoring.

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