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Detection of Gait Event and Supporting Leg during Overground Walking with Mediolateral Swing Angle

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Abstract. Walking is one of the basic human activities. Several well-defined, motion tracking systems have been used for gait analysis. However, these systems such as the optical motion tracking system are very expensive and limited to laboratory usage. Recently, microelectromechanical systems (MEMS)-based inertial sensors have made it possible to overcome these disadvantages. The aim of this study was to identify gait events and the supporting leg by measuring the mediolateral swing angle. An inertial sensor unit with a 3-axis accelerometer and 2-axis gyroscope was attached to the subject's lower trunk using an elastic band. Five, healthy and young (20–29 yrs.) subjects participated in this experiment. Each walked twice along a straight, 25-m path at three different speeds. During each trial, the sensor transmitted signals to a PC via Bluetooth technology. In this study, gait events and the supporting leg were identified using the peak and sign of the mediolateral swing angle. The mediolateral swing angle was calculated using the integrated gyroscope signal. For comparison, a well-defined spatiotemporal gait analysis technique was also applied. In this reference method, the gait event was identified with the last peak of the vertical acceleration before the sign change from positive to negative. The supporting leg was identified using the sign of the mediolateral acceleration double integration. Identification of the supporting leg was difficult in the reference method because of the offset and gravity components in the mediolateral acceleration. However, the proposed method reported here, showed stable identification of gait events and the supporting leg. This study could be expanded to more detailed gait analysis with the additional fusion of a 3-axis acceleration, gyroscope and magnetometer.

Introduction

Walking is an essential daily activity and a fundamental body movement [1]. Most gait analyses are aimed at rehabilitation, by comparing rehabilitating patients to the characteristic patterns of normal patients [1,2]. The basic requirement for gait analysis is the evaluation of spatiotemporal gait parameters during subsequent stride cycles. For this purpose, there is a need to record continuous foot contacts [3].

There are a variety of gait analysis systems such as foot switches, which use pressure sensors or force sensitive resistors (FSR) [4], and various motion analysis systems, which are based on optic, magnetic, or acoustic sensors. Though these methods are highly accurate and provide reliable measurement, they are limited to certain laboratory environments with proper equipment and sufficient funding. The external signal emitting sources for motion detection suffer from a limited range of measurement and sometimes by a blocked field of view [5]. Additionally, the systems are not suitable for practical walking gait analysis. Therefore, a novel method, which is free from the above limitations and is easy to use in an everyday experimental setup, is necessary [3].

Recent improvements in micro electromechanical systems (MEMS) technology are promising for the study of motion analysis using inertial sensors [6,7]. MEMS technology overcomes the high cost and specialized equipment involved in the conventional system. Their intrinsic sensing affords operation without external obstruction [5] and with a greater range of measurement than the conventional system by using wireless data acquisition devices.

Some studies proposed gait analysis systems based on inertial sensors. Tien et al. [8] and Schwesig et al. [9] used a 3-axis accelerometer and gyroscope attached to both feet to evaluate the stride cycles. Pappas et al. suggested a stride-detection system using a gyroscope and a FSR attached to both feet [10]. Aminian et al. suggested gait analysis using gyroscopes and footswitches attached to each shaft and beneath the feet, respectively. Greene et al. detected the heel-strike and toe-off by integrating the outputs of a 3-axis accelerometer and 3-axis gyroscope attached to both feet and the shanks using a force plate and an optical motion analysis system [11]. Zijlstra detected foot contacts by recognizing an increase of the forward acceleration signal at heel strike [3,12]. They verified that the body's center of mass (COM) moves in accordance with each foot support phase. However, there are still some errors in detecting and identifying the foot contacts and the subsequent swing leg.

This study used one inertial sensor attached to the body's COM for improved operation and increased portability. A gyroscope is not as sensitive to gravity as an accelerometer, making attachment of the former easier [13]. The purpose of this study is to record stride cycles and identify the supporting leg using a 1-axis gyroscope.

Method

Inertial sensing module and wireless data acquisition. For the experiments, a myARS-USB (Withrobot Inc., Korea) inertial sensing module was used. The physical dimensions were 14.84 × 19.94 × 2.62 mm^3 with a weight of ±4 g. The device measures and outputs both 3-axis acceleration and 2-axis angular velocity within ±300° range. The movement signal was sampled every 10 ms (100 Hz) using a micro-controller (Atmega 128, Atmel, USA). A Bluetooth transceiver (Parani-ESD110, Sena Technologies. Inc., Korea) was used for wireless transmission of the measured data to PC.

The data was plotted and stored in real-time on specific software dedicated to this project, which was developed using Visual C++ 6.0. All the data analyses and detection algorithms were implemented using MATLAB 7.0 (Mathworks Inc., USA).

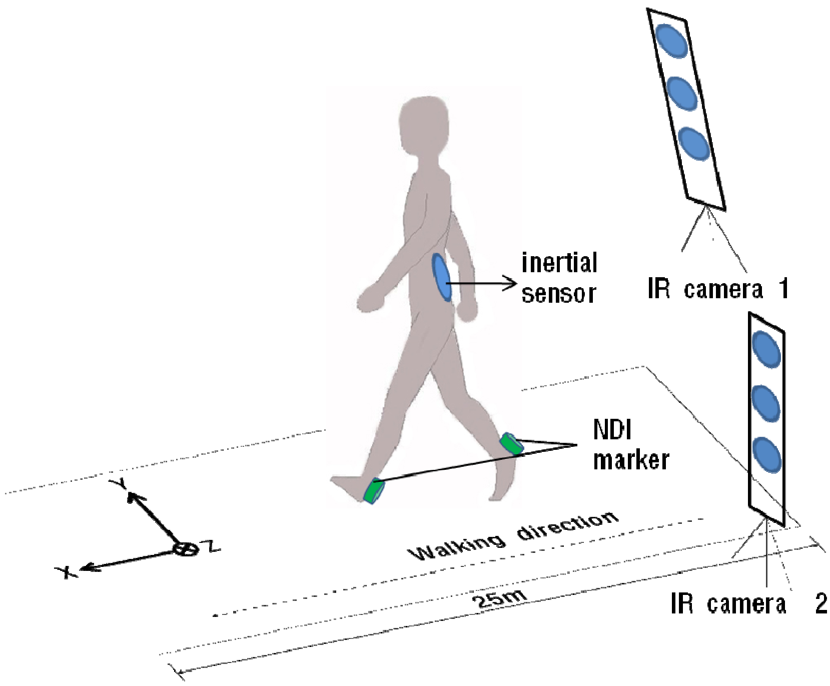

Fig. 1 Measurement coordinate axes for inertial sensor and the 3-dimensional infra red (IR) motion tracing system.

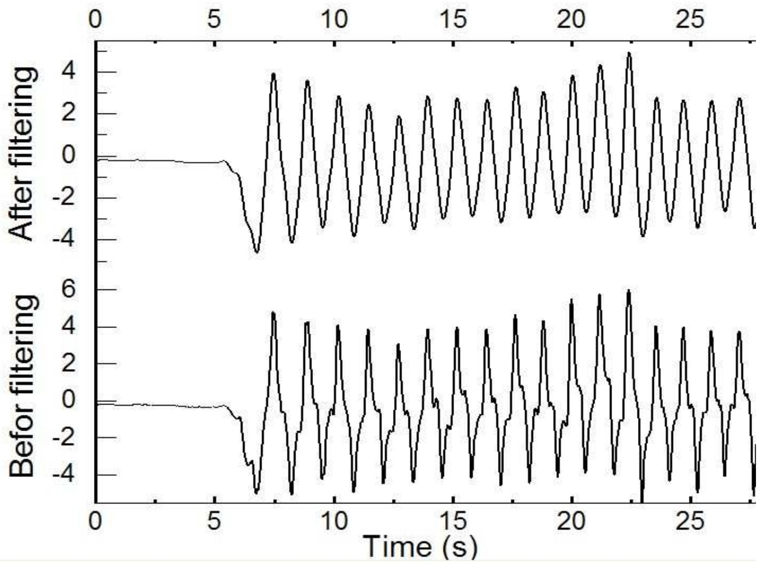

Fig. 2 Mediolateral angle signals before and after filtering.

Experimental protocol. Five male subjects (mean age, 26.6 yrs) participated in the experiments. All displayed normal gait patterns. Each subject had the sensing module attached at the pelvic level using an elastic band as shown in Fig. 1. The gait examination was done along a 25-m straight, flat path. Each subject walked at 3 different speeds in a random order (twice per speed).

Figure 1 illustrates the experimental setup and directional coordinates. The 3-dimensional motion tracking system (Optotrak Certus, Northern Digital Inc, Canada) was used for the validity of the algorithm development. The positive X-axis indicates forward direction walking, positive Y-axis is to the right, and positive Z-axis is directed into the ground.

The stride detection algorithm was tested. The sensor was attached to the lower trunk near the lumbosacral joint and pelvis. The placement affected the movement of the pelvis. From mid stance to terminal stance (swinging leg passes supporting leg and prior to heel strike) the swinging side of the pelvis is reported to decline approximately 4° during a stride to minimize the displacement of the center of gravity [14].

Gait cycle detection using a gyroscope sensor requires the selection of mediolateral components from the 2-axis angular velocity signals and integration to obtain the rotational angle around the X-axis (roll). After low-pass filtering with a 2 Hz cut-off frequency, the positive and negative peaks in the sine-shaped waveform were detected and identified. Figure 2 shows the mediolateral angle signals before and after filtering.

Fig. 3 The foot markers (left) with the measurement coordinate axes and the IR motion tracking camera (right).

The tilting movement of the pelvis along the swing and support phase can be extracted from the gyroscope signal. During right leg swings, the left leg supports and the pelvis tilts to the right. The movement yields an increase of the rotational angle from the negative to the positive peak. Therefore, we marked foot contact between the peaks.

Evaluation of the stride detection algorithm. The 3-dimensional motion tracking system has a spatial resolution of 0.01 mm and provides a precise measurement of 0.1 mm. In Fig. 1, we installed 2 IR cameras for more reliable tracking of the 2 active optical markers within the 25-m walking path. Figure 3 shows the positions of the 2 markers and the IR camera for the motion tracking. Camera 1 is only able to track the markers within a 3-step distance and therefore an additional camera was installed for the remainder of the tracking to an 8-step distance. The additional camera was located higher and tilted toward the ground for a better marker view angle. The Z-axis component of the tracking signals traces the vertical displacements (heights) of both feet, therefore making it possible to recognize the swinging and supporting legs. One of the five subjects walked under this integrated experimental setup to examine the exact moments of foot contact for valid evaluation.

The forward acceleration signal was low-pass filtered with a cut-off frequency of 2 Hz and marked at every foot contact as reported by Zijlstra [3]. The offset error was eliminated by subtracting the baseline level measured during the standing period from the original signal. In Zijlstra, the supporting legs were also identified using zero-crossing polarity detection of the mediolateral displacement at the marked foot contacts [3,12].

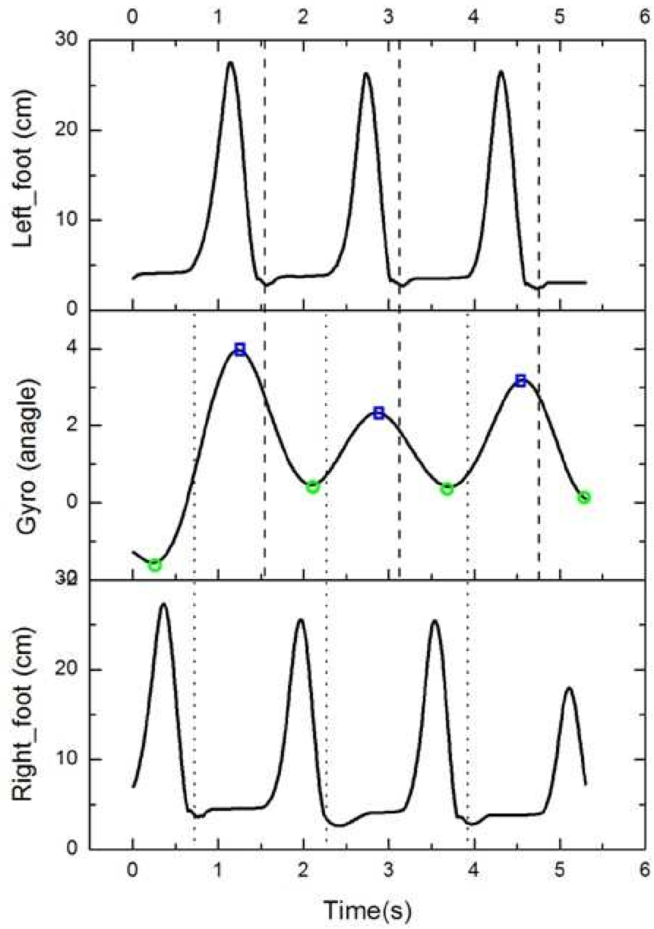

Fig. 4 Vertical displacement from the markers attached on both feet and the mediolateral angle displacement obtained from the gyroscope are displayed in the same plot to record stride cycles. Dashed lines indicate left foot contacts, dotted lines indicate right foot contacts, green circles mark negative peaks in the gyroscope signal, and blue rectangles mark positive peaks in the gyroscope signal.

Results

IR motion tracking system and gyroscope. The vertical position signal of both feet traced using the motion tracking system provided true data for the supporting legs during stride cycles.

During the right leg support, between the right foot contact to the left foot contact in the motion tracking signal, the mediolateral angle displacement obtained from the gyroscope signal displayed increasing transition from a negative peak to a positive peak. Similarly, during the left leg support, the mediolateral displacement showed transition from a positive to negative peak as shown in Fig. 4.

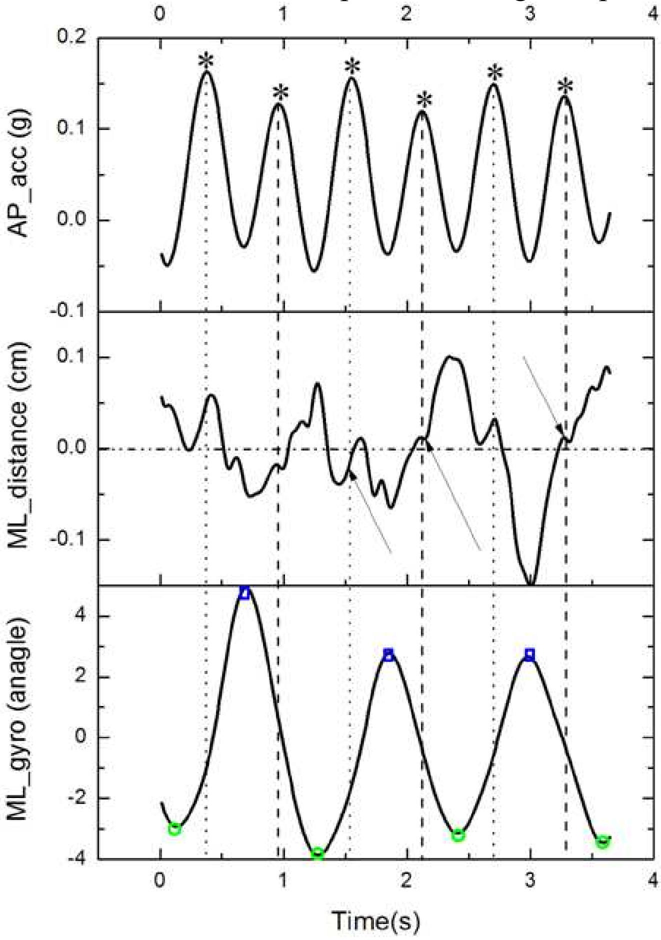

Fig. 5 The accelerometric signals and gyroscopic signals are plotted together to identify the supporting leg. Dashed lines indicate the moment of left foot contacts and dotted lines indicate right foot contacts. Green circles mark negative peaks and blue rectangles mark positive peaks in the mediolateral angle displacement obtained from the gyroscope signals. Asterisks indicate positive peaks in the anteroposterior acceleration. Arrows point to errors in identifying the supporting leg using the accelerometric method.

Table 1. Detection accuracy for foot contact and supporting leg by both the accelerometric and gyroscopic methods.

No	Step	Accelerometric			Gyroscopic		
		Step count	L/R error	Accuracy (%)	Step count	L/R error	Accuracy (%)
1	209	209	122	41.60	209	0	100
2	216	216	77	64.35	216	0	100
3	218	218	99	54.59	218	0	100
4	200	200	128	36.00	200	0	100
5	226	226	8	96.46	226	0	100

Table 2. Detection rates of the supporting legs using the accelerometric method.

No	Slow		Normal		Fast	
	Step	Accuracy (%)	Step	Accuracy (%)	Step	Accuracy (%)
1	82	98.86	65	7.92	62	1.56
2	80	100	70	71.43	66	13.69
3	82	96.43	72	40.28	64	16.37
4	78	66.38	64	25	58	6.9
5	86	100	78	98.75	62	89.08
Mean	81.6	92.33	69.8	48.68	62.4	25.52

Accelerometer vs. gyroscope. The stride cycle detection results based on the mediolateral angle displacement obtained from the gyroscope signal in this study were compared to those calculated from the forward acceleration and mediolateral displacement suggested using the Zijlstra method [3,12]. There are reasonable errors in detecting foot contacts using acceleration signals as in Zijlstra [3,12] due to some differences in experimental conditions such as walking speed and inertial sensor attachment. However, the proposed method using mediolateral angle displacement measured by the gyroscope showed 100% detection for both stride cycles and the supporting legs as shown in Fig. 5.

Table 1 shows the detection results for all the subjects and calculations for the accelerometric method and the proposed gyroscopic method for comparison. Moreover, the proposed gyroscopic method is able to identify the stride cycle and supporting leg even when the accelerometric method detects the foot contacts, but fails in identifying the supporting leg due to a change in gait.

Effects of different walking speeds. The motion tracking system and the proposed gyroscopic system results were not affected by varied walking speeds during experiments. The selection of the cut-off filtering frequencies of the sensor signals may be important when walking speed is abruptly changed. However, filtering considerations can be automatically implemented in the algorithm or system.

However, in case of the accelerometric method, the detection rate of the supporting legs decreased as the walking speed increased. The decreased mediolateral displacement with the speed increment made the detection more difficult as shown in table 2.

Conclusions

This study proposed a stride cycle detection method that encompassed the supporting legs during gait analysis. The study was based on mediolateral angle displacement using a gyroscope. The experimental results verified the accuracy of the proposed method. The proposed method provides an easy and useful tool for gait analysis, which is easy to use, portable, and inexpensive. Though it is not able to give the exact moment of foot contacts, the mediolateral angle displacement obtained from the gyroscope readings can distinguish each stride cycle and the supporting leg with great accuracy regardless of speed. However, it is necessary to compensate for the inertial sensor attachment errors for accurate analysis. The ongoing study is focusing on the combination of the current system with geomagnetic sensors for sensor coordinate system correction, which should provide more reliable gait analysis.

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