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Estimation of Walking Direction Estimation using a Shoe-mounted Acceleration Sensor

Je-Nam Kim[1], Mun-Ho Ryu[2,3], Yoon-Seok Yang[2,3]and Jun-Yong Hong[4]

[1] Department of Healthcare Engineering, Chonbuk National University, 567 Baekje-daero, deokjin-gu, Jeonju-si, Jeollabuk-do 561-756, Republic of Korea
[2] Division of Biomedical Engineering, Chonbuk National University, 567 Baekje-daero, deokjin-gu, Jeonju-si, Jeollabuk-do 561-756, Republic of Korea
[3]Research Center of Healthcare & Welfare Instrument for the Aged, Chonbuk National University, 567 Baekje-daero, Deokjin-gu, Jeonju-si, Jeollabuk-do 561-756 Republic of Korea
[4]e-Clio, Inc, 824 Palbok-dong 2-ga, Deokjin-gu, Jeonju-si, Jeonbuk, Republic of Korea
zero-day@nate.com, {mhryu, ysyang}@jbnu.ac.kr, junyong.hong@cliotech.co.kr

Abstract

Estimation of walking direction is important for providing detailed information about an individual's gait. This study proposes a method for estimating walking direction using a shoe-mounted acceleration sensor. Heel contact is determined from the negative peak of the acceleration magnitude, and foot inclination is calculated for estimating the horizontal acceleration. The stepping direction of each foot is calculated through principle component analysis along the horizontal acceleration. The walking direction is estimated by averaging consecutive left- and right-step directions. The proposed method was applied to out-door straight ground walking for 658 steps, and yielded a mean difference of 0.48° with a standard deviation of 1.98°.

Keywords: *Walking direction, acceleration sensor, shoes, mobile phone, smartphone*

1. Introduction

Estimation of walking direction has been attracting interest in the field of context recognition [1-4], dead-reckoning navigation [5-7], and biomechanics [8-11]. In the field of context recognition, especially in cases where a mobile phone is used, an acceleration signal is acquired from the on-body mobile phone and processed through principle component analysis (PCA) for estimating the user's walking direction [12]. However, these methods estimate the walking direction over several meters but not within each step. Estimating the orientation and, occasionally, even its relative position using an inertial sensor is possible using an inertial navigation system [13]. When an absolute positioning system such as GPS is not available, optimal estimation algorithms such as Kalman filter fusion any available sensor signal such as acceleration, angular velocity, or earth magnetic field [14]. Although the abovementioned methods afford reasonable performance, they are computationally expensive.

The authors of this study are developing a shoe that is equipped with various types of motion sensors and transmits healthcare information to a mobile phone. For an instance, any information related to the degree and balance of internal or external foot rotation during walking can be useful in determining gait pattern [15]. However, for providing any

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information on walking pattern, calculating the walking direction itself remains an essential challenge. In this study, we propose a method for detecting walking direction using a shoe-mounted acceleration sensor. Its functional feasibility is evaluated through an outdoor, straight flat surface walking test.

2. Materials and method

2.1. Sensor-equipped shoe

A three-axis micro-electromechanical system (MEMS) acceleration sensor (LSM303DLM, STMicroelectronics) was surface-mounted on a printed circuit board (17.8 mm × 13.0 mm), which was inserted in a sole, below the arch of foot (Figure 1). The sensor was connected to a commercial micro-control unit (MCU) board (MSP-EXP430G2 LaunchPad, Texas Instruments) using wires. The MCU board provided the sensor with power and inter-integrated circuit communication. The MCU reads the acceleration data and sends it to a mobile phone via a Bluetooth module (Parani ESD200, Sena Technology, Korea) at 100 Hz. The saved data is later analyzed on a PC using MATLAB 7.12 (MathWorks).

Figure 1. Sensor-equipped shoe. A three-axis MEMS acceleration sensor was inserted in a sole

Each component of acceleration signal varies periodically according to the gait phase, as shown in Figure 2. In this study, the X, Y, and Z directions point to the left, forward, and bottom, respectively. The Y-axis acceleration varies most significantly because it corresponds to the mediolateral direction. The acceleration magnitude was calculated as the norm of the three components. It is well known that the negative peaks of the acceleration magnitude correspond to heel strikes [16].

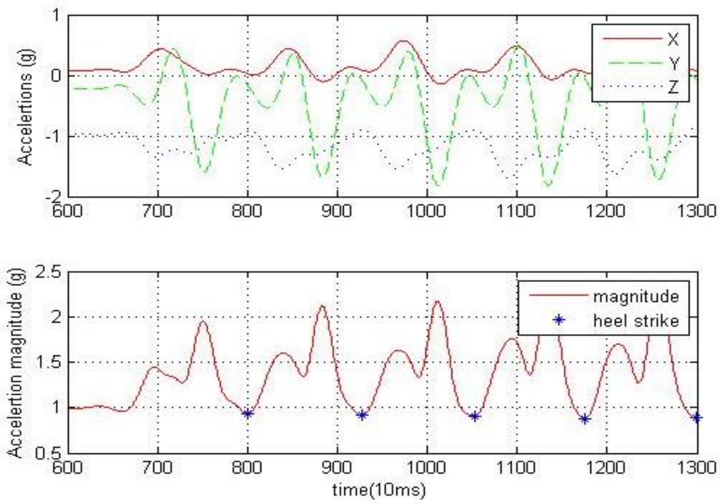

Figure 2. Acceleration signals with heel strikes

The X, Y, and Z directions point to the left, forward, and bottom, respectively. The Y-axis acceleration varies most significantly because it corresponds to the mediolateral direction

2.2. Heel strike detection

The inclination of the acceleration sensor, *i.e.*, rotations along the X- and Y-axes, is calculated according to gravimetry, which uses the projection of gravity on the X- and Y-axes [17]. However, this calculation is contaminated when the sensor moves with any acceleration because the acceleration sensor detects gravity and motion acceleration simultaneously [18]. Nonetheless, the inclinations calculated at the heel contacts can be trusted. The heel-strike timing, which corresponds to the negative acceleration magnitude, is detected as shown in Figure 3. When a heel strike is detected, the X- and Y-axis acceleration signals are rotated at an inclination to the horizontal accelerations. At the positive peak, acceleration magnitude |A| is stored as a positive peak value, $|A|_{(+)peak}$. At the negative peak, $|A|$ is compared with the walking threshold, *Th_walking*. If $|A|$ at the negative peak is greater than *Th_walking*, the step is considered as being in the normal walking mode at that moment. In addition, $|A|_{(+)peak}$ is compared with the mid-stance threshold, Th_mid_stance, for confirming whether a given step is a normal walking step. If these conditions are met, this moment is detected as a heel strike.

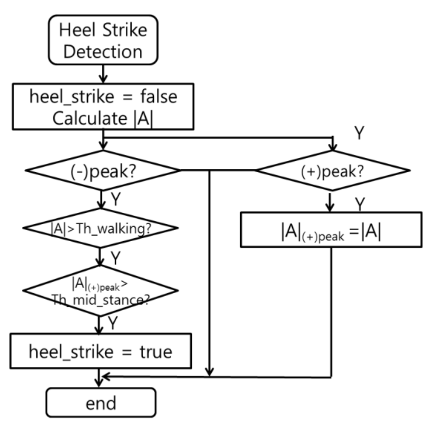

Figure 3. Flowchart for heel strike detection

At the positive peak, the acceleration magnitude $|A|$ is stored as a positive peak value $|A|_{(+)peak}$. At the negative peak, the acceleration magnitude, $|A|$, is compared with the walking threshold, *Th_walking*, and mid-stance threshold, *Th_mid_stance*. If the negative peak is greater than the thresholds, the given moment is considered as heel contact of a normal step.

2.3. Walking direction estimation

The horizontal acceleration signals during a step are processed using PCA for estimating the stepping directions of each foot. In our study, the angle between the horizontal *X/Y* axes and the calculated first coefficient pair corresponds to the walking direction, as shown in Figure 4. The walking direction is determined by averaging the consecutive left and right stepping directions. The rotation between *X/Y* and Components *1/2* corresponds to the estimated waking direction. The coefficients of the principle component, *i.e.* Components *1/2* are calculated as follows. The horizontal acceleration signals, A_i, are arranged in a 3 × *N* acceleration matrix A as in Eq. (1). The N is the number of samples between two heel strikes.

$$\mathrm{A} = \begin{bmatrix} a_1^T & a_2^T & \dots & a_N^T \end{bmatrix} \qquad (1)$$

The 3 × 3 covariance matrix C_A is calculated from the acceleration matrix as in Eq. (2). The c_{ij} corresponds to the covariance between the *i*-axis acceleration and *j*-axis acceleration.

$$C_{\mathrm{A}} = \frac{1}{N-1}\mathrm{AA}^T = \begin{bmatrix} a_{xx} & a_{xy} & a_{xz} \\ a_{yx} & a_{yy} & a_{yz} \\ a_{zx} & a_{zy} & a_{zz} \end{bmatrix} \qquad (2)$$

The PCA calculates a coordinate transform with which the largest acceleration covariance is projected the basis of a new coordinate frame. This transform is calculated from the relationship between an eigenvalue ($\lambda_X, \lambda_Y, \lambda_Z$) and eigenvector ($v_X, v_Y, v_Z$) pair as in Eq. (3).

$$C_{\mathrm{A}} \upsilon_i = \lambda_i \upsilon_i \qquad (3)$$

From the calculated eigenvalues, the eigenvector with the largest eigenvalue and the eigenvector with the second largest eigenvalue are determined as the Component *1* and Component *2*, respectively.

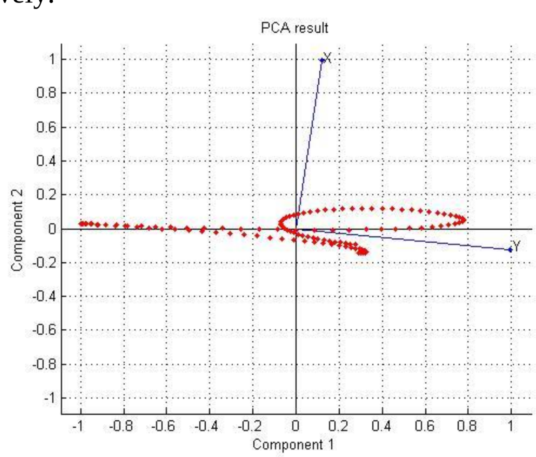

Figure 4. PCA results of over 117 acceleration samples

X and Y correspond to the horizontal axes. Component 1 and Component 2 correspond to a coefficient pair calculated using PCA on the horizontal axes.

2.4. Experimental setup

The proposed method was applied to outdoor, straight ground walking by a healthy subject. The subject walked along a path marked by a line (26 m) at a self-determined comfortable speed and retraced the path back to the starting point. This commutation was repeated five times. The same process was repeated along a path perpendicular to the abovementioned path. Hence, 20 instances of walking in four directions were recorded and analyzed.

For each walk along the paths, the first two and the final two steps were excluded from the analysis because they are transitional. *Th_walking* and *Th_mid_stance* were empirically set to 1.5 g and 0.9 g.

3. Results

Table 1 summarizes the estimated walking directions for 658 steps. Given that the subject tried his best to walk along the straight paths marked by the lines, the real walking directions were assumed as 90°. However, the actual walking directions of both feet varied slightly from 90°. This deviation can be ascribed to several reasons. Firstly, even though the sensor was aligned to the sole with visible sight to the best possible extent, there could be constant misalignment or orientation offset. Secondly, the differences between the left and the right feet are larger than the averaged direction because walking directions of a single side vary to a greater degree. This result justifies the averaging of consecutive left and right directions. Finally, a small outer rotation during the stance itself is normal in a healthy subject, even though the degree of rotation varies according to the individual's gait characteristics.

Table 1. Estimated walking directions over 658 steps (°).

Foot Direction	Mean	Standard Deviation
Left	99.37	3.08
Right	81.58	3.05
Average	90.47	1.97

Because the estimated walking direction varies according to each left and right step pair, *i.e.*, with each stride, the estimated walking directions were averaged over several strides. Figure 5 shows the means and standard deviations of the estimation error according to the averaging window size from 1 to 25 strides. The direction error decreases significantly up to window size seven. For window size 7, the mean and standard deviation were 0.47° and 0.95°, respectively.

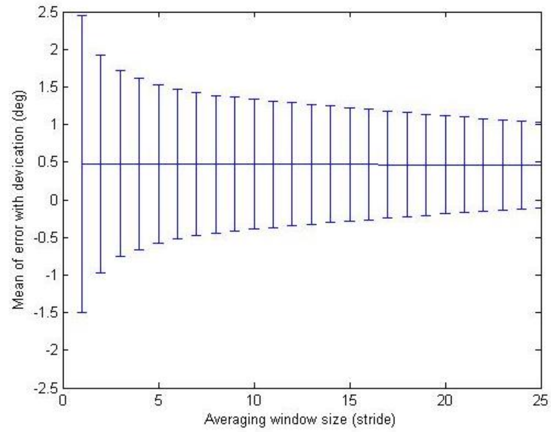

Figure 5. Means and standard deviations of estimation error according to averaging window size

The verticals bars indicate the standard deviation of errors for 320 strides. For window size seven, the mean and standard deviation were 0.47° and 0.95°, respectively

4. Conclusions

This study proposed and demonstrated the functional feasibility of a method for detecting walking direction using a shoe-mounted acceleration sensor. The proposed method estimated the walking direction by averaging the left and right stepping directions, which were calculated using PCA of the horizontal acceleration during the stance phase. This method was applied to outdoor, straight flat surface walking for 658 steps, and the calculated mean difference and standard deviation were 0.48° and 1.98°, respectively. For the averaging window comprising seven strides, the mean difference and deviation were 0.47° and 0.95°, respectively. The estimated walking direction could be used for providing detailed, including the degree and balance of internal or external foot rotation, of an individual's walking gait.

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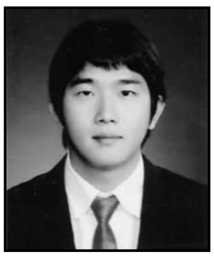
Authors



Je-Nam Kim, he received a B.S. degree in Division of Biomedical Engineering and M.S. degree in Department of Healthcare Engineering from Chonbuk National University, Korea in 2009 and 2011, respectively. From 2011, he has been pursuing Ph.D. degree in Department of Healthcare Engineering from Chonbuk National University, Korea. His research interests include human motion tracking and telerehabilitation.

Mun-Ho Ryu, he received a BS degree in Control and Instrumentation Engineering and a PhD degree in Biomedical Engineering from Seoul National University, Korea, in 1990 and 2004, respectively. He worked for Daewoo's Heavy Industry Machine Tool Division from 1990 to 2000. He also worked for Biomedlab Co., Ltd. from 2000 to 2005. He has been a professor at Chonbuk National University since 2005. His research interests are human motion tracking, inertial navigation, telerehabilitation, rehabilitation, and embedded system.

Yoon-Seok Yang, he received a BS degree in Control and Instrumentation Engineering and a PhD degree in Biomedical Engineering from Seoul National University, Korea, in 1996 and 2002, respectively. He worked for Electronics and Telecommunications Research Institute (ETRI) at BioMEMS group as a senior researcher from 2002 to 2005. He has been a professor at Chonbuk National University in South Korea since 2005. In 2007, He worked for ETRI at Neural System Interface group as a visiting professor. He also worked at a Center for Energy Harvesting Materials and Systems (CEHMS) in Virginia Polytechnic Institute and State University (Virginia Tech) in U.S. as a visiting researcher from 2010 to 2011. His research interests are energy harvesting, human computer interface (HCI), and embedded system.

Jun-Yong Hong, he received a BS degree in Department of Japanese Literature from Chonbuk National University, Korea in 2007. He has been worked for e-Clio corporation from 2008. He has been a manager of R&D planning department since 2011. His research interests are web based system, embedded system, Healthcare system, and IT convergence.