Estimation of Walking Behavior Using Accelerometers in Gait Rehabilitation

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Abstract – Estimation of walking behavior such as gait pattern, speed and distance of walking, is discussed in this paper. In gait rehabilitation, measurement of the temporal and spatial parameters during gait is of critical importance for monitoring functional recovery. The 3-axis accelerometer on the waist belt is used to detect acceleration of body movement. From the filtered signal, we can estimate information about the subject such as gait pattern, speed of the subject, total walking distance, and improvement of walking function. Speed and distance are estimated by using step length. We performed on two healthy subjects to show the practical aspect of the proposed algorithm. The proposed scheme is simple to implement and it can be applied as a virtual controller to human-machine interfaced system.

Keywords: Gait Pattern, Walking Behavior, Accelerometer

1. Introduction

The information of the human behavior in gait rehabilitation such as walking speed, walking distance, and gait pattern is very importance for medical diagnosis of ambulation, progress of gait pattern, and estimation of energy consumption.

In the clinic, 3-D imaging systems are used to obtain accurate kinetic data during walking. These systems are powerful but it requires technical skill and specialized experience to operate. Usage of the systems is confined within laboratory. A simple and accurate ambulatory system is required to evaluate the efficiency of rehabilitation. The system should also offer the efficiency and flexibility [3]. Foot switches, plantar pressure sensors, and accelerometers have been used previously to evaluate human gait. Morris has reviewed the advantages and potential uses of accelerometers [4].

Aminian et. al. estimated the speed and incline of walking using neural network with accelerometers[1]. They placed four accelerometers in a waist belt and on the top of the right heel to measure acceleration during walking. They applied neural network after parameterization of the raw signals into 10 features. Training data of neural network were obtained from the treadmill environment with various speeds and incline patterns. Although the accuracy of estimated speed and incline were high, the method requires training phase of the subjects prior to the real experiment. It is valid only for the subject whose gait pattern is similar to the group who generated training data. Sagawa proposed a method for non-restricted measuring walking distance without the subjects’ features such as stride length or asymmetric walk [2]. They measured three-dimensional acceleration of the subject’s toe using a three dimensional accelerometer and a piezoelectric gyro sensor. The acceleration was projected to the horizontal plane to produce the horizontal velocity and the horizontal distance. The gyro was used to compensate the rotation of the accelerometer.

In this paper, we used 3-axis accelerometer to measure acceleration components of body movement during walking in forward, lateral, and vertical direction. The accelerometer is based on the ADXL05 from Analog Devices. Technical specifications are shown in Table 1. Using the obtained acceleration signals, we propose a new identification technique for gait pattern. After identifying gait pattern, we can estimate the speed of walking by using the subject’s step length which is measured a priori. By counting the number of steps, we can estimate the distance of walking.

This paper is organized as follows: The next section describes the measurement environment in detail. Section 3 explains feature extraction technique for identifying gait pattern. Section 4 shows the experimental results on two healthy subjects using the proposed algorithm. Summary of the result and further study topics will conclude this paper.
2. Measurement System

2.1 System Components

Movements in all three dimensions are to be recorded using portable recording system. Three-axis accelerometer placed in a waist belt to measure forward, lateral, and vertical acceleration. Data acquisition with 200 Hz sampling frequency was performed for each channel. All signals are stored in SRAM memory of the portable recording system, and the stored data are transferred to the main computer through USB interface. See Fig. 1.

Table 1: Accelerometer specifications

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>±49 m/s²</td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td>±0.5 m/s²</td>
<td></td>
</tr>
<tr>
<td>Freq. Response</td>
<td>0-100 Hz</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1. Block diagram of the measurement system.

2.2 Digital Filter

In a repetitive movement such as walking, the frequencies present will be multiples (harmonics) of the fundamental frequency. When walking at 120 steps/min (2 Hz), the stride frequency is 1 Hz. Normal walking has been analyzed by digital computer and the harmonic content of the trajectories are studied [5]. The highest harmonics were found to be in the toe and heel trajectories, and it was determined that 99.7% of the signal power was contained in the lower seven harmonics (below 6 Hz).

The format of a digital filter, which processes the acceleration data in the time domain, is as follows:

\[ y(k) = a_0 x(k) + a_1 x(k-1) + a_2 x(k-2) + b_1 y(k-1) + b_2 y(k-2). \]  

If we choose coefficients of the above filter as,

\[ y(k) = 0.0201x(k) + 0.0402x(k-1) + 0.0201x(k-2) + 1.5610y(k-1) - 0.6414y(k-2). \]

then, the cut-off frequency will be 10 Hz.
Fig. 2 shows the original acceleration signal and the filtered signal using second-order butterworth filter.

Fig. 2 Performance of the second-order digital filter.

Unwanted high frequency components are rejected and we obtain smooth signals for further signal processing.

2.3 Experimental Protocol

Two volunteer health subject (two males, age 28/23, height 170/180cm, weight 55/72 kg) walked on the ground at his own preferred speed. He walked 20 seconds for each time and repeated 5 times.

3. Feature Extraction

We first applied low-pass filtering to obtain noise-rejected signals as explained in section 2.2. From the filtered signal, we want to estimate information about the subject such as gait pattern, speed of the subject, total walking distance, and improvement of walking function, if possible. Walking speed and distance are difficult to obtain accurately because of numerical error of integration. Sagawa calculated the speed and distance with the
accelerometer attached at the toe by the help of gyro sensors [2]. In this paper, since we use only accelerometer, we use additional information, the subject’s step length, to estimate walking speed. This assumption is not restrictive since normal walking shows very similar walking pattern.

Fig. 3 shows the overall procedure to obtain useful features in human walking. Vertical acceleration signal plays an important role in our algorithm. Peak in vertical acceleration corresponds to the foot strike point. Successive foot strike points can be found by searching peaks in the vertical acceleration data.

![3-axis Accelerometer Diagram](image)

**3-axis Accelerometer**

- $a_x$
- $a_y$
- $a_z$

LPF $f_c=10\text{Hz}$

**Foot Strike Detection**

**Peak Detection: $a_y$**

**Foot Identification**

**Stance/Swing Time**

**Speed Distance Gait Pattern**

Fig. 3 Overall feature extraction procedure.

We can identify which leg corresponds to each foot strike point by checking the sign of integration value of lateral acceleration from foot strike time to the next foot strike time.

From the Fig. 4, let $t_a$, $t_b$, and $t_c$ are detected foot strike time at point A, B, and C, respectively. Points $t_a$ and $t_c$ correspond to right foot strikes, and $t_b$ corresponds to left foot strike since

$$\int_{t_a}^{t_b} a_x \, dt < 0,$$  $$\int_{t_b}^{t_c} a_x \, dt > 0.$$

Therefore, stance time and swing time for right foot can be defined as

$$T_{STANCE} = t_b - t_a,$$  $$T_{SWING} = t_c - t_b.$$

If we know step length, $L_s$, the speed of walking can be calculated by

$$v = \frac{2L_s}{T_{STANCE} + T_{SWING}}.$$  

Let the number of foot strike points during the experiment, $N_F$, then the total walking distance can be estimated as

$$d = N_F \cdot L_s.$$

These two values give only approximations of them, however, they may be used as an important data for medical diagnosis of ambulation and degree of gait training.

![Foot Strike Time by Peak Detection](image)

The simple peak detection algorithm was used.

Step 1: Find the segment of signal greater than the predefined threshold value.

Step 2: Search the point where the gradient of signal is zero.

For an abnormal gait pattern, peak detection may skip corrupted foot strike points, however, foot identification algorithm by integration will compensate missing foot strikes. Therefore, we can apply the mentioned procedure reliably for various subjects.
4. Experiment

Two male subjects performed real experiment wearing accelerometer on their waist belt. Fig. 5-6 shows the obtained acceleration signals in three dimensional directions. Using the described algorithm in section 3, we estimated gait parameters which is shown in Table 2. Step length is the known value before the experiment. By sensing vertical acceleration of body movement, we can identify foot strike time. Using the integration of lateral acceleration between two successive foot strike points, we can recognize swing phase and stance phase during walking. With the a priori knowledge about the step length for the subject, we may estimate speed of walking and total distance he traveled.

5. Conclusion

A measurement method for gait patterns has been proposed. By utilizing the characteristics of accelerometer, we can estimate some gait parameters accurately. Without using integration of acceleration signals directly, we estimated speed of walking with known step length. The total measurement equipment is relatively simpler than other techniques, therefore, this method can be used to gait training system [6]. We confirm that the proposed method can be applied to human-machine interfaced system.

Acknowledgments

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References