33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Repeatability of the Accelerometric-Based Method to Detect Step Events for Hemiparetic Stroke Patients

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***Abstract*—This study is to evaluate the repeatability of the accelerometric-method to detect step events for hemiparetic stroke patients. To evaluate this method, four adults with chronic hemiparetic stroke were participated. The repeatability of this method using a single three-axis accelerometer was evaluated with a six optical camera motion capture system. The correlation statistics and Bland-Altman plot were then used to evaluate the agreement between the step-time differences from the accelerometer data and the reflective markers data. The correlation coefficient of each two data was 0.99 ($p < 0.001$) and retest result was 0.99 ($p < 0.001$). The mean ± standard deviation (SD) between each two data along with the 95% limits of agreement (LOA = ±1.96 SD) was 2.58±2.37 ms (LOA = -2.07 ms and 7.23 ms), and retest result was 3.73±2.02 ms (LOA = -0.22 ms and 7.68 ms). These results show that the suggested method is useful to detect step events for hemiparetic stroke patients.**

I. INTRODUCTION

PORTABLE gait monitoring devices using accelerometer is more comfortable, inexpensive and easy-to-use than conventional motion capture system with either opto-electronics or ultrasounds. Thus, various portable gait monitoring devices were developed and many researches to monitor gait pattern and daily activity were performed by using these devices [1]–[3]. Especially, some related researches to detect step events were performed [1], [4]. Recently, we have developed novel computational methods to detect step events for gait evaluation using an accelerometer [5]. One of the computational methods is based on both the least squares acceleration filter and the morphological operators. This study demonstrated that the performance and application of the method were useful and accurate in detecting and distinguishing the step events in normal and pathological populations. However, the evaluation of the repeatability in the method was not performed.

In this paper, we evaluated the repeatability of the developed accelerometric-based method to detect step events for gait monitoring of hemiparetic stroke patients. The repeatability was based on the correlation statistics and the Bland-Altman plot.

This work was supported by Industrial Strategic Technology Development Program (10030006, “The Development of Biosignal Convergence DxR Platform for Wellness-Care & Integration technology”) funded by the Ministry of Knowledge Economy, Republic of Korea.

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II. MEASUREMENTS

A. Subjects

Four adults with chronic hemiparetic stroke (2 men and 2 women, age 55.7 ± 8.0, weight 67.2 ± 10.1 kg, height 164.24 ± 6.3 cm) volunteered and provided informed consent prior to participation in this study.

B. Data acquisition

Laboratory setting diagram is illustrated as Fig. 1. A three-axis accelerometer (CXL02LF3, Crossbow, US) was placed on the surface of the 2nd sacrum near body center of mass to detect step events for hemiplegic gait monitoring. A 3-D motion capture system with the six optical cameras (Vicon, Oxford Metrics Ltd., UK) as reference was applied to evaluate our proposed method and two reflective markers were attached on each heel. Data from an accelerometer and two heel markers were synchronously recorded at 120 Hz sampling rate by 3-D motion capture system while the subjects walked on the 8-meter long walkway at their self-selected speed. All subjects walked 3 times repeatedly.

III. COMPUTATIONAL METHOD

The computational method based on the least squares acceleration filter and the morphological operators to detect step events for hemiparetic stroke patients is introduced as below. Fig. 2 and Fig. 3 illustrate the procedure and its results of this computational method. Detailed description is given at [5].

A. Pre-processing

A vector magnitude of the three axes accelerometer data ($\mathrm{ACC} = \sqrt{\mathrm{ACC}_X^2 + \mathrm{ACC}_Y^2 + \mathrm{ACC}_Z^2}$) was computed in order to emphasize the sharpest peak points of the raw accelerometer data and to synthesize the information contained within the accelerometer data.

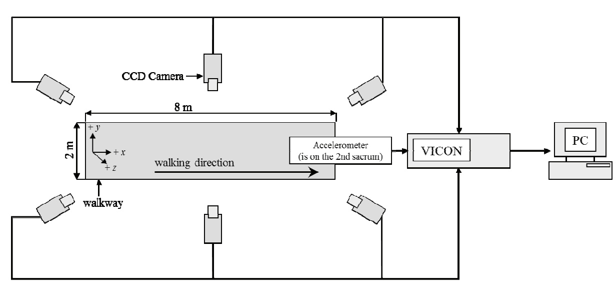

Fig. 1. Laboratory setting diagram

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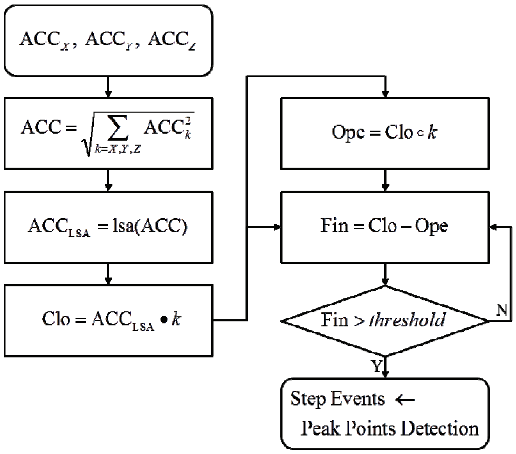

Fig. 2. The block diagram for detecting step events based on the least squares acceleration filter and the morphological operators.

B. Least Squares Acceleration Filter

The least squares acceleration filter [6], which can be processed in real-time, was employed for more emphasizing the sharpest peak points of the vector magnitude data. In this study, a fourth-order least squares acceleration filter is applied.

C. Morphological Operators

The morphological operators were finally employed to detect step events from the least squares acceleration-filtered data. A morphological operator, which is one of the most fundamental nonlinear signal processing tools that include the shape information of a signal, consists of four operators based on set operation as below Eq. (1) ~ (4) [7].

Erosion:

$$(f \ominus k)(m) = \min_{n=0,\cdots,M-1} f(m+n) - k(n), \quad \text{for } m = 0,\cdots,M-N \tag{1}$$

Dilation:

$$(f \oplus k)(m) = \max_{n=m-M+1,\cdots,m} f(n) + k(m-n), \quad \text{for } m = M-1, M, \cdots, N-1 \tag{2}$$

Opening:

$$f \circ k = (f \ominus k) \oplus k \tag{3}$$

Closing:

$$f \bullet k = (f \oplus k) \ominus k \tag{4}$$

where f is the original data and k is a structuring element. Also, M and N are the length of the data k and f, respectively.

In this study, a function f of the closing operation (Clo) is the least squares acceleration filtered data (ACC_{LSA}) and a function f of the opening operation (Ope) is the data after closing operation. The structuring element k for closing operation has a length of 24 and a constant value of 1. And k for opening operation has a length of 12 and a constant value of 1.

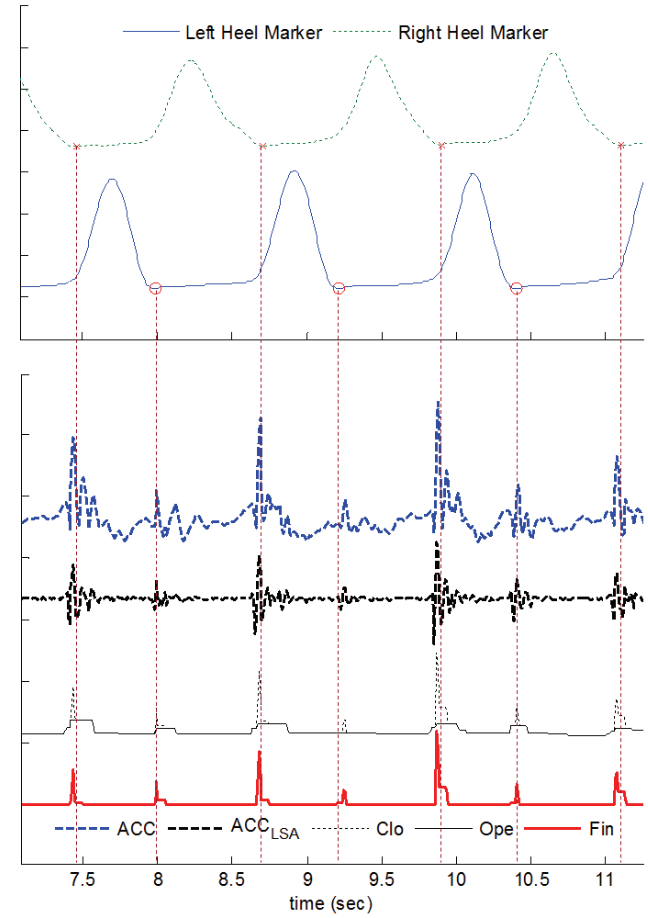

Fig. 3. The signal morphology of the reflective marker as reference (upper) and the signal processed results based on Fig. 2 (lower).

D. Post-processing

The subtraction operator (Fin) was employed to obtain the proper data for detecting the peak points. In order to detect the peak points, the experimental threshold was applied. Then, the step events were finally determined by the peak points over the threshold value.

IV. Evaluation Method

To evaluate our proposed method, we calculated both the step times of the heel markers data and one of the accelerometer data. Using calculated step times, the correlation statistics and the Bland-Altman plot were analyzed.

A. Correlation Statistics

Correlation statistics were employed to determine the relationship between step times of the heel markers and the accelerometer. Fig. 4 presents results of the correlation statistics between the step times computed by heel markers and an accelerometer.

B. Bland-Altman Plot

The Bland-Altman plot is based on a graphical method used to compare measurements by two different methods [8].

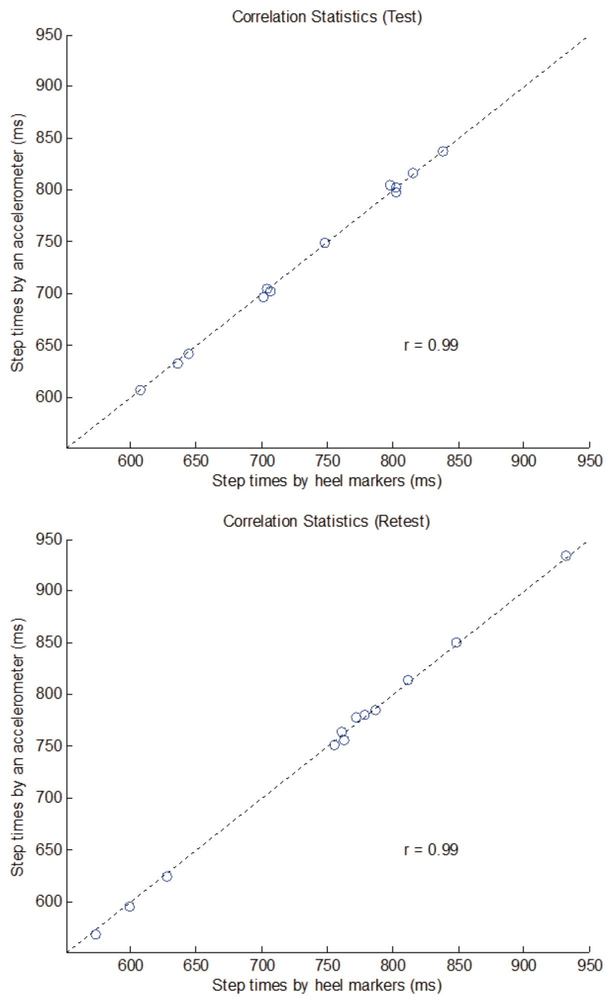

Fig. 4. The correlation statistics results of the test (upper) and retest (lower) data.

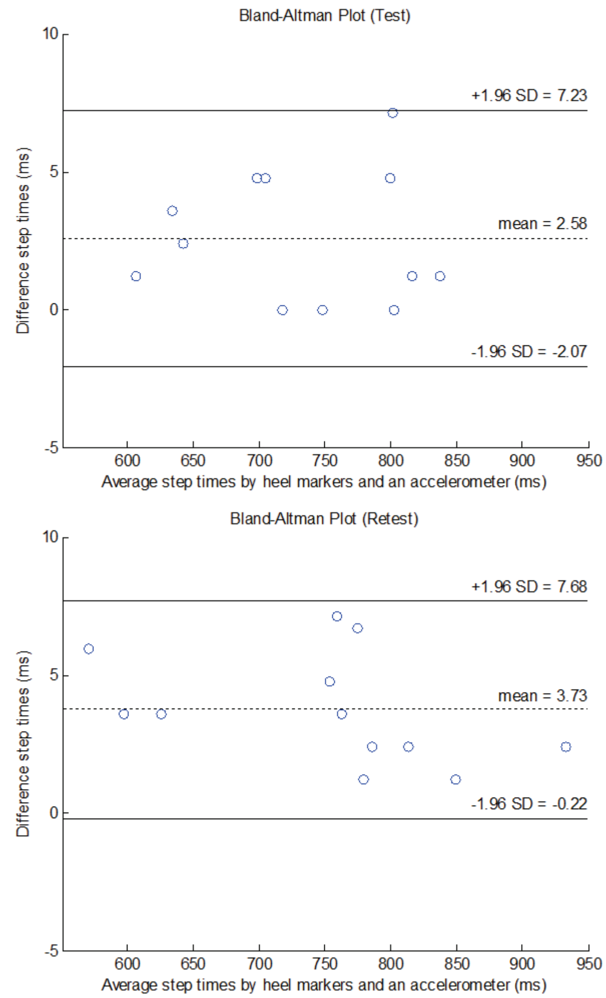

Fig. 5. The Bland-Altman plot of the test and retest data.

In this study, the Bland-Altman plot was employed to evaluate the agreement of proposed computational method. And it is able to estimate whether the method has structured errors or not. Fig. 5 presents the Bland-Altman plot of the test and retest data. The mean step times by the heel markers data as reference and an accelerometer data are plotted along the x-axis. The differences of step times by two data are plotted along the y-axis.

V. Results & Discussion

Fig. 3 highlights the example of the signal morphology by the left and right heel markers (upper) and the signal processed results based on Fig. 2 (lower). The position of signs (o, x) of heel contact points by left / right heel markers and one of the peak detection points by the newly transformed data based on proposed computational method are similar. It means that the method can be applied to the portable gait monitoring and the daily activity monitoring using an accelerometer.

Fig. 4 presents that the correlation relationship of both test and retest results between the heel markers and an accelerometer is very high as 0.99 ($p < 0.001$). It reveals that the performance of the accelerometric-based computational method is good. However, the high correlation coefficient is not guarantee the agreement of two results. Thus, the Bland-Altman plot was included.

Fig. 5 highlights that the computational method is reliable and repeatable. The mean ± standard deviation (SD) of difference between the step times from two heel markers and an accelerometer data along with the 95% limits of agreement (LOA = ±1.96 SD) was 2.58±2.37 ms (LOA = 2.07 ms and 7.23 ms), and retest result was 3.73±2.02 ms (LOA = –0.22 ms and 7.68 ms). All results are included within the 95% LOA. It means that the results of step times computed by the heel markers and an accelerometer are reliable.

Various researches were implemented for portable gait monitoring and activity monitoring using the accelerometer-based measurement. Especially, two or multiple accelerometers were attached on the body trunk and the other side to monitor the gait pattern and the activity of daily living. However, the use of multiple accelerometers interferes with movement during walking. Also, many researches have analyzed or monitored the normal gait pattern and not the hemiplegic gait pattern. And the video camera is used to evaluate the performances of their methods. However, these have some drawbacks such as the expensive cost, lack of portability, difficult clinical settings and so on.

It notes that just one accelerometer was used to monitor gait pattern or daily activity in this study unlike some studies using multiple accelerometers. Also, our computational method based on least squares acceleration filter and morphological operators has a small computing time.

The limitations of this study are as follows. First, the samples of the subjects are not sufficient. Second, the hemiparetic stroke patients have just walked 3 times repeatedly because of the fatigue of patients. In the future, we will implement this study with more trial and sufficient sample size.

VI. Conclusion

This paper evaluates the repeatability of the developed accelerometric-based method to detect step events for hemiparetic stroke patients. This method is based on least squares acceleration filter and four morphological operators. The results demonstrate that this computational method is highly helpful to monitor gait pattern or daily activity for hemiparetic stroke patient. Furthermore, this method needs not any filtering technique such as digital low pass filter. It may be that the accelerometer-based system based on this method are more portable and comfortable than the 3-D motion capture system and provide clinical insights when designing an portable and inexpensive gait monitoring tool for hemiparetic stroke patient.

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