Automatic Step Detection in the Accelerometer Signal

H. Ying[1], C. Silex [1], A. Schnitzer[1], S. Leonhardt[2], and M. Schiek[1]

[1] Central Institute for Electronics, Research Centre Jülich, Germany
[2] Philips Chair for Medical Information Technology, RWTH Aachen University, Germany

Abstract— **The automatic step detection is a crucial component for the analysis of vegetative locomotor coordination during monitoring the patients with Parkinson's disease. It is aimed to develop the algorithms for automatic step detection in the accelerometer signal, which will be integrated in sensor networks for neurological rehabilitation research. In this paper, three algorithms (Pan-Tompkins method, template matching method and peak detection based on combined dual-axial signals) are detailed described. Finally, these methods will be discussed by means of dis- and advantages.**

Keywords— **Step detection, accelerometer, Pan-Tompkins method, template-matching method, neurological rehabilitation research**

I. INTRODUCTION

Parkinson's disease (PD) is associated with reduced coordination between respiration and locomotion [1]. For the neurological rehabilitation research, it requires a long-time monitoring system, which enables the online analysis of the patients' vegetative locomotor coordination. The online analysis allows the later integration of bio-feedback protocol for the rehabilitation purpose. This system will facilitate the identification of the therapeutic effect and measuring the patients' health status. To monitor the phase synchronization between respiration and locomotion, the accurate time of step event has to be determined. The commercial pedometers, which count each step a person makes, can not fulfill this requirement. For this purpose, the online algorithm is developed for the automatic step detection. Since the characteristics of the PD patients' gait are pronounced different from the normal gait [2], the database for algorithm development in our work is acquired only from the PD patients.

The first experiment on the locomotion measuring is carried out using accelerometer. The accelerometer signals show considerable difference in morphology and amplitude among the individuals. We attempt to design a fast and robust algorithm, which should be suitable for individual patients, without any user-specified parameters. So far, three methods have been investigated for this project:

- Pan-Tompkins Method
- Template-Matching Method
- Peak-detection method based on combined dual-axial signals.

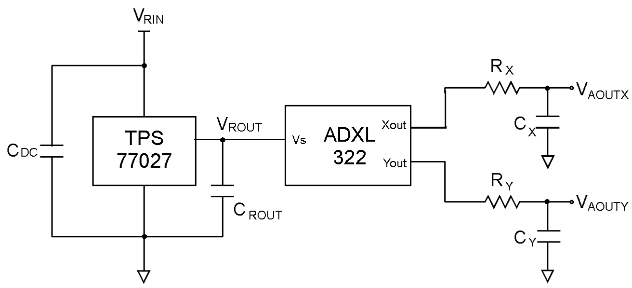
These three algorithms will be described in detail below, as well as their preliminary results on the patients' data. Finally, the dis- and advantages of these methods will be discussed.

II. METHODOLOGY

A. Subjects and Equipment

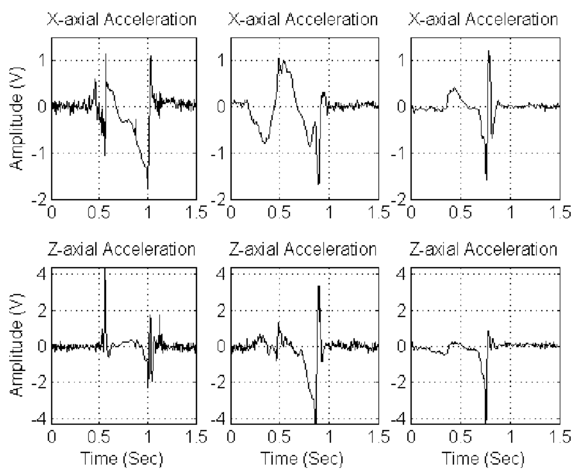
Subjects: In total, eight patients suffering from PD were measured in the Clinic Ambrock for Neurology, Centre for Sleep- and Rehabilitation Research, Germany. The patients are at different stage from 1 through 4 according to unified rating scale (UPDRS). To evaluate the algorithms, data in total duration of 115 minutes were collected from eight recordings. They are acquired at a sample rate of 200 Hz. The patients were walking on a treadmill with accelerometers attaching on the lateral side of the left and right feet during the measurement. Meanwhile, the abdominal and thoracic respiration signals were measured and acquired with a sample rate of 20 Hz.

Equipment: The horizontal and vertical acceleration in x- and z-axis generated from the locomotion during steps is measured by ADXL322, a low power dual-axis accelerometer, produced by Analog Devices, Inc. The schematic circuit diagram of the accelerometer for activity measuring is provided in Fig.1 below. The accelerometer is supplied by battery voltage through a low-dropout voltage regulator (TPS77027) to maintain constant 2.7 V level. To improve transient response and noise rejection, a 1 μF ceramic capacitor (C_{DC}) is connected between V_{RIN} and GND. The voltage regulator requires a 4.7 μF capacitor (C_{ROUT}) connected between V_{ROUT} and GND. The output of regulator is brought into ADXL 322 through pin Vs. The ADXL322 contains two 32 $k\Omega$ resistors (R_X and R_Y) in each output inside IC, respectively. The 0.1 μF capacitors (C_X and C_Y) are added at the pins X_{OUT} and Y_{OUT} to implement passive low-pass filtering of 50Hz, first order, to eliminate high frequent noise. The output signals: V_{AOUTX} and V_{AOUTY} are analog voltages that are proportional to acceleration.



F*ig. 1* Schematic diagram of the accelerometer application circuit

Fig. 2 depicts the acceleration of three patients on the left feet in the horizontal (x-axial) and vertical (z-axial) direction during walking. Each column of figures shows the data of one patient. The morphology of the acceleration, which depends upon the posture and gait of the individuals, shows great difference among the patients. The accelerometer signal on the left foot is similar with the signal on the right foot. Observe from Fig. 2 that normally, one step consists of two positive peaks, which occur when the foot lifts off the ground and heel strikes the ground, respectively. Either of them is the significant feature of steps in the time domain. The peaks of varied amplitude and morphology are attempted to be detected using the following three algorithms.



(a) Patient 1 (b) Patient 2 (c) Patient 3

F*ig. 2* The acceleration signal measured on the left feet of three patients in the horizontal and vertical directions

B. Algorithm Overview

I Pan-Tompkins method: Pan and Tompkins proposed a real-time algorithm for detection of R peak in ECG signal [3],[4]. An experiment is made to investigate, whether this algorithm can also be used for step detection in the accelerometer signal. This algorithm includes a series of filters and methods that perform low-pass, derivative, squaring, integration for preprocess and adaptive thresholds for peak-searching. Fig. 3 illustrates the steps of the algorithm in schematic form. And the results of each step processed on a signal segment of 6 s as shown in Fig. (a) are plotted in Fig. 4 (b) through (g) in sequence.

F*ig. 3* Block diagram of the Pan-Tompkins algorithm

Bandpass-filter: The bandpass filter reduces the influence of artifacts in the signal. In this work, the highpass filter is not applied. The digital lowpass filters with small integer coefficients are designed for fast execution. The following lowpass filter with a cutoff frequency of 20 Hz was applied:

$$H(z)=\frac{1}{16}\frac{(1-z^{-4})^2}{(1-z^{-1})^2} \qquad (1)$$

Derivative operator: The derivative operator is specified as:

$$y(n)=\frac{1}{8}[2x(n)+x(n-1)-x(n-3)-2x(n-4)] \qquad (2)$$

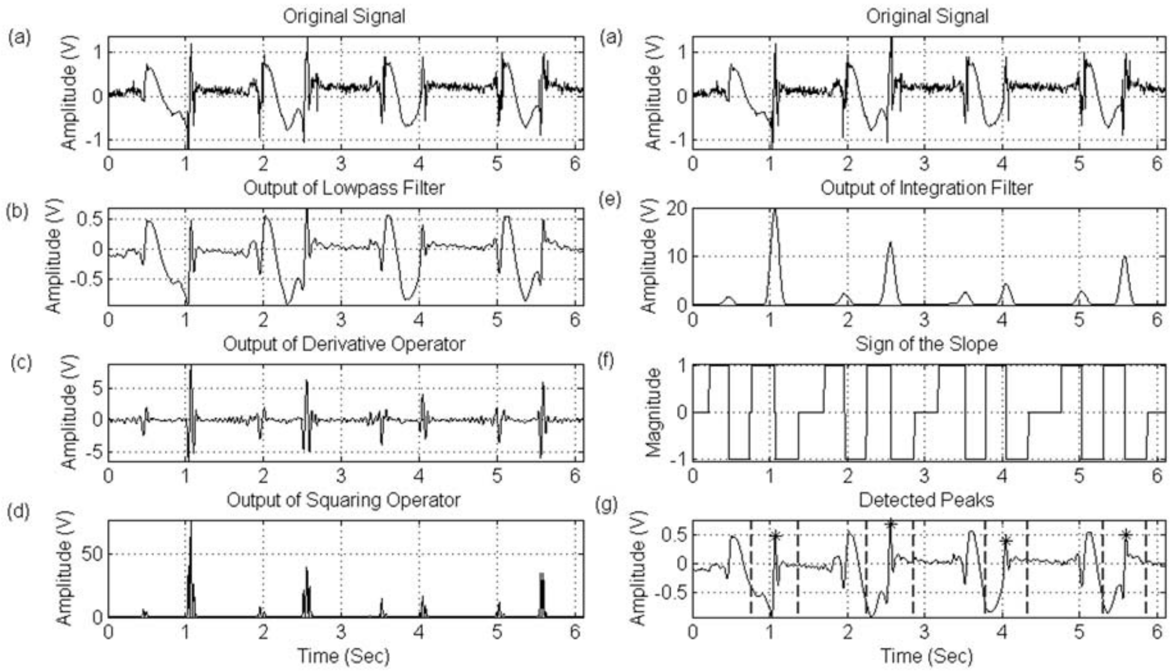
Note that eqn. (2) approximates the ideal derivative operator up to 30 Hz. Fig. 4 (b) illustrates the effect of the derivative, i.e., to suppress the low-frequency components and enlarge the high frequency components from the high slopes.

Squaring: The squaring operation leads to positive result and enhances large values more than small values. As shown in Fig. 4 (c), the squaring operator increases the high-frequency components further.

Integration: The output resulted from the preceding operation in Fig 4 (c) exhibits multiple peaks and hence needs to be smoothed. It is smoothed through a moving-window integration filtered:

$$y(n)=\frac{1}{N}[x(n-(N-1))+\dots \qquad (3)$$
$$x(n-(N-2))+\cdots+x(n)]$$

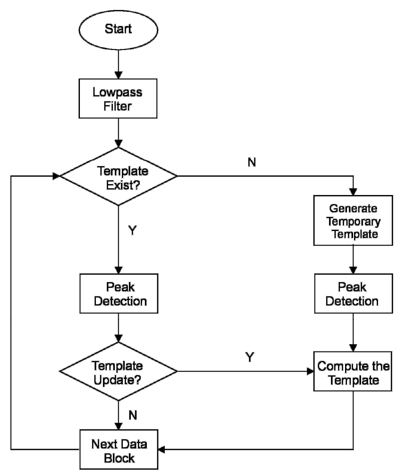
where N is chosen to be 20 empirically. The Fig. 4 (e) depicts the preprocessed signal beneath the original one in Fig 4 (a) for comparison. Each step cycle yields double peaks with monotonic ascend and descend.



F*ig. 4* Results of the Pan-Tompkins method on the x-axial acceleration of 6 s measured on the left foot in the step procedure

Fiducial mark: The so-called fiducial point, which is defined as location of the peak, is detected using an adaptive threshold within the Pan-Tompkins method. Unfortunately, the magnitude of the peaks in the accelerometer signal varies with time, stance of walking and the struck intensity of the foot on the ground, etc. Furthermore, the mathematical transform amplifies the difference in magnitude remarkably. Therefore, the peak-searching algorithm using threshold is not adequate for this solution. In this work, the property of the successive ascends and descends in the transformed signal is utilized for peak detection. The ascend and descend result in positive and negative slope, respectively. Fig. 4 (f) demonstrates sign of the slope arising from the preprocessed signal, in which the positive slope is equal to 1, whereas the negative one is transformed to -1. In this way, one step cycle signal is converted into a pair of consecutive 1 and -1 value, i.e., [1 -1 1 -1] in Fig. 4 (f). The second [1 -1] interval, corresponding to the onset and offset of the second peak in Fig 4 (e) is defined as peak-searching interval, which is plotted with dashed line in Fig. 4 (g). The local maximum within the peak-searching interval on the filtered signal is detected as step, which indicates the struck of feet on the ground, and marked with asterisk in Fig. 4 (g).

II Template-matching method: The main concept of the template-matching method is to generate a template, which represents a typical step cycle. In the unknown signal, an event is declared to be detected when there is a match between the signal and the template to certain degree. Fig. 5 illustrates a flow chart in schematic form explaining the template matching method.



F*ig. 5* Flowchart of the template matching method

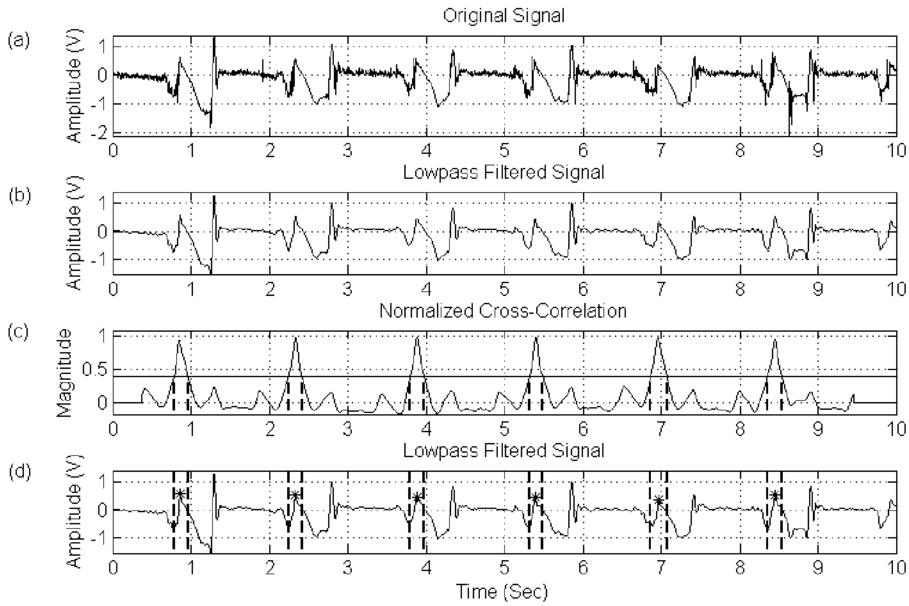


Fig. 6 Results of template matching on a data block of x-axial acceleration on the left foot in step procedure

Initially, the whole recording is broken into several non-overlapping data blocks of 10 seconds each. Fig 6 (a) depicts a data block measured on the left foot in the x-axis of 10 seconds, containing six step cycles. Then the signal is filtered by a lowpass filter with cutoff frequency of 20 Hz as shown in Fig. 6 (b).

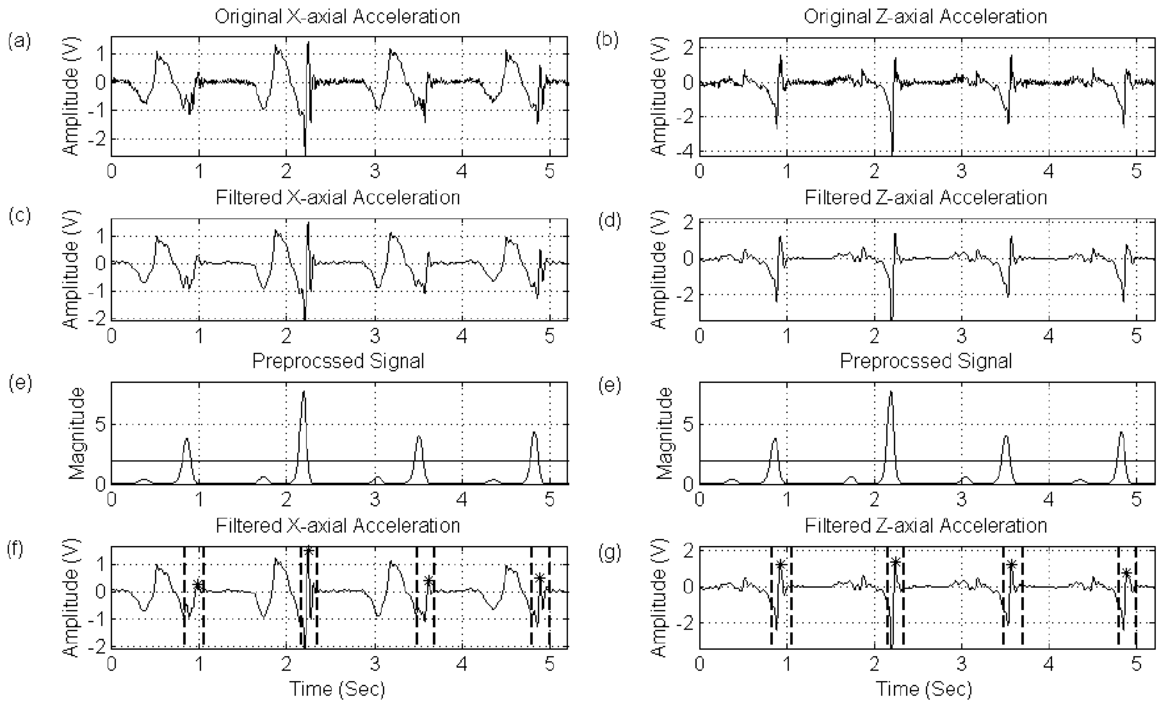
Next, the algorithm will check whether there is any template present in memory. If not present, the first step cycle is extracted as a temporary template. All the parameters are approximated, since the characteristic of the step is unknown. This template is slid across the whole data block and the normalized cross-correlation, is calculated between the template and signal, shown as in Fig 6 (c). The normalized cross-correlation indicates the similarity between two vectors X and Y, which is given in the eqn. (4) [5]:

$$R_N[k] = \frac{< X, Y >}{\sqrt{\|X\| \cdot \|Y\|}} = \frac{R_{XY}(k)}{\sqrt{R_{XX}(0) \cdot R_{YY}(0)}} \tag{4}$$

where $< X \cdot Y >$ is the inner product of X and Y, $\|X\|$ is the norm of the Vector X, $R_{XY}(k)$ is cross-correlation of X and Y for arbitrary k, and $R_{XX}(0)$ is autocorrelation of X[n] at point of zero.

The bound value for the maximum is 1 for absolute identity, which allows setting an uniform threshold for all the data despite different amplitudes. The peaks in the normalized cross-correlation in Fig. 6 (c) indicate great similarity between the step template and signal segment, thus the occurrence of the event. The interval, in which the cross-correlation exceeds the threshold 0.4, is defined as peak-searching interval. It is marked with dashed line in Fig 6 (c) and (d). The threshold is plotted as solid straight line in Fig 6. (c). The local maxima falling within the peak-searching interval in the filtered signal are marked as fiducial points of the steps, and symbolized with asterisk in Fig 6 (d). Using the template matching method, the first positive peaks of steps, which occur when the feet lift off the ground, are detected. A more representative template should be generated instead of the temporary template, when the peaks in the first data block are detected. These six step cycles are aligned with the peaks and averaged together to generate a new template, which will be applied for the further data processing.

If it is decided that a template has already been present, the peaks are detected using the same solution procedures stated above. Before the next data block is processed using the same template, a determination need to be made as to whether the template will be updated. The step signal may change dynamically with time; accordingly the template may not represent the current step signal. If the major peaks in the normalized cross-correlation are lower than 0.55, the new template is generated using the steps cycles in the current data block. Otherwise the peak detection is done in the next data block. The algorithm stops when the size of the recording is reached.



F*ig. 7* Results of the method based on the combined signals processed on the x- and z-axial acceleration.

III Peak-detection method based on combined dual-axial signals: Observe from the acceleration signal of each step that the negative wave in the x-axial signal occurs coincident with the negative wave in the z-axial signal. Sometimes, the negative peak due to the deceleration before the foot hitting the ground within one step is more apparent than the positive peak. The third method is based on the coincident negative wave in the x- and z-axial acceleration signal. Fig. 8. depicts the entire procedure of the algorithm. And this block diagram will be explained accompanied with an example of the acceleration signal segments of 5 s measured on the left foot in the x- and z-axial direction, which are shown in Fig 7 (a) and (b), respectively.

F*ig. 8* Block diagram of the peak detection algorithm on the combined dual-axial signal

The preprocess procedure consisted of bandpass filtering, summing up negative elements, a moving-window integrator and a squaring operation. At first, both signals are passed through a lowpass filter with cutoff frequency 20 Hz. The out-coming results are depicts in Fig 7 (c) and (d), respectively. According to the results of spectral analysis, highpass filter is not applied. Then the positive elements in both arrays are set to zero, whereas the negative elements remain. Both arrays are summed up entry-by-entry. Next, the intermediate results are smoothed using the moving-window integration filter, specified in eqn. 3. Then the squaring operator boosts the large value, which is associated with the deceleration before the feet striking on the ground, and suppresses the other waves of small amplitudes. The preprocessed signal is shown in Fig. 7 (e). For comparison purpose, the preprocessed signal is plotted at the same location in the left and right columns.

The preprocess procedures transform the complex signal of each step to a sloping wave of great amplitude. The location of the peak within this wave is very close to the second positive peak in the filtered signal for the short temporal distance between the both events. Shortly after the maximal deceleration, the impact force, exerting on the feet by the ground during the struck, results in the second positive peak in the step signal. The peaks in the preprocessed signal are detected using a threshold, one fourth of the maximum in array, which is marked with solid straight lines in Fig 7 (e).

The location of these peaks is defined as the onset of the peak-searching interval in the filtered signal and twice half-width of the sloping waves is defined as the width of the interval. The onset and offset of the interval is marked with dashed line in Fig 7 (f) and (g). The maxima within the peak-searching interval in the filtered signal are marked with asterisk in Fig 7 (f) and (g). This method allows detection of the second positive peak of each step signal.

III. Conclusions

Accelerometers are commonly integrated into body sensor networks. And the automatic step detection in the accelerometer signal provides useful information for the patients monitoring. Three algorithms have been developed for this purpose. Pan-Tompkins method is easy to implement, but the fluctuation in the signal, yielding the positive and negative slopes as the useful feature, can result in false peak-searching interval. The great advantage of the template-matching method is that the algorithm is capable of detecting the steps self-adaptively and generating the representative template according to the current step signal, under the condition that the first template should be correct. But the first template is estimated since the parameters are unknown; hence it may not approximate the real step signal. As a sequence, all the processing on the further data is false. Peak detection based on combined dual-axial signals is the fastest and easiest among the three algorithms. So far, it provides good performance in the first experiment. Moreover, it can be easily written in fixed-point algorithm, which is suitable for integration into microprocessor of limited computing power. This method still needs to be verified on more patients' data. In the future, the three algorithms will be compared quantitatively by means of complexity and precision, namely how many peaks are detected correctly in contrast to annotation on the database. According to the result of the comparison, one algorithm will be chosen, optimized and implemented in embedded system. Additionally, pressure sensors will be tested for step detection in the nearly future, which is commonly used for gait analysis [1],[6].

Acknowledgment

We wish to acknowledge the contribution of Prof. M. E. Schläfke at Clinic Ambrock for Neurology, Centre for Sleep- and Rehabilitation Research, Germany, and PD. Dr. D. Schäfer from Medical Department, Ruhr-University Bochum. Without their efforts of collecting the original data, the data processing would not have been possible.

References

1. Schiermeier S and Schäfer. D and Schläfke. ME, Breathing and locomotion in patients with Parkinson's disease (2001), Eur. J. Physiol., 443:67–71
2. Melnick ME and Radtka S, Gait analysis and Parkinson's disease (2002), Rehab. Manag., 58: 46-48
3. Pan. J and Tompkins. W, A real-time QRS detection algorithm (1985), IEEE Transactions on Biomedical Engineering, 32: 230-236
4. Rangayyan R. M, Biomedical Signal Analysis (2002), IEEE Press Series on Biomedical Engineering
5. Kincke. U and Jäkel. H, Signale und Systeme (2002), Oldenbourg Verlag, München
6. Hegewald, G, Ganganalytische Bestimmung und Bewertung der Druckverteilung unterm Fuß und von Gelenkwinkelverläufen (2000), Dissertation, Humboldt Universität zu Berlin

Address of the corresponding author:

Author: Hong Ying
Institute: Central Institute for Electronic (ZEL)
Street: Research Centre Jülich
City: Jülich
Country: Germany
Email: h.ying@fz-juelich.de