Gait Phases Recognition from Accelerations and Ground Reaction Forces: Application of Neural Networks

Nikola Mijailović, Marijana Gavrilović, and Stefan Rafajlović
(Mentors: dipl. eng. Milica Đurić-Jovičić, prof. dr Dejan B. Popović)

***Abstract* — The goal of this study was to test the applicability of accelerometer as the sensor for assessment of the walking. We present here the comparison of gait phases detected from the data recorded by force sensing resistors mounted in the shoe insoles, non-processed acceleration and processed acceleration perpendicular to the direction of the foot. The gait phases in all three cases were detected by means of a neural network. The output from the neural network was the gait phase, while the inputs were data from the sensors. The results show that the errors were in the ranges: 30 ms (2.7%) – force sensors; 150 ms (13.6%) – non-processed acceleration, and 120 ms (11%) – processed acceleration data. This result suggests that it is possible to use the accelerometer as the gait phase detector, however, with the knowledge that the gait phases are time shifted for about 100 ms with respect the neural network predicted times.**

***Keywords* — accelerometers, force sensing resistor, gait phase, neural network.**

I. INTRODUCTION

HUMAN gait analysis is important in following of the recovery of function in individuals with sensory-motor impairment. Gait phases recognition is likely one of the most important elements, since it allows the analysis of symmetry and comparison with the parameters known to be characteristic for healthy individuals when walking. In parallel, the recognition of gait phases allows external control of assistive systems for individuals with gait deficiencies alike: drop foot, Parkinson's disease (PD), individuals with spinal cord injury (SCI), etc. One among the key problems is to apply a practical system that does not require calibration, is easy to place on a subject, and is robust.

A *gait cycle* is defined as a period starting with an initial sole-to-ground contact and lasting up to the moment when the contact is repeated with the same sole. A gait cycle can be divided into two phases: a *stance* and a *swing*. A *stance* phase starts with a *heel contact* and continues with subphases: *loading response, mid stance, terminal stance* and *preswing.* The separation of toes from the ground marks the beginning of *swing* phase which involves the following subphases: *initial swing, midswing and terminal swing* (Fig. 1).

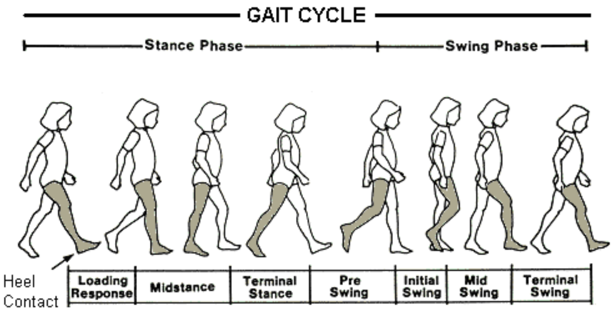

Fig. 1. Diagram of the gait phases characteristic for normal walking.

Many gait analysis systems are available today, which differ in sensor types, price, applicability, ease of handling and robustness. The most accurate system for gait analysis comprises an optical system based on the use of cameras and reflective markers, and force plates mounted in the floor. Infrared cameras record the positions of markers placed on a subject's body and these records can later be used to reconstruct the motion or determine desired parameters such as gait phases, angles, gait speed, step length, sole acceleration, etc. Force platform record by means of strain gauges the vector of ground reaction and determine the torques about the center of pressure. These systems are widely used in modern gait laboratories [1].

The alternative is to employ portable, body mounted systems that use goniometers, magnetic sensors, accelerometers, gyroscopes and force sensors. Reasons for using these systems are their lower price and their suitability for clinical measurements. Various realizations with the stated components exist; however, they are still difficult to apply in clinical environment. The one among them is the shoe-integrated system [2], [3], which provides reliable information on the exact moment of heel contact and separation of the sole from ground. The data obtained from multisensor apparatus that involved gyroscopes as well [4], [5], have been used to trigger automatically the peroneal nerve in individuals with SCI or stroke patients. Gait characteristics in PD patients have been recorded using three axial accelerometers [6]. Accelerations of both ankles during gait have been measured and a video system has been used as a reference. Experiments have been reported in which acceleration sensors have completely replaced force sensors from the heels and they have proved equally successful in swing phase detection [7].

N. Mijailović, M. Gavrilović, S. Rafajlović, students of Faculty of Electrical Engineering, Universitu of Belgrade; e-mail yonim12@yahoo.com, marijana.gavrilovic@yahoo.com, srafajlovic@yahoo.com

The same system was used for control of functional stimulation in persons who had a stroke. Acceleration sensors combined with force sensors together with the use of neural networks have also been used for control of functional electrical stimulation (FES) in hemiplegics [8]. A system comprising three capacitive sensors was also used for control of FES in paraplegics [9]. The literature suggests that the stance and swing phases have been recognized successfully by this system.

Based on the literature, it appears that robust and reproducible recognition of the beginning and end of stance and swing phases is sufficient for many clinical needs and also for controllers for assistive systems, including artificial extremities. This is why our study has focused on this subject. Gait phases recognition has been based on the use of a simple neural network and sensors suitable to be applied with disabled persons in a clinical environment. The method has been tested on signals obtained from force sensors, which are most often used for this application, as well as on signals from accelerometers, whose application is in expansion at present, because of their low price, robustness, and ease of installation.

II. METHODS AND MATERIAL

Experiments have been performed in laboratory conditions. Five young, healthy subjects aged 22±2 were recorded. They walked along a straight path, on a six-meter long flat ground, at their usual gait speed. Signals from force sensing resistors (FSR) and accelerometers were recorded at the same time. Ten passes along the path were recorded for each subject.

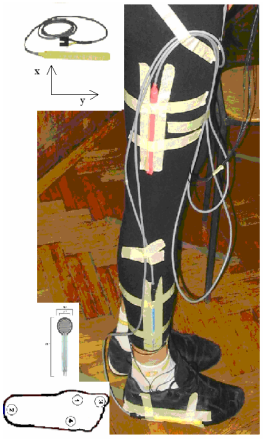

Fig. 2. Sensors positioned on a subject. The insert on the top shows the rigid bar with two ADXL330 accelerometers and the insert at the bottom the insole with sensor placing positions and force sensing resistor.

Two acceleration sensors were mounted on each of the three bars positioned along the leg segments. In this way six accelerometers recorded acceleration in the direction along the leg segment and two axes perpendicular to the segment (Fig. 2). Force sensors were mounted into the insole at forefoot (three sensors) and heel zone. An example of recorded signals is shown in Fig. 3.

Original and processed accelerometer signals were analyzed. Signal processing was performed using a simple moving average technique (with five successive points). For reasons of simplicity, the attention was on the possible use of only one accelerometer. After signal analysis, the target sensor was the bar mounted at the foot (Fig. 2). The signal analysis also suggested that the component that is in the sagittal plane and perpendicular to the foot is the most suitable one. An example of recorded accelerometer signals used in the analysis is given in Fig. 4.

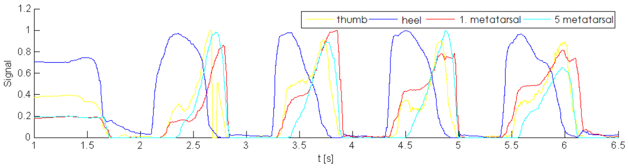

Fig. 3. Force sensor signals for four successive gait cycles.

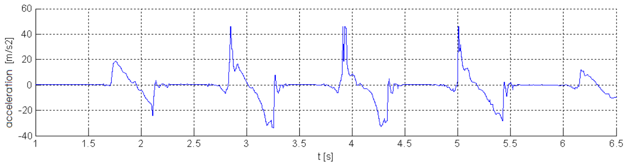

Fig. 4. Acceleration perpendicular to the foot sensor in the sagittal plane for the same four strides shown in Fig. 3.

We used the multilayer perceptron for mapping of gait phases and sensors' signals. We used the network with four input neurons, one output neuron and with fifteen neurons in each of the two hidden layers. The neural network trained by acceleration sensor signals comprised one input neuron, one output neuron and fifteen neurons in a hidden layer. A tansig function was used as the activation function, with the exception of the output neuron where a linear function was used. The network was trained by a backpropagation algorithm. The first training was performed on the basis of FSRs with 350 epochs and this signal shape appeared suitable for network training. The second network was trained in 200 epochs. Signals obtained from only one subject were used as training data.

III. RESULTS

Force sensing resistors (FSR) are commonly used for gait phase recognitions because of the simplicity of analysis, as already said in the introduction. When sensors are positioned carefully in such a way that there is no sensor bending or a constant pressure on some point during the whole gait cycle, a phase is considered to be a swing if the sum of signals from a FSR approaches zero, otherwise it is a stance. Force sensor signals were used as a reference system with respect to which deviation was calculated.

The results of phase recognition obtained from neural networks were compared with analytically obtained results from force sensors, as described in the preceding paragraph. These comparisons are presented in Figures 5, 6 and 7.

As a criterion for assessing the quality of mapping, we analyzed the timing of the beginning and end of phases between analytically obtained results and network outputs. Table 1 gives network test results for subjects whose gait was used for network training (A) and subjects whose gait was not used for network training (B). The average time deviation of recognizing the beginning and end of phase (Ts) is presented, as well as the relative error with respect to gait cycle duration (Err).

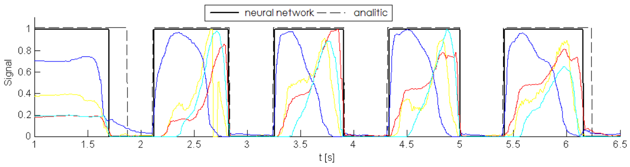

Fig. 5. Phase recognition on the basis of force sensors: 0 - Swing, 1 - Stance.

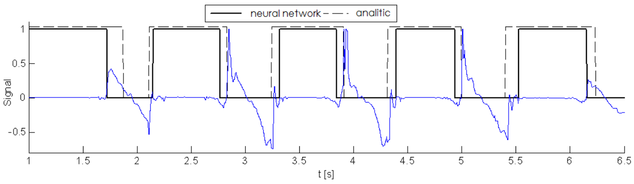

Fig. 6. Phase recognition from non-processed accelerations: 0 - Swing, 1 - Stance.

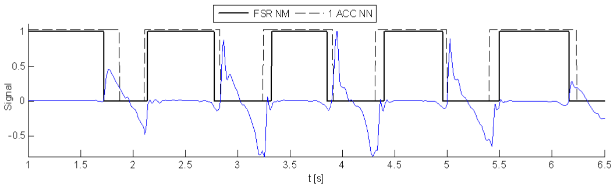

Fig. 7. Phase recognition on the basis of processed accelerations: 0 - Swing, 1 - Stance.

TABLE 1 TEST RESULTS

Signal	***A***		***B***	
	Ts [ms]	Err [%]	Ts [ms]	Err [%]
FSR	14	1.27	31	2.8
ACC	120	11	154	14
fACC	90	8.2	127	11.5

Fig. 8 presents the comparison of the results of the neural network trained by force signals and the network trained by an accelerometer signal.

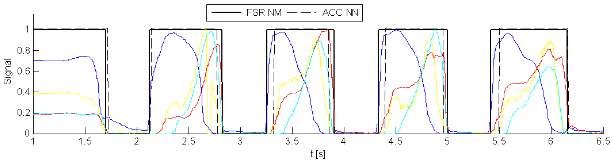

Fig. 8. Comparison of the results of two networks.

IV. CONCLUSION

Results have shown that the network using data from FSR is the most precise for gait phase recognition, even for subjects on whom the network has not been trained. However, our goal has been to find out the extent to which acceleration sensors are really worse for phase recognition compared with force sensors. The FSRs are far more impractical for use, more difficult for positioning and go out of order more easily. As the rehabilitation of patients is one of the main applications of gait phase recognition, it is exceptionally important to provide sensors that are quick and simple to mount as well as comfortable to use. A typical problem arising in the use of force sensors is that they deform easily during gait and may saturate in the presence of impact and high forces and thus become unusable, whereas accelerometers do not have such shortcomings.

In gait phase recognition based on an accelerometer signal, the number of sensors was reduced to a minimum by using a single sensor which is simple and quick to position on a subject, i.e. on a patient in the future. Recognition by using accelerometers does produce a larger error, but these results are still satisfactory from a practical viewpoint. Experiments have shown that filtered signals give a smaller error and this will be one among the future steps in our research. Although filtering reduces the error, it also introduces a delay which is an important factor in considering a method quality if we wish to use such a network in real time.

An important advantage of accelerometers lies in that they allow determining the subphases of *swing* and *stance* [11]. If the number of acceleration sensor signals at network input was larger, the network could be used for more detailed recognition of phases and subphases during gait, and this may be a subject of some future considerations.

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