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„Novel Gait Phase Detector System“

I. Pappas, T. Keller and M. Popovic
Laboratory of Automatic Control, Swiss Federal Institute of Technology, ETH Zürich, Switzerland
E-Mail:i.pappas@ieee.org

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A Novel Gait Phase Detection System

Ion P. Pappas, Thierry Keller and Milos R. Popovic

Laboratory of Automatic Control, Swiss Federal Institute of Technology, ETH Zürich, Switzerland

Abstract—**This paper presents the architecture and algorithm of a novel gait phase detection system. The system detects four distinct gait phases (stance, heel off, swing and heel strike). It consists of three force sensitive resistors integrated in a shoe sole which measure the applied pressure and a miniature gyroscope attached to the shoe heel which measures angular velocity. A novelty of this system is that it can reliably distinguish walking from loading, unloading or sliding of the foot during stance. Thus the system can be used continuously over long time periods in every day activities which may include walking, standing, sitting and even stair climbing. The necessary signal processing is performed in real time using a microcontroller board. The reliability of the gait phase detection is better than 99% as shown by laboratory experiments. The time delay in the detection of the gait phase transitions is smaller than 70ms for all phases.**

Index terms— gait, phase, identification, detection, sensor, FES

Introduction

Being able to detect in real time the different phases in the human gait cycle with a portable system is interesting for many areas such as medicine, biomechanics, sports or virtual reality applications. Such a system can also be used to properly trigger the stimulation sequences during walking assisted by Functional Electrical Stimulation (FES). Several gait phase detection systems have been proposed in the past using force sensitive resistors (FSR) [1], [2] and/or goniometers, accelerometers and tilt sensors [3], [4]. However, according to our experience none of these systems can provide the reliability required for an every day life application. We suggest that a reliable way to detect the gait phases is by using a combination of force sensitive resistors in a shoe sole and a miniature gyroscope attached to the shoe. The proposed system provides a radical improvement in reliability and can be used over long periods of time comprising periods of walking, standing, sitting and is not perturbed by loading, unloading or sliding of the foot.

Materials and Methods

The gait phase detection system consists of an instrumented shoe sole, a miniature gyroscope and microcomputer board.

The shoe sole incorporates three FSRs[1] located as shown in Figure 1. Two FSRs are used in the front part of the sole instead of one for more robustness in the measurements, especially in the case of asymmetrical or pathological loading of the foot.

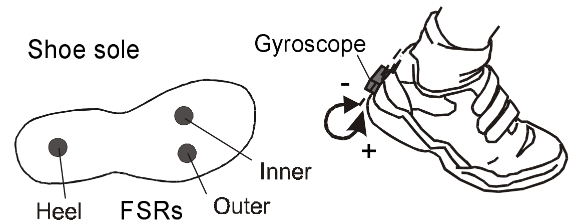

Figure 1 Position of the FSRs and the gyroscope used for the gait phase identification.

The gyroscope[2] is a small vibratory piezoelectric device which measures angular velocity using the coriolis effect. It is attached at the heel of the shoe, as shown in Figure 1, but can also be inserted inside the sole of the shoe, where it is also protected from collisions. To measure angular excursions the angular velocity signal must be integrated.

The gait phase detection algorithm which includes the processing of the sensor signals and a rule based observer is implemented on the Hitachi SH7032 microcontroller. The sensor signals are sampled with a frequency of 100Hz and 8bit resolution within a range of 0-5V. A new, pocket-size microcontroller board is currently developed in our laboratory.

Rule Based Detection Algorithm

The gait phase detection algorithm detects four different gait phases: STANCE, HEEL OFF, SWING and HEEL STRIKE. Upon startup the algorithm assumes that the initial gait phase is either STANCE or SWING. The transition from one active gait phase to the next is dictated by a set of rules listed in Table 1.

During the STANCE phase the aim of the algorithm is to detect the beginning of the HEEL OFF phase. To do so, the algorithm cannot rely solely on the heel FSR signal, since the heel may be momentarily unloaded, if the subject carries its weight on the contra-lateral leg without any intention of walking. Instead, the inclination of the foot with respect to the ground must be measured. This is achieved by filtering and integrating the gyro signal each time the heel force sensor is not loaded. The HEEL OFF phase is detected when the measured inclination exceeds a preset threshold.

*Corresponding author: Ion P. Pappas, i.pappas@ieee.org, Laboratory of Automatic Control ETH, ETL, CH-8092 Zürich.

[1] FSR 174N, Interlink Electronics, Inc.,Camarillo, CA, USA.

[2] ENC-05EA, Gyrostar, Murata Electronics Kyoto, Japan.

If the inclination threshold is set too low the system becomes very sensitive. In this case the HEEL OFF phase may be wrongly triggered by perturbations caused for example when the subject slides its foot. On the other hand if the threshold is set higher detection delay becomes larger.

Active Gait Phase	Condition to Change to Next Gait Phase
STANCE	heel inclination > threshold
HEEL OFF	rotation=positive AND heel=off AND outer=off AND inner=off
SWING	heel=on OR outer=on OR inner=on
HEEL STRIKE	heel=on AND (outer=on OR inner=on)

Table 1. The table shows the implemented rules for the gait phase detection algorithm which allow the passage from one gait phase to the next.

To detect during the HEEL OFF phase the transition to the SWING phase it is necessary to examine the three FSRs and the gyroscope signals. The beginning of the SWING phase is characterized by all of the FSRs being unloaded and by a change of the foot rotation from negative to positive direction, as defined in Figure 1.

The HEEL STRIKE phase which follows the SWING phase begins with the instant when the foot establishes the first contact with the ground. It terminates as soon as the entire foot sole contacts the ground. In normal gait the first contact is established with the heel. However, in pathological gait or when climbing stairs, the front part of the foot may strike the ground first. Therefore, in the algorithm the transition to HEEL STRIKE phase is triggered as soon as any of the FSRs transits from an unloaded state to a loaded state.

Finally, the STANCE phase which follows the HEEL STRIKE phase is characterized by both the rear and the front part of the foot being in ground contact. Thus in the algorithm the detection of the STANCE phase requires that the heel and one of the front FSRs are loaded. For more robustness we do not require that both of the front FSRs are loaded since in pathological gait styles one side of the foot may be not properly loaded.

Results

The gait phase detection algorithm has been evaluated so far by ten able bodied subjects and three incomplete spinal cord injured patients. The evaluation protocol for each of the subjects included level-ground walking at various speeds 0.5-2km/h, standing, shifting the body weight from one leg to the other, sliding the feet on the ground, standing up and sitting down. Figure 2 shows typical sensor signals and phase detection signals for two gait cycles. The gait phase recognition was practically faultless except for rare cases where subjects shook their feet too violently during foot sliding. To measure the gait phase detection delay we used as established measurement reference the optical 3D measurement system Vicon™. At the employed level of sensitivity the detection delay was smaller than 70ms for all gait phases. As mentioned in the previous section, there is an inevitable compromise between sensitivity and detection delay. If the HEEL OFF threshold is lowered the detection delay is reduced but the system becomes more sensitive to perturbations, like those present during foot sliding. Additionally, it was verified that the system performs equally well when walking on varying inclinations up to ± 35% and that it is also effective during stair climbing. By contrast, during descending of the stairs the system fails due to the fact that the heel is not necessarily inclined during the HEEL OFF phase.

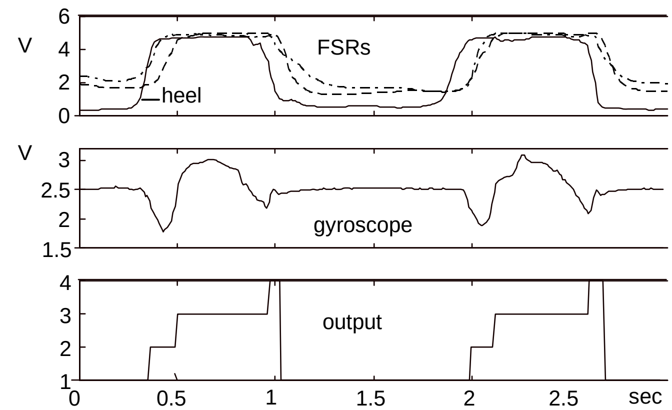

Figure 2 The first two plots display the sensor signals for two gait cycles. The last plot shows the gait phase detection output: 1=stance, 2=heel off, 3=swing, 4=heel strike.

Discussion

Although the first experiments have shown very satisfactory results further test have to be conducted in the near future with a greater variety of pathological gait styles and under different terrain conditions in the outdoor environment. Moreover, it has to be verified that the system is sufficiently robust to external electromagnetic interference (e.g. walking inside electrical trains) and insensitive to temperature variations (e.g. indoor-outdoor temperature difference during winter).

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