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Adaptive method for real-time gait phase detection based on ground contact forces

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ABSTRACT

A novel method is presented to detect real-time gait phases based on ground contact forces (GCFs) measured by force sensitive resistors (FSRs). The traditional threshold method (TM) sets a threshold to divide the GCFs into on-ground and off-ground statuses. However, TM is neither an adaptive nor real-time method. The threshold setting is based on body weight or the maximum and minimum GCFs in the gait cycles, resulting in different thresholds needed for different walking conditions. Additionally, the maximum and minimum GCFs are only obtainable after data processing. Therefore, this paper proposes a proportion method (PM) that calculates the sums and proportions of GCFs wherein the GCFs are obtained from FSRs. A gait analysis is then implemented by the proposed gait phase detection algorithm (GPDA). Finally, the PM reliability is determined by comparing the detection results between PM and TM. Experimental results demonstrate that the proposed PM is highly reliable in all walking conditions. In addition, PM could be utilized to analyze gait phases in real time. Finally, PM exhibits strong adaptability to different walking conditions.

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1. Introduction

Walking is a basic capability that allows humans to pursue their daily lives and function as productive members of society [1]. Human walking is a cyclic movement consisting of a series of continuous gait phases. Gait analysis is a clinically useful tool to quantify the state of the gait function [2]. Gait phases can be detected by many sensor platforms, such as air pressure sensors [1], foot switch platforms [3], force-sensitive resistors (FSRs) [4–9] and inertial sensors [2,10–20].

Motion phases during walking are characterized by the gait phases, and each gait phase has a unique ground contact force (GCF) pattern [1]. Force platforms, such as FSRs, are the gold standard means for gait analysis [21]. Specifically, an FSR is a sensor whose electrical resistance changes in proportion to an applied pressure [6]. As applied to gait phase detection, FSRs are located in shoe soles so that changes in the plantar pressure can be directly correlated to the gait phase.

One classic method for processing GCFs is the threshold method (TM) which sets a threshold to divide the GCFs into on-ground and off-ground statuses. A number of studies [10,13,21] have presented methods to compute the threshold. Mariani et al. [13] defined 5% body weight as a threshold. However, because subjects have different weights, thresholds would have to be calculated before each experiment for each subject. Lopez-Meyer et al. [10] and Catalfamo et al. [21] used the maximum and minimum GCFs of walking cycles to compute the threshold. However, the magnitude of GCFs changes with walking speeds, i.e., the magnitude of GCFs increases as the walking speed increases. As a result, the maximum GCF changes with the walking speed, and different thresholds are used for different walking speeds. In a word, the TM is not adaptable to different people and different walking speeds.

A real-time, automated monitoring system can provide the observation of human movement over extended time periods [20]. Therefore, the capability to capture real-time data can be regarded as another important feature for gait phase detection. For the TM, defining 5% body weight as a threshold can differentiate gait phases in real-time. The use of the maximum and minimum GCFs for the threshold computation cannot detect gait phases in

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real-time because the maximum and minimum GCFs are obtained in data post-processing.

Hong and Li [7] analyzed the influence of loading-carrying methods on gait phases in children during stair walking. In their study, double support and single support durations were significant parameters in the loading-carrying movements. The detection of double stance and single stance played an important role in the examination of human movement.

This paper proposes the proportion method (PM) which calculates the total and proportional GCFs as obtained from FSRs. Volunteer subjects wore our designed shoes on a treadmill. In each experiment, the data were processed by TM and PM. This paper also proposes a gait phase detection algorithm (GPDA), which provides the rules that determine calculations for TM and PM. Additionally, GPDA is able to be used to detect double stance and single stance.

This study aims to develop a real-time gait phase detection method that is adaptive to different subjects and different walking speeds. By using proportion factors (β and γ; defined in GPDA), the PM can detect gait phases for different individuals with variable walking speeds. To evaluate the reliability of the proposed method, three TM methods are introduced as references. The detection results of the proposed PM are compared with those of the reference methods.

2. Methods

2.1. Participants and procedures

Twenty-nine subjects (19 males and 10 females of average age 24.2 ± 2.1 years and average mass 62.9 ± 11.2 kg) volunteered in the project. All participants were free from walking injuries, diseases or limitations.

In our experiments, two FSRs (LOSON LSH-10, LOSON Instrumetation, Nankin, China) were embedded in each shoe for gait phase detection as shown in Fig. 1(a). One FSR was placed in the sole of the ball while the other in the sole of the heel. The measuring range of each FSR is 0–200 kg. FSRs were calibrated using standard load cells (5 kg, 10 kg, 20 kg, 25 kg, 50 kg, 100 kg and 200 kg). FSRs have comprehensive accuracies (including linearity and repeatability) of ±0.5% full scale (FS) with a small size (ϕ 20 mm). Because the FSR outputs a weak micro-voltage signal, an amplifying circuit is needed. Through the circuit, the output FSR signal is amplified to 0–5 V, which correlates with the measured mass of 0–200 kg. The signals were sampled at a frequency of 2000 Hz at 16 bits resolution to an ARM11 computer (S3C6410) through an AD converter. The acquired data from FSRs were filtered by a Butterworth low pass filter with a cut-off frequency of 120 Hz.

Each subject walked on the treadmill for 30 s per experiment at a designated constant speed of 2 km/h, 3 km/h, 4 km/h, 5 km/h, and 6 km/h in turn. After data acquisition, the results of the gait phase detection were processed in Matlab using TM and PM.

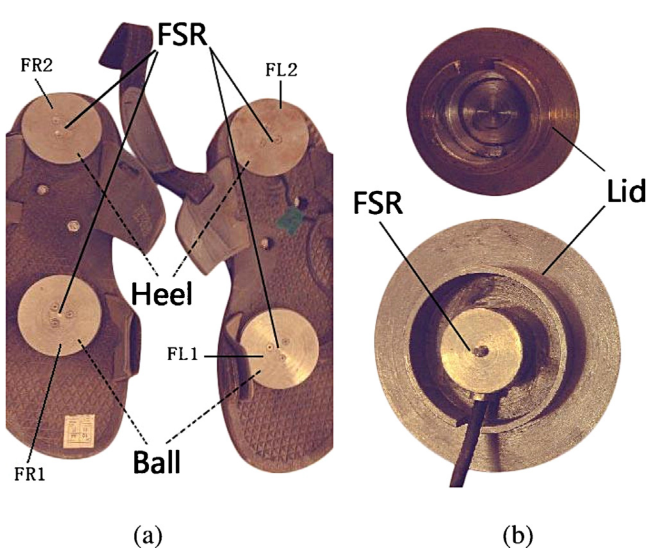

Fig. 1. (a) FSRs placed inside each shoe in the ball and in the heel. (b) A pairs of lids are made to enlarge the contact area.

2.2. Threshold method

By setting a threshold T, GCFs measured by an FSR can be divided into on-ground and off-ground statuses:

$$G(i) = \begin{cases} 1, & f(i) \geq T \\ 0, & f(i) < T \end{cases} \quad (1)$$

where $f(i)$ is the GCF of the i-th (i = 1–4) FSR and T is the threshold. $f(1)$, $f(2)$, $f(3)$, and $f(4)$ are the GCFs from the FSRs placed in the right ball, right heel, left ball and left heel, respectively. For $G(i)$, "1" indicates an on-ground status (FSR pressed) and "0" indicates an off-ground status (FSR not pressed).

In our experiments, three threshold methods were applied. One method defined a body weight percentage as the threshold [13]. The other two ways, as Lopez-Meyer method [10] and TAM method [21] did, used the maximum and minimum GCFs of gait cycles to calculate the threshold T.

2.2.1. Mariani method

Mariani defined the threshold T as 5% body weight [13]:

$$T = 0.05\,mg \quad (2)$$

where m is the subject mass and g is the acceleration due to gravity. For the four sets of FSRs in all experiments on an individual subject, the same threshold T was used.

2.2.2. TAM method

In [21], Catalfamo et al. used TAM software as their reference method. The TAM method used a force threshold T in the following formula, given the maximum and minimum GCFs (i.e., $T_{\max}$ and $T_{\min}$, respectively) for each set of FSR in each experiment:

$$T = T_{\min} + (T_{\max} - T_{\min}) \times \frac{10}{100} \quad (3)$$

Here, T was calculated for each set of FSR in each experiment.

2.2.3. Lopez-Meyer method

Lopez-Meyer et al. [10] calculated the threshold T by defining the average values of the maximum and minimum GCFs in the gait cycles. Thresholds were calculated for each set of FSRs in each experiment. The calculation of the threshold T required the local maximum and minimum GCFs (i.e., $T_{\max}(i)$ and $T_{\min}(j)$, respectively) from the gait cycles in each experiment. A complete gait cycle was measured from the initial stance to the terminal swing. In a complete gait cycle, there was only one set of $T_{\max}$ and $T_{\min}$ for each set of FSR. In one experiment, there were many gait cycles. For one set of FSR, there were k $T_{\max}$ and l $T_{\min}$ measurements in one experiment. Note that k was not necessarily equal to l as incomplete gait cycles may have occurred.

$$T_{\mathrm{MAX}} = \frac{1}{k}\sum_{i=1}^{k} T_{\max}(i) \quad (4)$$

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