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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.

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 $\pm$ 2.1 years and average mass 62.9 $\pm$ 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 $\pm$0.5% full scale (FS) with a small

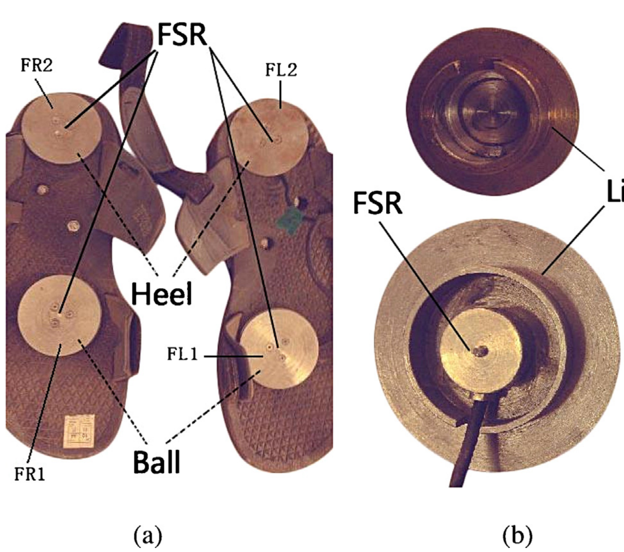

Fig. 1. (a) FSRs placed inside each shoe in the ball and in the heel. (b) A pairs of lids are made to enlarge the contact area.

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.

2.2. Threshold method

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

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

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]:

$$T = 0.05\,\mathrm{mg} \tag{2}$$

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:

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

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.

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

$$T_{\mathrm{MIN}} = \frac{1}{l}\sum_{j=1}^{l} T_{\min}(j) \quad (5)$$

$$T = T_{\mathrm{MIN}} + \alpha(T_{\mathrm{MAX}} - T_{\mathrm{MIN}}) \quad (6)$$

where α is a proportional factor that adjusted the threshold as a fraction of the difference between the average maximum and the average minimum of the GCFs to compensate for inter-individual pressure variability [10]. In our experiments, $\alpha = 0.084$ was used for the Lopez-Meyer method.

2.3. Proportion method

After measuring GCFs from four sets of FSRs, the sums and proportions were calculated using the following formulas:

$$FR = FR1 + FR2 \quad (7)$$

$$FL = FL1 + FL2 \quad (8)$$

where $FR1$, $FR2$, $FL1$, and $FL2$ are the GCFs measured by the FSRs placed in the right ball, right heel, left ball, and left heel, respectively (see in Fig. 1(a)). FR and FL are the sums of the GCFs from the right ball and heel and the left ball and heel, respectively, and represent the total body force that the right and left feet support.

$$d1 = \frac{|FR|}{|FR| + |FL|} \quad (9)$$

$$d2 = \frac{|FL|}{|FR| + |FL|} \quad (10)$$

where $d1$ and $d2$ are calculated proportions representing the fraction of body force the right and left feet supports, respectively.

$$s1 = \frac{|FR1|}{|FR1| + |FR2|} \quad (11)$$

$$s2 = \frac{|FR2|}{|FR1| + |FR2|} \quad (12)$$

$$s3 = \frac{|FL1|}{|FL1| + |FL2|} \quad (13)$$

$$s4 = \frac{|FL2|}{|FL1| + |FL2|} \quad (14)$$

where $s1$, $s2$, $s3$, and $s4$ are calculated proportions representing the fraction of body weight that the right ball, right heel, left ball, and left heel support, respectively.

When the sums and proportions are calculated, the gait phases can be delineated using the rules of the proposed gait phase detection algorithm (GPDA).

2.4. Gait phase detection algorithm

The gait cycle can be divided into jump-phase, stance-phase and swing-phase. The stance-phase consists of double stance and single stance. The transitions between phases are gait events [22]. In this paper, two gait events were detected for each transition, such as heel-strike and heel-off. The GPDA analyzes the gait phases and the gait events in three steps: initial gait phase detection, double foot gait phase detection, and single foot gait phase detection.

2.4.1. Initial gait phase detection

The initial gait phase detection is used to determine if both feet are off-ground (i.e., jump-phase) or if at least one foot is on-ground (i.e., stance-phase). In the experiments, jump-phase was rarely observed, and only occurred when the subjects walked at a sufficiently rapid pace. The initial gait phase was primarily stance-phase.

For TM, when the GCFs measured by all four sets of FSRs are recorded as off-ground, the gait phase is jump-phase. Otherwise, the gait phase is stance-phase (Table 1).

The PM requires the sums (FL and FR) calculated in Eqs. (7) and (8) for the initial gait phase detection:

$$F = FR + FL \quad (15)$$

$$N = \begin{cases} 1, F \geq \sum_{i=1}^{4} \delta(i) \\ 0, F < \sum_{i=1}^{4} \delta(i) \end{cases} \quad (16)$$

where F is the total force supporting the human weight, and N is the result of the initial gait phase detection. $\delta(i)$ is a force that is greater than the maximum GCF while the i-th FSR is not pressed. The magnitude of δ depends on the zero drift, creep deformation, stability and linearity of the FSR. A high-quality FSR produces a small δ. However, δ is affected by the attachment of the shoe to the foot. If the shoe and the foot are tightly attached, the FSR will output larger values. Because of this concern, a larger value should be set for δ to accommodate variations in shoe attachments.

When N is 1, the gait phase is stance-phase. When N is 0, the gait phase is jump-phase (Table 2).

2.4.2. Double foot gait phase detection

Double foot gait phase detection divides the stance-phase into more detailed subphases, such as double stance (or double support) and single stance (or single support). Double stance is defined when both feet are on-ground, and single stance is defined when one foot is on-ground and the other foot is off-ground.

For TM, when at least one point (i.e., ball or heel) of each foot is judged to be on-ground, the gait phase is double stance. When both the ball and heel in one foot are judged to be off-ground and one

Table 1
Rules of gait phase detection for TM.

Left foot		Right foot		IGP	DFGP	SFGP	
Heel	Ball	Heel	Ball			Left foot	Right foot
0	0	0	1	ST	SS	SW	HO
0	0	1	0	ST	SS	SW	HS
0	0	1	1	ST	SS	SW	FS
0	1	0	0	ST	SS	HO	SW
0	1	0	1	ST	DS	HO	HO
0	1	1	0	ST	DS	HO	HS
0	1	1	1	ST	DS	HO	FS
1	0	0	0	ST	SS	HS	SW
1	0	0	1	ST	DS	HS	HO
1	0	1	0	ST	DS	HS	HS
1	0	1	1	ST	DS	HS	FS
1	1	0	0	ST	SS	FS	SW
1	1	0	1	ST	DS	FS	HO
1	1	1	0	ST	DS	FS	HS
1	1	1	1	ST	DS	FS	FS
0	0	0	0	JP	–	–	–

IGP = initial gait phase, DFGP = double foot gait phase, SFGP = single foot gait phase, ST = stance, SW = swing, JP = jump, SS = single stance, DS = double stance, HS = heel-strike, HO = heel-off, and FS = flat-stance.

Table 2
Rules of gait phase detection for PM.

N	$L(d1)$	$L(d2)$	$T(s1)$	$T(s2)$	$T(s3)$	$T(s4)$	IGP	DFGP	SFGP	
									Right	Left
1	0	1	–	–	0	1	ST	SS	SW	HS
					1	0	ST	SS	SW	HO
					1	1	ST	SS	SW	FS
	1	0	0	1	–	–	ST	SS	HS	SW
			1	0			ST	SS	HO	SW
			1	1			ST	SS	FS	SW
	1	1	0	1	0	1	ST	DS	HS	HS
					1	0	ST	DS	HS	HO
					1	1	ST	DS	HS	FS
			1	0	0	1	ST	DS	HO	HS
					1	0	ST	DS	HO	HO
					1	1	ST	DS	HO	FS
			1	1	0	1	ST	DS	FS	HS
					1	0	ST	DS	FS	HO
					1	1	ST	DS	FS	FS
0	–	–	–	–	–	–	JP	–	–	–

IGP = initial gait phase, DFGP = double foot gait phase, SFGP = single foot gait phase, ST = stance, SW = swing, JP = Jump, SS = single stance, DS = double stance, HS = heel-strike, HO = heel-off, and FS = flat-stance.

point of the other foot is on-ground, the gait phase is single stance (Table 1).

For PM, a proportion factor β is provided for double foot gait phase detection.

$$L(d) = \begin{cases} 1, d \geq \beta \\ 0, d < \beta \end{cases} \tag{17}$$

where d is $d1$ or $d2$ as defined in Eqs. (9) and (10), and $L(d)$ is the result of double foot gait phase detection. The values of $L(d1)$ and $L(d2)$ determine the detected detailed gait phases.

When both $L(d1)$ and $L(d2)$ are 1, the gait phase is double stance. When either $L(d1)$ or $L(d2)$ is 0 and the other is 1, the gait phase is single stance (Table 2).

The magnitude of proportion factor β is set lower than 0.5 to avoid 0 values for both $L(d1)$ and $L(d2)$.

2.4.3. Single foot gait phase detection

Many studies [1,2,4,5,11,16,17] have identified gait phases and gait events for a single foot. As proposed by [4,5], swing-phase, stance, heel-strike and heel-off are the most common gait phases and gait events for a single foot. However, there are other types of gait phases and gait events, such as initial-stance [1], loading-response [1,2,11,17], mid-stance [1,2,11,17], terminal-stance [1,11,17], pre-swing [1,2,11,17], foot-flat [16], toe-off [16], and terminal-swing [11]. In this paper, the gait phases and gait events of a single foot are selected and observed as reported by Pappas et al. [4,5]. To differentiate from the initial gait phase detection, the stance-phase is referred to as flat-stance for single foot gait phase detection. Heel-strike is defined when the foot first contacts the ground. Heel-off is defined when the foot begins to rise from the ground [22]. Flat-stance is defined when the foot fully touches the ground. Swing-phase is defined when the foot totally leaves the ground.

In TM, the rules for single foot gait phase detection are provided as follows. When the heel and ball are on-ground, the gait phase is flat-stance. When the heel and ball are off-ground, the swing-phase is observed. The transitions between gait phases are gait events [22]. When the heel is on-ground and the ball is off-ground, the transition from swing to flat-stance is detected as heel-strike. When the heel is off-ground and the ball is on-ground, the transition from flat-stance to swing is detected as heel-off (Table 1).

For PM, the proportion factor γ is provided to detect the single foot gait phases:

$$T(s) = \begin{cases} 1, s \geq \gamma \\ 0, s < \gamma \end{cases} \tag{18}$$

where s is the proportion ($s1$, $s2$, $s3$ and $s4$) calculated in Eqs. (11)–(14). $T(s)$ is the result of single foot gait phase detection. $T(s1)$ and $T(s2)$ are used for the right foot gait phase detection, while $T(s3)$ and $T(s4)$ are used for the left foot gait phase detection.

The right foot gait detection is determined by the following rules. $L(d1)$ is calculated by Eq. (17). If $L(d1)$ is 0, the gait phase is swing phase. When $L(d1)$ is 1, the gait events and other phases can be detected. When $T(s1)$ is 1 and $T(s2)$ is 0, heel-off transition occurs. When $T(s1)$ is 0 and $T(s2)$ is 1, heel-strike transition occurs. When both $T(s1)$ and $T(s2)$ are 1, the gait phase is flat-stance (Table 2).

The left foot gait detection can also be detected using $L(d2)$, $T(s3)$ and $T(s4)$ with the same rules (Table 2).

3. Experimental results

3.1. Selection of coefficients

To determine the reliability of PM, three methods using TM (mentioned in Section 2.2) were chosen as references. The detection results of PM were compared with those of the Mariani, TAM and Lopez-Meyer methods.

In these experiments, the same δ was used for all 29 subjects. Because four sets of FSRs were used to implement the gait phase detection, each set of FSR had its own δ ($\delta(1)$ = 2.2 N for the right ball, $\delta(2)$ = 1.7 N for the right heel, $\delta(3)$ = 2.3 N for the left ball, and $\delta(4)$ = 2.1 N for the left heel).

Table 3
Reliability of the proposed method.

Subjects	Gender	Compared with TM		
		With Lopez method	With TAM method	With Marian method
1	Male	90.91%	90.44%	92.96%
2	Male	89.50%	89.14%	91.24%
3	Male	91.83%	90.72%	91.46%
4	Male	90.24%	91.54%	93.89%
5	Male	88.07%	83.75%	88.99%
6	Male	86.29%	85.10%	89.76%
7	Male	86.54%	82.58%	92.30%
8	Male	89.60%	89.65%	91.71%
9	Male	86.89%	81.14%	90.35%
10	Male	91.46%	90.15%	91.14%
11	Male	92.37%	91.23%	91.88%
12	Male	91.76%	90.68%	91.34%
13	Male	91.04%	89.18%	88.39%
14	Male	89.42%	88.80%	90.15%
15	Male	91.15%	88.70%	88.76%
16	Male	90.45%	88.56%	86.78%
17	Male	87.89%	87.19%	86.89%
18	Male	89.32%	87.33%	84.45%
19	Male	88.75%	88.06%	89.83%
20	Female	91.43%	95.50%	95.48%
21	Female	81.77%	85.70%	86.56%
22	Female	88.29%	90.83%	86.06%
23	Female	85.45%	90.34%	85.95%
24	Female	92.19%	94.18%	94.09%
25	Female	87.96%	88.02%	92.54%
26	Female	86.99%	92.21%	91.59%
27	Female	91.04%	91.11%	92.47%
28	Female	90.25%	90.30%	93.03%
29	Female	87.49%	90.36%	90.85%
Average	–	89.18%	89.05%	90.38%

To determine the highest reliability of PM, β and γ were optimized. Using the data from 8 subjects as training data, optimum values of $\beta = 0.11$ and $\gamma = 0.13$ were used. Data from the remaining subjects were processed using the selected β and γ.

3.2. Results of gait phase detection

The proposed PM was highly reliable when compared with the three methods using TM (Table 3). The average reliabilities were 89.18%, 89.05% and 90.38% when compared with the Lopez-Meyer, TAM and Mariani methods, respectively.

In this paper, acquired data were processed by both TM and PM. When processed by TM, each of the four GCFs could be in either on-ground or off-ground statuses when compared with a corresponding threshold (Fig. 2(a)). When processed through PM, as shown in Fig. 2(b), by comparing $L(d1)$ and $L(d2)$, defined in Eqs. (9) and (10), with the proportion factor β, the right foot and the left foot, respectively, could be determined to be on-ground and off-ground. By comparing $T(s1)$ and $T(s2)$, defined in Eqs. (11) and (12), with the proportion factor γ, the right ball and the right heel, respectively, could be judged to be on-ground and off-ground. Similarly, the left ball and the left heel could be judged to be on-ground and off-ground through $T(s3)$ and $T(s4)$ as defined in Eqs. (13) and (14). Thus, the double foot and single foot gait phases can be determined using the rules of the proposed GPDA (Fig. 2(c) and (d)).

4. Discussion

4.1. Advantages and disadvantages

When compared with methods using TM, the proposed method is highly reliable (see in Table 3). The Mariani method requires the weights of all subjects, while the Lopez-Meyer method and the TAM method requires the maximum and minimum GCFs in the gait cycles. To sum up, the TM is not adaptable to variable body weights and walking speeds (as mentioned earlier, magnitudes of GCFs change with variations in walking speeds). In this case, the Mariani method could be used in real-time to determine gait phases; however, the Lopez-Meyer and TAM methods would require data post-processing. Instead of using the body weights or the maximum and minimum GCFs, the proposed PM was used to detect in real-time the gait phases and gait events. The same δ and two pre-determined proportion factors (β and γ) were used for all

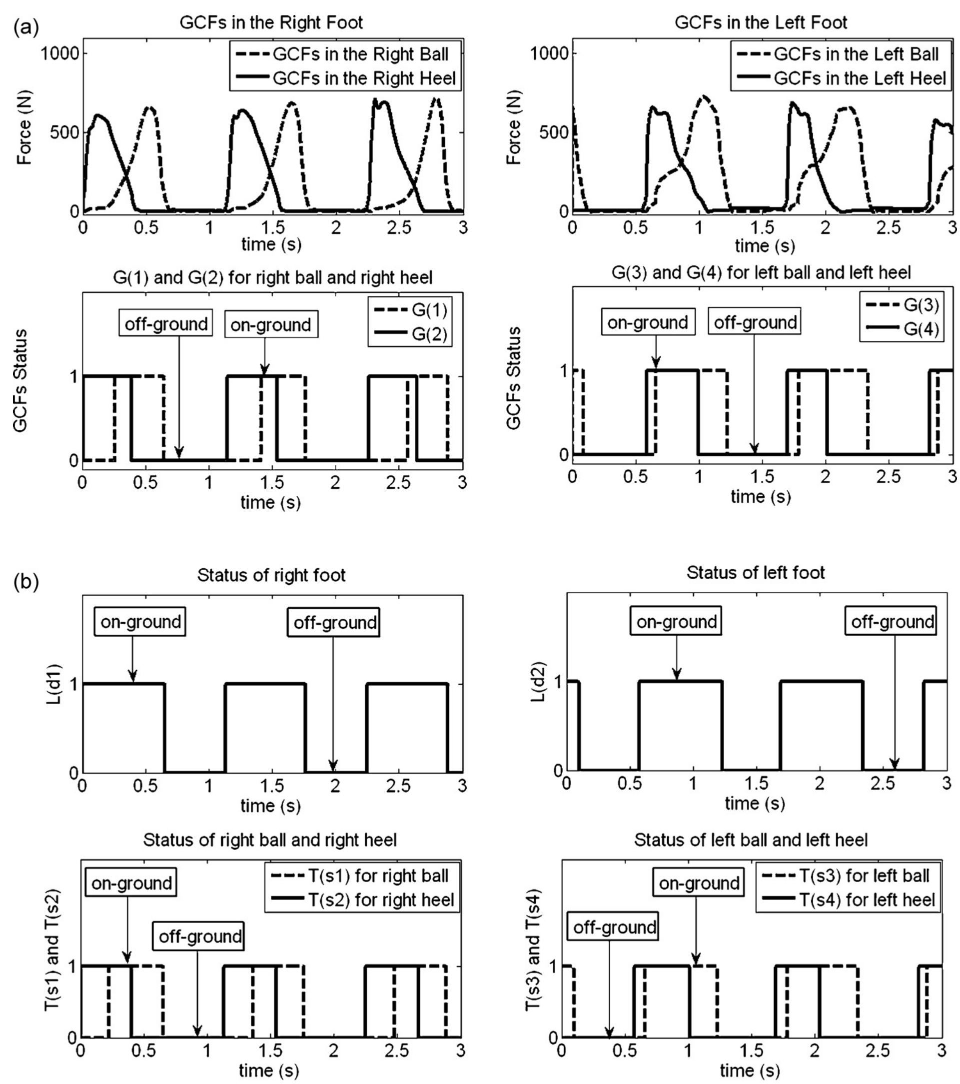

Fig. 2. (a) GCFs from four set of FSRs were divided to on-ground or off-ground statuses in TM. (b) Values of $L(d1)$, $L(d2)$, $T(s1)$, $T(s2)$, $T(s3)$ and $T(s4)$, the right foot, left foot, right ball, right heel, left ball and left heel, respectively are evaluated for on-ground and off-ground in PM. (c) The results of double foot gait phase detection. (d) The results of single foot gait phase detection.

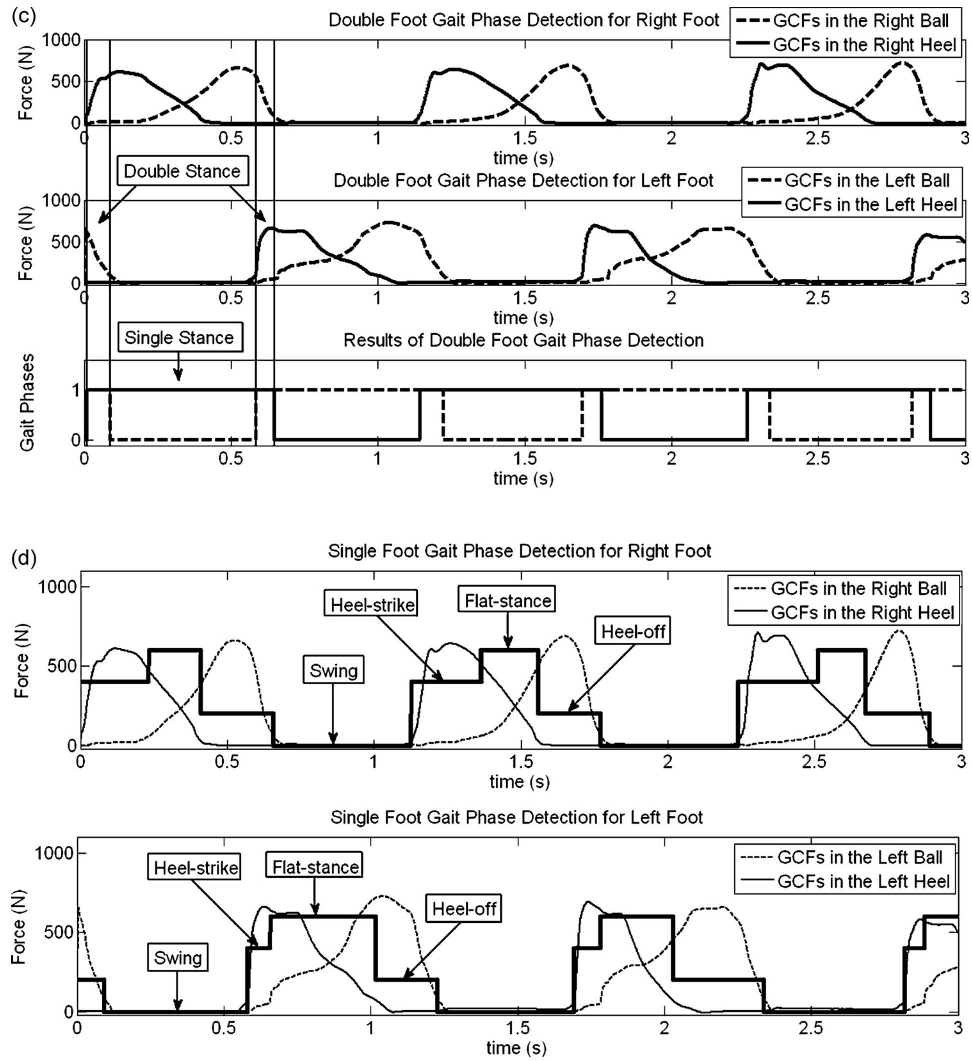

Fig. 2. (*Continued*).

29 subjects. The proposed PM was also adaptable to different walking conditions.

As an example, we consider the experimental results from the third subject (aged 24, weighing 71.6 kg). For the Lopez-Meyer method in five separate experiments, four sets of FSRs (placed in right ball, right heel, left ball and left heel) provided a series of thresholds: 17.59 N, 20.31 N, 18.33 N, and 20.57 N, respectively, at 2 km/h walking speed; 29.66 N, 19.41 N, 28.50 N, and 22.84 N at 3 km/h walking speed; 33.69 N, 18.53 N, 35.45 N, and 15.22 N at 4 km/h walking speed; 37.88 N, 20.82 N, 41.98 N, and 22.21 N at 5 km/h walking speed; and 45.47 N, 27.56 N, 47.23 N, and 29.43 N at 6 km/h walking speed. The series of thresholds for the TAM method were 34.09 N, 41.27 N, 40.73 N, and 33.60 N at 2 km/h walking speed; 38.47 N, 39.49 N, 41.05 N, and 26.13 N at 3 km/h walking speed; 48.39 N, 40.09 N, 52.66 N, and 28.78 N at 4 km/h walking speed; 56.92 N, 49.18 N, 62.84 N, and 40.28 N at 5 km/h walking speed; and 64.47 N, 54.43 N, 68.09 N, and 49.24 N at 6 km/h walking speed. The results showed that the thresholds for the right ball and left ball became larger as the walking speeds increased. The thresholds for the right heel and left heel remained nearly constant at the walking speeds of 2 km/h, 3 km/h, 4 km/h and 5 km/h, but they increased at 6 km/h. Only one threshold (i.e., 35.12 N) was used for the Mariani method. In the five experiments, the proposed PM accomplished the gait phase detection with the uniform $\beta = 0.11$ and $\lambda = 013$.

To obtain optimal values of β and γ, the data from 8 subjects were processed for training. When the optimal values of β and γ were determined, the data from the remaining subjects were processed using the optimal values of β and γ.

The contacting area of an FSR was too small to provide information about a foot contacting the ground. Past studies utilized three [4,5], four [11] and five [10] FSRs to detect the gait phases. In this research, only two FSRs were placed in the shoe sole; a pair of special lids was designed to increase the FSR contact area (see Fig. 1(b)).

4.2. Limitation of the research

In our study, the stance-phase can be divided into specific subphases, including double stance and single stance. However, the subphases of the swing-phase cannot be differentiated. Kong and Tomizuka [1] arranged three air pressure sensors in the ball, one of which was placed close to the foot toe for detecting the pre-swing. Rueterbories et al. [2] placed two accelerometers in each thigh, shank and foot for recognizing pre-swing. Chathuri et al. [11], in addition to FSRs, made use of an IMU sensor to obtain the angle of knee movements to identify the initial swing, mid-swing and terminal swing. The detection of subphases of swing needed more FSRs or other types of sensors.

The experiments were carried out on a treadmill (i.e., flat ground) because rough terrain was not appropriate for PM or TM. Obstacles on the ground or uneven road conditions may lead to misdetections.

If a shoe and a foot were attached too tightly such that the FSR recorded larger values, the attachment between shoe and foot should be loosened. Another solution could be to provide a large δ value (as previously mentioned in Section 2.4.1).

Several rules (see in Tables 1 and 2) of GPDA were not observed in the experiments (e.g., both heels were judged to be on-ground but both balls off-ground). However, the specific walking habits of a few individuals may result in invoking the unused rules. The GPDA rules could be used to detect abnormal gaits for podiatric diagnoses.

5. Conclusions

This paper proposes an adaptive method that could be used for the real-time detection of gait phases. Compared with previous studies, the proposed method can detect gait phases by utilizing the sums and proportions of GCFs, instead of the thresholds based on variable subject body weight or GCF extremums. The proposed method is adaptable to different walking conditions using the same proportion factors for different subjects and different walking speeds. Additionally, high reliabilities were obtained when the proposed method was compared with prior studies in the literature. It is surely concluded that this proposed method is adaptable for most walking conditions on level ground.

Conflict of interest statement

The authors declare no conflicts of interest.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gaitpost.2014.10.019.

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