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Gait Phase Detection in Able-bodied Subjects and Dementia Patients

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***Abstract*— Accurate detection of gait phases allows identification of specific functional deficits at each phase of the gait cycle for motor function assessment. This paper proposes a robust gait phase detection method to identify the seven gait phases in overground walking for normal and pathologic gaits. Four inertial sensors are used to obtain knee angles, tibia angles and feet angular rate patterns in the sagittal plane. The key events segmenting the gait cycles are searched using an adaptive threshold in adaptive searching intervals to make sure it works well for different subjects with high variation in cadence and step length during walking. The subjects involved in this study are categorized into three groups: five healthy adult subjects, two healthy elderly subjects and two severe dementia patients. The experimental results have shown our method can reliably detect all gait phases for able-bodied subjects and dementia patients without subject-specific calibration.**

I. Introduction

A gait cycle of human walking is defined from the initial contact (IC) with the ground of the foot to the subsequent contact of the same foot. Key gait events divide the gait cycle of walking into seven phases: loading response (LR), mid-stance (MSt), terminal stance (TSt), pre-swing (PSw), initial swing (ISw), mid-swing (MSw), and terminal swing (TSw). The stance phase covers the first four phases, and the last three phases constitute the swing phase. The key gait events to segment these gait phases are IC (For normal gait, it is heel strike, HS), opposite toe off (OT), heel off (HO), opposite heel strike (OH), toe off (TO), feet adjacent (FA), and tibia vertical (TV), respectively [1]. This classification provides a framework for functionally organizing the gait cycle harmoniously with the three fundamental gait tasks, namely, weight acceptance, single limb support, and swing limb advancement [2].

Human gaits can be impaired by spinal cord injuries, stroke, cerebral palsy, or dementia. Research has shown that gait disorders are more prevalent in dementia patients than in normal aging elders [3], [4]. For patients with gait abnormalities, their gait phases may present irregularities, such as not following the aforementioned sequence. Gait phase-based gait analysis has proven to be very useful for identifying specific functional deficits or gait impairments during each phase of gait [5], [6]. Researchers have proposed many algorithms to distinguish between gait phases. Three states in a gait cycle were determined based on the ground reaction force (GRF), joint ankle, and switch signal beyond a specified normal range in [7] to achieve adaptive control of an Ankle-Foot Orthosis (AFO). Eric *et al.* [8] proposed a hidden Markov event model (HMEM) to segment the gait cycle into four gait phases.

Although many gait phase detection methods have been proposed, most of the previous work only detected a few gait phases, such as the four stance phases, not to distinguish the three phases of swing phases. The objective of this paper is to propose a robust method to detect the seven gait phases in every gait cycle applicable to normal and pathologic gaits. Four inertial sensor modules are used to obtain knee angles, tibia angles, and feet angular rate patterns in the sagittal plane. The subjects involved in this study are categorized into three groups: five healthy adult subjects, two healthy elderly subjects and two severe dementia patients. These subjects walk overground in a straight line at a comfortable speed. The key events that segment the gait cycles are searched using an adaptive threshold in adaptive searching intervals to make sure it works well for different subjects with high variation in cadence and step length during walking. The experimental results have shown that our method can reliably detect all gait phases for normal and pathologic gaits.

The rest of the paper is organized as follows: Section II presents the proposed method to detect the gait phases. Experimental results are reported in Section III, with the discussion is in Section IV. Section V concludes the paper.

II. Method

A. System Setup

During walking, the gait cycle of the left foot goes through exactly the same sequence of events as the right foot, but with half a cycle delay or in advance. Therefore, without losing generality, detecting the gait phases of right foot is taken as an example in this paper. To detect the gait phases of right foot, four inertial sensor modules are placed on the lower body of the subjects, including the right thigh, right shank and both feet, as shown in Fig. 1. Each sensor module includes triaxial accelerometers, gyroscopes and magnetometers. The sensor model is ADIS16405 from Analog Devices. These sensor modules are connected to a base station placed on the pelvis through SPI serial data buses. The base station synchronizes the data channel and transmits the data packets via USB to the PC for data processing. All data are sampled at 100 Hz.

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Fig. 1. System setup. Four inertial sensor modules were placed on human body segments, i.e. right thigh, right shank, and both feet.

B. Subjects

The subjects involved in this study fall into three groups: five healthy adult subjects, two healthy elderly subjects and two dementia patients. The first group of healthy adult subjects includes two females and three males, with an average of 25.4±3.13 years old. The subjects do not report a history of gait disorders. They walked in a straight line on level ground at a comfortable speed. We also recruited two healthy elderly subjects and two severe dementia patients, and these two groups are of similar age, with a average of 70±3.16 years old. The healthy elderly subjects showed no sign of gait abnormalities, however, the two dementia patients suffering from cognitive decline and gait disorders were diagnosed with severe Alzheimer's dementia by clinicians. Overground walking experiments were carried out after receiving the signed consent form from them.

C. Gait Phase Detection Method

The knee angles and tibia angles of right leg in the sagittal plane are estimated using the method proposed in [9] by fusing the three types of sensor measurements, including acceleration, angular velocity and magnetic field strength. Although we can estimate the knee joint angle and tibia angle in three planes, only the angles in the sagittal plane are used for gait event detection. Fig. 2 shows the estimated knee and tibia angles and the measured angular velocity of both feet in the sagittal plane. The gait data of all the subjects were combined to form a sequence including 233 gait cycles with a total duration of 307 seconds. The first 191 seconds are the gait data of the five healthy adult subjects, from 192 seconds to 254 seconds are the gait data of the two healthy elderly subjects and the gait data of the two dementia patients are from 255 seconds to 307 seconds.

From Fig. 2, foot angular velocity reaches a maximum peak t_{SW} around MSw in a gait cycle. Prior to this peak, a negative angular velocity peak associated with TO can be observed. There is another negative angular velocity peak at the end of the swing period associated with HS. Previous studies have confirmed the presence of these two negative peaks in different populations of young and elderly subjects with normal and pathologic gaits [10], [11]. Jasiewicz *et al.* [12] have also illustrated these two peaks associated with TO and HS using foot switches. In the MSt phase, the foot stays stationary on the ground with near zero angular velocity. When HO occurs, the angular velocity will reduce gradually to a minimum point at TO. For the two events that segment the swing phase, FA occurs when the knee flexion angle reaches the maximum point [2], and TV can be detected when the tibia angle is around zero in the swing phase.

To detect the HS and TO events of both feet, the maximum peaks t_{SW} are detected first using an adaptive threshold. Given a threshold τ, if the signal value P of an oncoming peak is higher than τ, it is classified as a true peak, then the estimated signal peak value P_T is updated using $P_T = \alpha P + \beta P'_T$, where P'_T is the previous estimated signal peak value, $\alpha, \beta \in \Re$ are positive satisfying $\alpha + \beta = 1$. Otherwise the oncoming peak is classified as a false peak, then the estimated false peak value P_F is updated using $P_F = \alpha P + \beta P'_F$, where P'_F is the previous false peak value. Then the threshold is updated by

$$\tau = P_F + \eta\left(P_T - P_F\right) \tag{1}$$

where η is the adjustable coefficient determining the optimal ratio between false positive and false negative detections [13]. After a t_{SW} peak is detected, local negative peaks of both feet angular velocity are searched during $[t_{SW} - t_{TO}, t_{SW} + t_{HS}]$, where t_{TO} and t_{HS} are defined as the interval for searching the negative peaks. To compensate the high cadence variation of different subjects, t_{TO} and t_{HS} are updated when new negative peaks are detected, as in

$$\begin{aligned} t_{TO} &= c\frac{(n-1)t'_{TO} + t^{(n)}_{TO}}{n} \\ t_{HS} &= c\frac{(n-1)t'_{HS} + t^{(n)}_{HS}}{n} \end{aligned} \tag{2}$$

where t'_{TO} and t'_{HS} are the mean distances between first $n-1$ TO or HS and t_{SW}, respectively, $t^{(n)}_{TO}$ and $t^{(n)}_{HS}$ are the distances between n^{th} TO or HS and t_{SW}, respectively, and $c (c > 1)$ is a constant. The negative peak before MSw is selected as TO, and the negative peak after it is assigned as HS. HO is detected by checking when the absolute value of the right foot angular velocity is higher than a predefined threshold after HS. The maximum points of the knee angles and zero crossing points of the tibia angles in the swing phases of the right foot are detected to get the FA and TV events. The detected results of the gait events are also illustrated in Fig. 2.

III. Experimental Results

The detected gait phase using the proposed method were checked by an expert. For the data sequence of 307 seconds including 233 gait cycles, all gait phases were detected without deletions or insertions, thus, we can conclude that our algorithm works with 100% reliability for normal and pathologic gaits. One example of the detection results for healthy adult subjects is shown in Fig. 3, from which we can see that all seven gait phases were detected continuously and follow the previous sequence. As there was no abnormality in the two healthy elderly subjects, the gait phases were also detected following the previous sequence, as can be seen in Fig. 4.

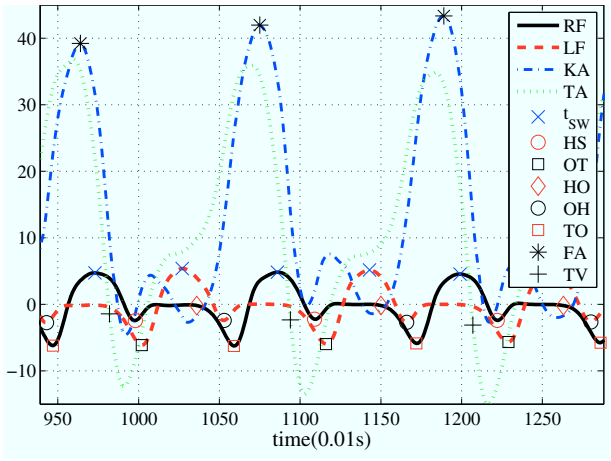

Fig. 2. The detected gait events to segment the gait phases. RF: Right foot angular velocity; LF: left foot angular velocity; KA: Knee angle of right leg; TA: tibia angle of right leg; t_{SW}: mid-swing peak; HS: heel strike; OT: opposite toe off; HO: heel off; OH: opposite heel strike; TO: toe off; FA: feet adjacent; TV: tibia vertical.

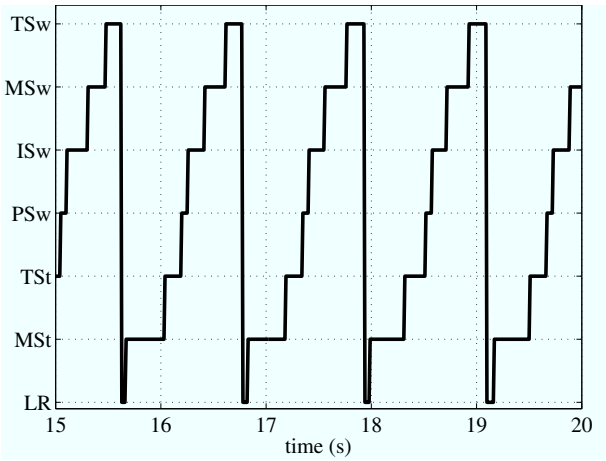

Fig. 3. The detected seven gait phases for healthy adult subjects.

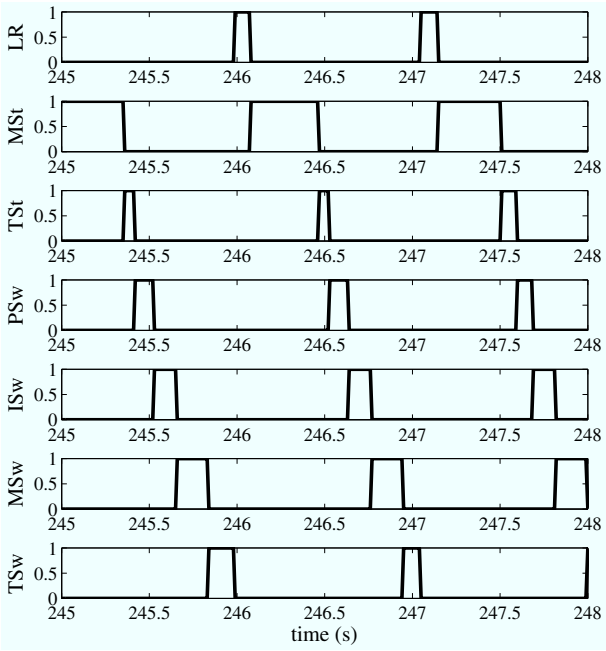

Fig. 4. The detected seven gait phases of healthy elderly subjects.

One of the dementia-related gait changes is the decrease in walking cadence. This phenomenon can be observed from the difference in angular velocity of both feet for healthy elderly subjects and dementia patients as shown in Fig. 5. In Fig. 5, the upper plot shows the angular velocity of healthy elderly subjects, and the lower plot is of the dementia patients. The angular velocity frequency of the dementia patients is lower than the healthy subjects, indicating the longer gait cycle and thus the lower cadence, as cadence is calculated by

$$Cadence = 120/GCT(steps/min) \tag{3}$$

where GCT is the gait cycle time, can be obtained by $GCT(k-1) = HS(k) - HS(k-1), k = 2, ..., N$, k is the index of the HS event, and N is the total number of HS.

The detected gait events of the healthy elderly subjects and dementia patients are also shown in Fig. 5. From Fig. 5, one of the biggest differences between the healthy subjects and dementia patients is that in dementia patients, the HS event of the opposite foot occurs before the HO event. HO usually marks the beginning of terminal stance in normal subjects, but in patients with gait abnormalities, this HO may delay into PSw, which would technically eliminate the terminal stance phase TSt. The detected gait phases of dementia patients are shown in Fig. 6. From Fig. 6, the gait phase of TSt was not detected at all in the gait phase sequence. One possible explanation is that for dementia patients, they want to achieve more stability during walking with both feet staying flat on the ground. Compared to the detected gait phases of elderly subjects shown in Fig. 4, we can see that the LR phase of dementia patients is much longer than the healthy elderly subjects. This means that dementia patients tend to need longer time to push their foot off the ground.

IV. Discussion

Even though different subjects walk with high variation in cadence and step length, an individual model calibration for different subjects is not mandatory. The mean and standard deviation of the estimated cadences and step length of the nine subjects are shown in Table I. Step length is estimated using the method proposed in [11]. The first five subjects are the healthy adult subjects, the next two are the healthy elderly subjects, and the last two are the severe AD patients. The 4th to 7th subjects are female, and others are male. As we can see from Table I, the cadence and step length of different subjects are distinct (59-108 step/min for cadence and 0.20-0.54 meters for step length). However, all gait phases can still be distinguished for different individuals using the adaptive threshold and adaptive searching interval. Therefore, we can safely conclude that our method works reliably with different subjects, including able-bodied subjects and dementia patients with gait abnormalities.

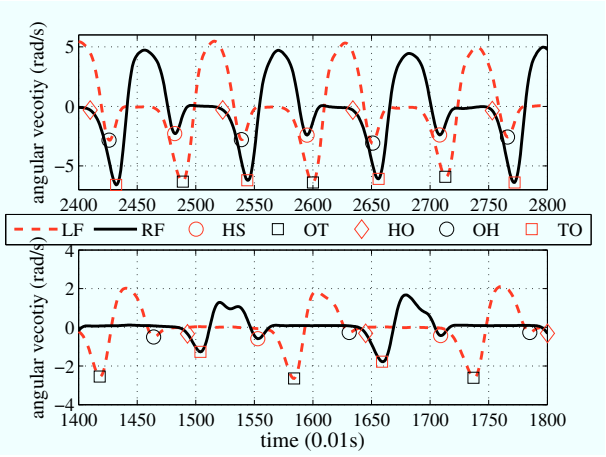

Fig. 5. The differences in gait event sequence between healthy elderly subjects and dementia patients. Upper: healthy elderly subjects; Lower: dementia patients. For dementia patients, the HS event of the opposite foot occurs before the HO event.

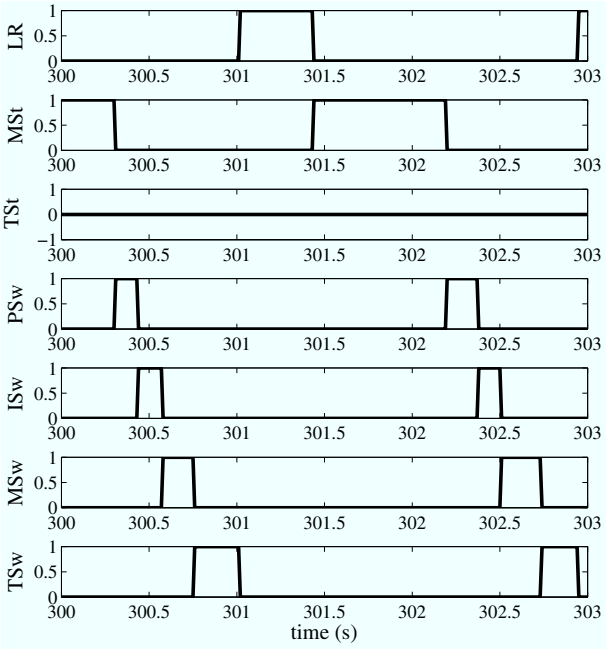

Fig. 6. Gait phases of dementia patients. The gait phase of TSt was not detected at all in the gait phase sequence.

V. Conclusion

This paper proposed a robust gait phase detection method to identify seven gait phases in overground walking. Experiments were carried out on five healthy adult subjects, two healthy elderly subjects, and two severe AD patients. The results have shown that the method works reliably for able-bodied subjects and AD patients with gait disorders. Our method can be applied to check the occurrence of abnormalities in AD patients' gaits based on the detected gait phases and can also be used as the gold standard method to evaluate other gait phase detection methods. To recruit more subjects with pathologic gaits to participate in our study has been considered as our future work. The long-term goal of this study is to quantify the abnormal muscle function during each phase in every gait cycle. The abnormal muscle function will be quantified by investigating Electromyography (EMG) signals. Interventions will be provided directly to correct the identified functional deficits in each gait phase using the human two-joint (knee and ankle) robot under development.

TABLE I

Cadence and step length of different subjects (mean±std)

Subject		Cadence(steps/min)	Step Length(m)
Adult	1	105.62±2.53	0.54±0.03
	2	89.82±4.06	0.45±0.03
	3	85.89±3.77	0.43±0.02
	4	105.86±5.10	0.54±0.02
	5	105.27±4.04	0.50±0.04
Elderly	6	106.89±7.20	0.38±0.02
	7	107.86±3.80	0.25±0.02
AD	8	69.88±11.04	0.22±0.06
	9	58.98±5.54	0.20±0.05

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