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Automatic initial contact detection during overground walking for clinical use

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ABSTRACT

The division of gait into cycles is crucial for identifying deficits in locomotion, particularly to monitor disease progression or rehabilitative recovery. Initial contact (IC) events are often used to separate movement into repetitive cycles yet automatic methods for IC identification in pathological gait are limited in both number and capacity. The aim of this work was to develop a more precise algorithm in IC detection. A projected heel markers distance (PHMD) algorithm is presented here and compared for accuracy to the high pass algorithm (HPA) in IC identification. Kinematic gait data from two clinical cohorts were analyzed and processed automatically for IC detection: (1) unilateral total hip arthroplasty (THA) patients ($n = 27$) and (2) cerebral palsy pediatric (CPP) patients ($n = 20$). IC events determined by the two algorithms were benchmarked against the IC events detected manually and from force plates. The PHMD method detected 96.6% IC events in THA patients and 99.1% in CPP patients with an average error of 5.3 ms and 18.4 ms. The HPA method detected 99.1% IC events in THA patients and 97.3% IC events in CPP patients, with an average error of 57.5 ms and 10.2 ms. PHMD identified no superfluous IC events, whereas 51.5% of all THA IC and 47.6% of CPP IC were superfluous events requiring manual deletion with HPA. With the superior comparison against the current gold standard, the PHMD algorithm appears valid for a wide spectrum of clinical data sets and allows for precise, fully automatic processing of kinematic gait data without additional sensors, triggers, or force plates.

1. Introduction

The separation of movement data into gait cycles is essential for processing large sets of gait data [1]. Rhythmic gait events, such as initial contact (IC) events, can accurately divide walking trials into gait cycles, assuming that right and left IC are correctly identified and follow an alternating sequence, e.g., R-L-R-L.

Numerous approaches for IC identification in both overground and treadmill walking exist in the literature, primarily developed using data collected from healthy subjects [2–8]. The gold standard for determining gait events uses force plates or attached sensors [2], which is not always practical. Sensors may be difficult to attach to the body during measurements or incomplete gait events can be detected, due to limitations in force plate size and quantity. Gait data assessed without such sensors cannot be processed properly for key parameters of gait such as stride length, speed, and others.

Consequently, some methods for gait event determination rely solely on kinematic data [3,5,6], many of which analyze raw marker positions or apply signal processing [6,7]. Patients with pathological gait cannot always alternate right and leg forward movement (R-L-R-L) and often need additional support, disallowing the use of existing methods. Furthermore, many approaches were neither tested in a clinical environment nor optimized for gait

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abnormalities. Extended stance phase, abnormal initial foot contact, unusual leg position, extreme differences in right and left leg velocities: such potential anomalies cannot be accounted for in techniques developed for healthy subjects. An accurate, automatic method for determining gait events across various types of pathologic gait remains to be developed.

Desailly et al. [5] determined gait events in patients with pathological gait patterns with their high pass algorithm (HPA). However, this particular method identifies an excessive number of gait events. These superfluous events need to be manually deleted from trials, excluding the possibility of automatic IC detection. Furthermore, the number of steps available for analysis was limited ($n = 40$) and taken from a single clinical cohort.

The goal of this study was to develop a method that automatically detects IC events, which can also reliably and accurately identify IC in pathological gait patterns. With such approach, additional triggers such as sensor signals or curve detection algorithms from ground reaction force measurements could be avoided. We validated the capacity of the new method by applying the HPA method [6] to different clinical cohorts with a relevant number of steps.

2. Methods

2.1. Projected heel markers displacement (PHMD) algorithm

The developed approach uses both legs for IC detection and analyzes their positions relative to another according to the physiological definition of gait, with alternating right and left leg steps. Left and right heel markers are required for analysis of the collected kinematic data, as well as the length of each foot. The PHMD algorithm is divided into four steps.

2.1.1. Step 1–Projection of heel markers

First, all heel markers for each frame are projected on the ground plane and the midpoints between the projected left and right heel markers are calculated. Assuming that $H_L(t)$ is the position of the projected left heel marker and $H_R(t)$ is the position of the projected right heel marker at the frame t, the midpoint $M(t)$ is defined as

$$M(t) = \frac{H_L(t) + H_R(t)}{2}. \tag{1}$$

The average value for all midpoints is calculated as

$$M_A = {}^1/_N \sum_t M(t), \tag{2}$$

where N is the total number of frames for the specified trial. The movement line is defined as a line connecting the midpoint from the first frame $M(0)$ and the averaged point with the direction vector $M_A - M(0) \rightarrow$. Next, we define $P_R(t)$ and $P_L(t)$ as the projection of $H_R(t)$ and $H_L(t)$ on the movement line. While Fig. 1a shows the heel marker projection onto the movement line, Fig. 1b shows the projected position of heel markers on the movement line which is used for gait pattern determination. In addition, the gait pattern is defined as a sequence of movement for both left and right legs. The resulting calculated distance $D(t)$ between $P_R(t)$ and $P_L(t)$ is used for determining gait cycle events (Fig. 1c), with the extremes of the curve corresponding to IC events.

2.1.2. Step 2–Gait pattern recognition.

After application of Eqs. (1) and (2), the sequences of right and left leg movement are identified. If the projected left heel marker remains in a constant position while the projected right heel marker is changing its position in the forward direction, it is assumed that the right leg is advancing and vice versa. This recognition is made by comparing the (leading) marker position to a minimum threshold value equivalent to approximately half of a foot length. If the right heel marker position is higher than the threshold value while the left is lower, this indicates the right initial contact to be expected. This process of recognition is illustrated in Fig. 1b. The gait pattern recognition procedure produces string values containing R and L symbols with R corresponding to the right leg movement and L to the left leg movement, respectively. This method of analyzing gait patterns is capable of identifying initial contacts that occur on the same leg twice in series (e.g., R-R-L), and excluding such patterns for separation into gait cycles. This is a typical occurrence in abnormal gait, when two or more initial contacts are performed with one leg, during which the opposite leg is not advanced forward to initiate the next step.

2.1.3. Step 3–Calculation of dynamic limits.

After the gait pattern is defined from the projected position of heel markers, the resulting data $D(t)$ is filtered with a low-pass Bessel filter (fourth order, $f_c = 2$ Hz).

After filtering, upper and lower envelopes will be calculated as cubic Bezier spline approximation from all extremes using the same techniques as Hilbert–Huang transformation [9] and empirical mode decomposition [10]. They are used to select the areas where an IC event occurs. The lower and upper envelopes of $D(t)$ as defined by this technique will be used to restrict search on the selected segments. Let $U(t)$ be defined as the upper envelope and $L(t)$ the lower envelope of $D(t)$. Only data segments that adhere to the following boundary conditions will be searched for extreme values as shown in Fig. 1c:

$$D(t) \geq 0.8 \times U(t) + 0.2 \times L(t)), \tag{3}$$

$$\text{or } D(t) \leq 0.8 \times L(t) + 0.2 \times U(t)). \tag{4}$$

2.1.4. Step 4–Event identification.

Segments, defined by (3) and (4), are processed sequentially. If a movement of the right leg is expected and the points on the segment satisfy Eq. (3), the first detected maximum in this segment will be identified as RIC while the rest of the segment will be ignored. If a movement on the left leg is expected and the points on the segment satisfy Eq. (4), the first detected minimum in this segment will be identified as LIC and the next segment will be processed. This loop will be repeated as long as the gait pattern contains movements or until the end of the data.

2.2. Data description

To test the robustness of the PHMD algorithm and to compare it to the HPA method described by Desailly et al. [5], two sets of marker and force data from clinical cohorts were analyzed for initial contact identification. Kinematic data were collected using eight reflective cameras (Vicon) and force data was collected using two embedded force plates (AMTI) with a detection limit of 10 N. Data were either collected at 100 Hz for kinematic data and 1000 Hz for force plate data, or at 120 Hz for kinematic data and 960 Hz for force plate data. All walking trials for analysis were used as exported from Vicon Nexus, including missteps and without manual cropping.

The first data set processed for IC recognition included kinematic and force plate data from 27 patients (18 female, 9 male; age: 65.3 ± 6.4) with a unilateral total hip arthroplasty (THA). All 257 gait trials were conducted on a 10-m marked walkway with patients walking at a self-selected speed. Measurements were taken