A New Simple Method for Kinematic Detection of Gait Events

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Abstract: The detection of gait events in locomotion, such as toe-off and heel-strike, provides a basic criterion for the division of a step cycle. This paper presents a new simple method for kinematic detection of gait events using kinematic data captured from only one marker attached to heel. We analyze the geometric distribution of the markers spatial positions over a small window of frames, and find there are new characteristics on the curve. These characteristics are used to detect the gait events for normal gaits. True errors (mean $\pm$ standard deviation) in the experiments on normal gaits are 8 ± 8 ms for heel-strike and 12 ± 20 ms for toe-off, where above 91% of subjects' heel strike events can be determined, with at most one frame (8.3 ms) error away from the ground reaction force (GRF) results.

1 INTRODUCTION

The detection of heel-strike (HS) and toe-off (TO) plays a very important role in walking gait analysis, which determines the stance and swing phase and allows normalization of gait kinematics. The gold standard method of defining gait events is dependent on the force plate. It would be necessary for a laboratory to be equipped with at least two force platforms to determine the temporal components of a complete strike. Unfortunately, the number of available force plates limits the number of consecutive gait cycles that can be analyzed (Hreljac and Marshall, 2000). As a result, researchers have discussed and presented many methods to detect gait events using other equipments, such as pressure-sensitive switches (Abernethy et al., 1995), photocell contact mat (Viitasalo et al., 1997), accelerometer (Mayagoitia et al., 2002), optical motion capture system (O'Connor et al., 2007; Desailly et al., 2009; Zeni Jr et al., 2008; Kiss, 2010).

The idea of methods using the optical motion capture device is to extract the characteristics of trajectories of markers attached to the specified location on the body and then infer the gait events by these characteristics. In the early research (Mickelborough et al., 2000) on kinematic detection of gait events, the events of the heel-strike and toe-off were inferred by naked eyes, where one made a subjective decision by observing the plots of marker's trajectory and velocity. It is difficult to implement this method (O'Connor et al., 2007), because of the inherent inaccuracy of the visual inspection. Automatic algorithms were proposed (Ghoussayni et al., 2004; Karčnik, 2003), where thresholds on the height and velocity of markers are needed. Hreljac and Marshall (2000) proposed a Hreljac-Marshall algorithm (HMA) method for detecting gait events based on the displacement, acceleration and jerk of heel and toe markers. O'Connor et al. (2007) introduced a foot velocity algorithm (FVA) which relies on the identification of local maximum and minimum of the vertical velocity signal from the midpoint of the heel and toe marker locations. Because the optimal filtering of each marker is used as an initial step in the HMA and FVA methods, results could be sensitive to the choice of cutoff frequency (Tirosh and Sparrow, 2003). By observing the characteristics of the gait events, Zeni Jr et al. (2008) used the distance between the projection of the sacrum's marker on the ground and the heel's or toe's marker to detect the gait events.

It can be seen that the advances of recent research using optical motion capture device are moving toward a more and more simple, robust and automatic direction. For example, some simple kinematic characteristics of locomotion are defined as the distance between the projection of root's marker on the ground and the heel's or toe's marker (Zeni Jr et al., 2008), or as local maximum and minimum in the vertical ve-

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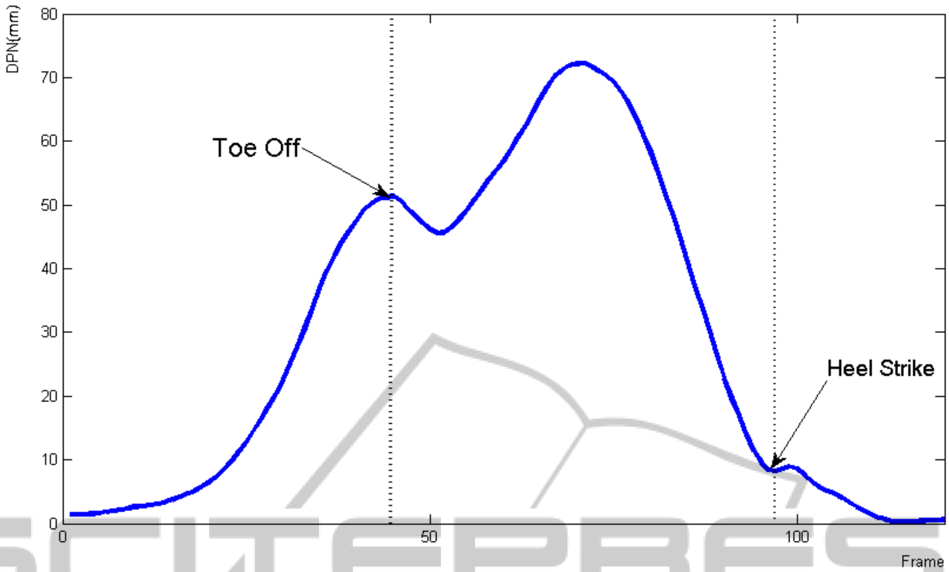

Figure 1: DPN as a function of frame number throughout a gait cycle with the gait events of toe-off and heel-strike indicated.

locity signal from the midpoint of the heel and toe marker locations (Desailly et al., 2009). Many efforts and achievements have been done, however, some research issues are not known yet. For example, could the number of markers used in gait event detection be reduced or not? Is there any new marker placement can be used to discover new gait patterns?

Different from previous work, we investigate how to define kinematic characteristics and explore gait's characteristics of locomotion using only one marker attached to heel. The key idea of our method is based on the fact that the velocity of the swing leg is greater than that of the supporting leg during locomotion. We consider the geometric distribution of the marker's spatial positions over a small window of frames, and introduce a metric called dispersion (DPN) for distinguishing whether the spatial data are dense or not. Experiments demonstrate the curve of DPN encodes the gait's characteristics.

2 METHOD

In this section, DPN is used to describe the movement range of the marker on the heel in some consecutive frames. The computation of DPN is illustrated as follows. This method analyzes the DPN and detects the gait events by some characteristics of the curve of DPN.

(1) For any $i-th$ frame, $2k+1$ frames ($i-k \leq t \leq i+k$) are taken into consideration. The geometry center $(\bar{x},\bar{y},\bar{z})$ of $2k+1$ consecutive markers' positions are computed by

$$\bar{x} = \frac{\sum_{t=i-k}^{t=i+k} x_i}{2k+1} \quad \bar{y} = \frac{\sum_{t=i-k}^{t=i+k} y_i}{2k+1} \quad \bar{z} = \frac{\sum_{t=i-k}^{t=i+k} z_i}{2k+1} \tag{1}$$

(2) The distances between the $2k+1$ markers' positions to the position of the geometry center are computed.

$$d_t = \sqrt{(x_t-\bar{x})^2+(y_t-\bar{y})^2+(z_t-\bar{z})^2} \quad (i-k \leq t \leq i+k) \tag{2}$$

(3) The average distance of $d_t(i-k \leq t \leq i+k)$ is computed:

$$\overline{d}_i = \frac{\sum_{t=i-k}^{t=i+k} d_t}{2k+1} \tag{3}$$

(4) The dispersion of the markers is defined as follows:

$$DPN = \overline{d}_i \tag{4}$$

When plotting the curve of DPN, a very clear characteristic can be observed (see Figure 1). The point of the specified local maximum is the moment of the toe-off. The point of the specified local minimum is the moment of the heel-strike.

In our experiments, kinematic data of the marker attached to heel and analog data which are output of the dual integrated force plates (Kistler 9286BA) are collected synchronously at 120 Hz using a 12-camera Vicon workstation. The analog data are filtered with a cutoff frequency of 20 Hz. Heel strike is determined when the vertical GRF is greater than 20 N for a width of at least 40 frames (Zeni Jr et al., 2008). Similarly, toe-off is determined when the vertical GRF is less than 20 N for a width of 40 frames. Only one marker is attached to each heel (see Figure 2).

Normal subjects' kinematic data with analog data (#subjects=7, 6 males, 1 female, age 22-26 years, mean ± standard deviation 23.3 ± 1.3 years, 64 groups of data, 64 cycles) are captured. All subjects have been given a copy of the informed consent. Walking speed was neither monitored nor controlled.

Figure 2: Marker placement.

3 RESULTS

True errors in the experiments (mean ± standard deviation) are 8 ± 8 ms for heel-strike and 12 ± 20 ms for toe-off. Above 91% of the normal subjects' heel strike events can be determined, with at most one frame (8.3 ms) error away from the ground reaction force (GRF) results. The Figure 3 and Table 1 show the detailed results. LHS refers as left heel strike. LTO refers as left toe off. RHS refers as right heel strike. RTO refers as right toe off.

Table 1: Percentages of computationally determined events offset by the frame error of the normal subjects.

Absolute Error(frame)	0	1	2	≥ 3
LHS	44.90	55.10	0	0
LTO	71.43	20.40	8.17	0
RHS	34.28	57.14	8.58	0
RTO	57.14	32.65	8.16	2.05

In our experiments, the variable k can be manually changed. As k increases, the curve of DPN becomes more and more smooth. Experiments show that a good result can be achieved when the k is set to 3 (see Figure 4).

The advantages of the method could be summarized as follows. Firstly, only one marker attached to heel is used in gait event detection. It would be helpful to set up a gait laboratory using optical motion capture system. Secondly, new gait's characteristics are explored and used for gait event detection. The accuracy of the detection of heel-strike is very high. Above 91% of the normal subjects heel strike events can be determined, with at most one frame (8.3 ms) error away from the ground reaction force (GRF) results. Thirdly, this method is easy to be implemented for automatic event detection without the use of thresholds and optimal filtering of kinematic data.

There are still some limitations in the proposed method. The result of the gait events' detection of the toe off is not satisfying. Feet's gestures are not the same for different subjects when the gait event of the toe off happens. There are many ways to measure the geometric distribution of marker's spatial positions. There may be a better measurement to achieve better results. The event detection of pathological gaits is still an open problem. In future, we will do further research on this issue especially for the pathological gaits.

4 CONCLUSIONS

In conclusion, the method proposed in this paper is simple and robust, which is accurate in the detection of heel strike. It validates that we can detect the gait events accurately with only one marker. The future work is to find a robust algorithm for the event detection of pathological gaits.

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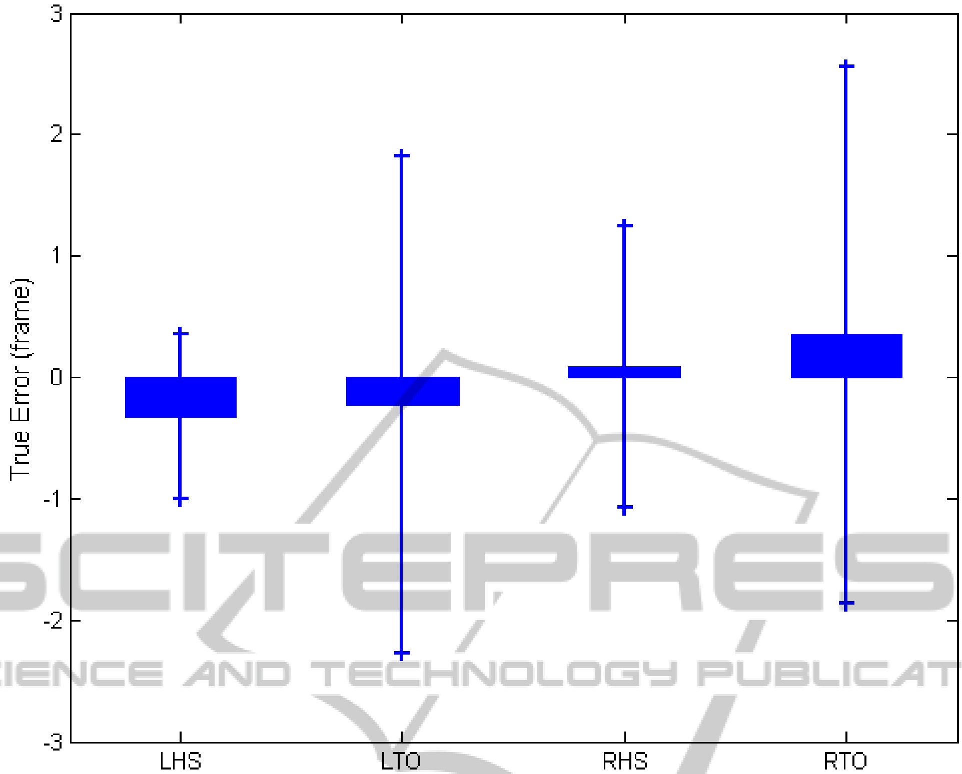

Figure 3: Candlestick chart with means and standard deviation of the true errors of normal gaits.

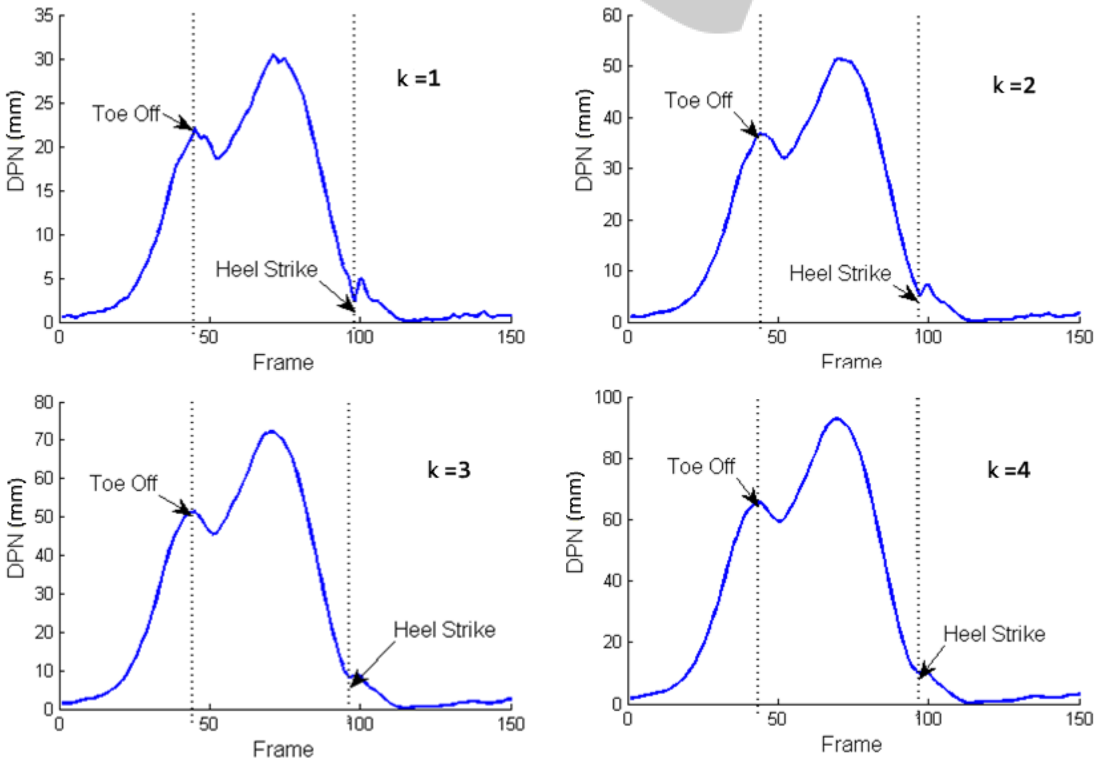

Figure 4: Curves of the DPN as the *k* varies. As *k* increases, the curve of DPN becomes more and more smooth.

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