EVALUATION OF THE ACCURACY OF GAIT EVENTS DETECTED USING THREE DIFFERENT METHODS DURING RUNNING

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Different methods have been proposed for determining initial contact and toe off with inertial measurement unit (IMU) attached to different anatomical positions. However, the accuracy has not yet been compared. This study aimed to evaluate the accuracy of three commonly used methods (S-, M-, and L-method) in detecting gait events at two running speed conditions (slow and fast). Obvious differences of detected initial contact and toe off and estimated stance duration among the three detection methods using IMU were found at the two running speed conditions. It was shown that initial contact detected using the S-method and toe off detected by the M-method were the best estimates of the gait events. Combined use of both methods is recommended for determining stance duration during overground running.

KEY WORDS: inertial measurement unit, initial contact, toe off, stance duration.

INTRODUCTION: Initial contact and toe off are two typical gait events, which are quite important for gait analysis, for determining gait phases and other tempo-spatial parameters (e.g., stride interval, stance duration) and understanding characteristics of joint movement and patterns of muscle activity. The accuracy of initial contact and toe off is critical: the kinematic changes at the two events were highlighted while studying running related injuries (Miller et al., 2008); the accuracy of stance duration relies on the two events and errors varied from 0 to 17 ms in previous studies (Purcell et al., 2005; Watari et al., 2016); the type of foot strike pattern, related to running related injuries, was determined based on initial contact (Altman & Davis, 2012).

Traditionally, initial contact and toe off are identified using force platform, high-speed camera, and footswitch. However, the use of force platform and high-speed camera are restricted in a laboratory and provide a small number of strides in each trial, while the footswitch is susceptible to mechanical failure and may induce discomfort during long-term wearing (Willemsen et al., 1990). Inertial measurement unit (IMU) has been used as a pragmatic method for studying locomotion (Strohrmann et al., 2012; Kwakkel et al., 2008; Patterson et al., 2011; Yang et al., 2011). IMU was used to identify initial contact and toe off and various methods were proposed: IMU was attached at different locations (sacrum, shank and foot) (Lee et al., 2010; Mercer et al., 2003; Strohrmann et al., 2012); acceleration from different directions (vertical, anteroposterior and resultant) was used (Lee et al., 2010; Mercer et al., 2003; Strohrmann et al., 2012); different detecting algorithms (peak detection, zero-crossing detection) and data processing methods (filtered or non-filtered) were used (Hanlon & Anderson, 2009; Trojaniello et al., 2014). Although initial contact and toe off could be identified using different methods, the accuracy is a concern. For walking, the reported error of initial contact varied from 9.5±9.0 ms to 34.0±25.0 ms, and from 9.0±54.0 ms to 19.0±36.0 ms of toe off (González et al. 2010; Hanlon & Anderson, 2009; Jasiewicz et al., 2006). However, there are limited studies in running. One study reported a mean error of 66.0±6.0 ms for initial contact and 16.0±1.0 ms for toe off during overground running with IMU attached to ankle (Heiden & Burnett, 2004).

Despite the effect from detection algorithm, data processing method and IMU location, the accuracy of identified initial contact and toe off may also be affected by the locomotion speed, which is correlated to the impact acceleration (Mercer et al., 2002). The errors of estimated stance duration were 0±12.0 ms, 2±3.0 ms, and 1±1.0 ms for jogging, running and sprinting, respectively (Purcell et al., 2005), and from 0.4±0.8 ms to 2.2±0.7 ms when running at low, medium and high speed by Lee et al. (2010). However, there was no study to investigate the speed effect on the accuracy of identified initial contact and toe off.

Three typical methods, widely used to study running, were introduced in this study. S-method (Strohrmann et al., 2012), a representative method applied in the smart shoe: the resultant acceleration from an IMU at the dorsal side of each foot were used, and initial contact was corresponding to the instant of peak acceleration and toe off was identified when the acceleration exceeded a threshold of 2 g. M-method (Mercer et al., 2003), widely used when investigating shock absorption during running: the vertical acceleration from an IMU attached to the frontal side of shank were used, and initial contact and toe off were the minimum before the peak and the following maximum, respectively. L-method (Lee et al., 2010): the anteroposterior acceleration from an IMU attached to the sacrum (S1) were used, and initial contact was detected at the instant of peak and toe off was at the following smaller peak. This method can detect bilateral initial contact and toe off by one IMU.

As typical methods of identifying initial contact and toe off when the IMUs were attached to different anatomical locations (foot, shank and sacrum), the aforementioned three methods were chosen and compared when running overground at two speeds in this study. It aimed to compare the errors of identified initial contact and toe off among different methods, as well as the accuracy of estimated stance duration. An optimal method was proposed to estimate stance duration.

METHODS: Six (2 females) recreational runners (25.8±4.1 yrs; 170.0±9.1 cm; 58.6±5.4 kg) were recruited to run on an 8-meter walkway at two speeds (slow: 3.15±0.07 m/s; fast: 3.85±0.24 m/s) with random order. Three force platforms (Bertec, USA; total surface: 1.8×0.4m) were embedded in the midway. Force signals were acquired at a sampling rate of 2000 Hz and low-pass filtered using a Butterworth filter at 70 Hz (Bergamini et al., 2012). Each subject was equipped with 5 IMUs (MyoMOTION MR3, Noraxon, USA). The IMU on the pelvis was affixed to the bony prominence of sacrum (L5-S1 level) and the IMU on each shank was affixed to the anterior-medial of the tibia using elastic Velcro straps. The IMU on each foot was affixed on the dorsi-foot using a flat and bracelet housing and fixed by shoe lace. Each IMU consists of a tri-axial accelerometer (±16g), gyroscope and magnetometer and was sampled at 200 Hz. All participants performed at least 15 trials at each speed and the clean strides were retrieved for analysis. Force and acceleration were recorded simultaneously using IMUs and force platforms, respectively. They were synchronised by recording the same event (a vertical jump-and-land movement on one force platform) (Bergamini et al., 2012).

The instants of initial contact and toe off were obtained from the force and acceleration. For the force, thresholds of 10 N on the rising and 25 N on the descending force signals were used to identify initial contact and toe off, respectively (Hunter et al., 2005). For the acceleration, the instants of initial contact and toe off were identified using S-, M- and L-methods. The stance duration was estimated by the interval between initial contact and toe off.

The number of identified initial contact and toe off was counted. Any falsely identified and unidentified events were marked, and the positive predictive values (PPV) were computed to evaluate the performance with $\mathrm{PPV\%} = \frac{\mathrm{n}}{\mathrm{N}} \times 100$ (n, the number of identified events by each method; N, the total number of events) (Trojaniello et al., 2014). Root mean square (RMS) error was computed to evaluate the accuracy.

RESULTS: Seventy-two steps and 52 steps at slow and fast speed were analysed, respectively. The three methods could identify all initial contacts whilst the M- and L-methods missed to identify some toe offs (slow: PPV=98.6% and 76.4%, respectively; fast: PPV=100% and 82.7%, respectively).

The S-method displayed the least RMS error of initial contact, while the M-method showed the minimum RMS error of toe off (Table 1). For the estimated stance duration, the combining method, initial contact by the S-method and toe off by the M-method, provided the minimum RMS error (Table 1). The RMS error of initial contact toe off and stance duration was smaller at fast speed (Table 1).

DISCUSSION: The identification of initial contact and toe off by IMU is based on the assumption that the two gait events are associated with specific features of acceleration. However, the acceleration magnitude reduced due to the shock absorption during transmission from foot to upper body (Lucas-Cuevas et al., 2016). Those specific features may be hardly identified from the acceleration with small magnitude. Initial contact and toe off could be hardly identified using acceleration from the hip (Heiden & Burnett, 2004). In this study, a smaller PPV was reported when the M- and L-methods (IMUs attaching at pelvis and shank, respectively) were used to identify toe off.

Table 1
RMS error of identified initial contact and toe off using S-, M-, and L-methods, and estimated stance duration using S-, M-, L- and M-S methods.

Methods	Initial Contact (ms)		Toe Off (ms)		Stance Duration (ms)	
	Slow Speed	Fast Speed	Slow Speed	Fast Speed	Slow Speed	Fast Speed
S-method **†**	**27±26**	**15±7**	90±68	52±5	70±13	63±4
M-method **§**	57±75	31±12	**28±34**	**12±5**	31±12	33±12
L-method	53±63	18±8	51±72	30±27	31±12	28±24
M-S method **‡**					**22±6**	**19±7**

†, minimum RMS error in identified initial contact; **§**, minimum RMS error in identified toe off;
‡, minimum RMS error in estimated stance duration

The accuracy of identified initial contact and toe off is affected by time lag due to IMU locations. A strong positive correlation (r^2=0.997) between the time lag and the distance of IMU location to collision point was reported (Heiden & Burnett, 2004), the further the IMU from the collision point, the longer is the time lag. Therefore, the S-method with the IMU attaching to the dorsal side of foot produced the minimum RMS error of identification of initial contact. The effect of time lag may reduce by modifying detection algorithms. However, the RMS errors were still bigger in this study while the M- and L-method were used. So, the accuracy should be considered when the two methods are used to identify initial contact.
For toe off, the M-method with vertical shank acceleration displayed the best prediction during running with RMS error of 0.028 s at slow speed and 0.012 s at fast speed. This may be due to an abrupt upward and forward movement of shank produced by the knee and hip joint flexion at toe off (Dugan & Bhat, 2005). However, the anteroposterior acceleration from the IMU at sacrum (L5-S1) in L-method may be affected minimally as the runner is usually suggested to maintain a stable movement of the center of mass during running (Novacheck, 1998). The foot resultant acceleration of 2 g was used as detection reference of toe off in the S-method but displayed the biggest RMS error. The reasons are (a) the IMU was affixed to the top of the foot and slightly below the ankle joint, but the motion of rear foot (heel off) is usually before toe off, and (b) noise signals due to unstable foot motion may be a challenge to accurate identification of toe off.
In this pilot study, the RMS error of stance duration was the smallest when estimated using toe off identified by M-method and initial contact by S-method. This method was recommended to predict accurate stance duration but at least 4 IMUs are required to get bilateral data.

CONCLUSION: The initial contact can be best estimated by the S-method and the M-method was shown to be the best estimation of toe off during overground running. The S-method based on foot resultant acceleration was suggested to identify initial contact, and the M-method based on vertical shank acceleration was suggested to identify toe off. Combining the M-method and S-method together can provide a better prediction of stance duration. But as limited subjects were recruited in this pilot study and the foot strike pattern was not classified, further studies are required in the future.

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