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Use of accelerometers for detecting foot-ground contact time during running

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ABSTRACT

A biomechanical variable of interest to sprint coaches is foot-ground contact time. Contact time can be easily measured in a laboratory environment using a force platform, but is difficult to measure in the field. The focus of this paper is on the development and validation of an accelerometer-based method for estimating contact time during sprinting that could be used in the field. Tri-axial accelerometers were mounted on the tibia of the right leg of 6 subjects who performed maximal running trials from a stationary start, and running trials at a range of steady state speeds (jog, run and sprint). Ground contact times were measured using a force platform, and estimated from 3D accelerometer data. The mean error between the force plate and accelerometer-based measures of contact time were 0 ± 12 ms, 2 ± 3 ms, and 1 ± 1 ms for the jog, run and sprint. For steps 1, 3 and 5 of the acceleration phase of the maximal sprint the mean errors were 8 ± 9 ms, 2 ± 5 ms, and 0 ± 1 ms respectively. Overall it was concluded from our analysis that close estimates of contact time during running can be obtained using body mounted accelerometers, with the best estimates obtained in conditions associated with the highest accelerations.

Keywords: Biomechanics, event detection, initial contact, toe-off, running kinematics, gait analysis.

1. INTRODUCTION

Evidence exists to suggest that foot-ground contact time is an important variable that influences top running speed, with athletes that have shorter contact times typically being faster sprinters[13]. Foot-ground contact time is also known to be affected by leg stiffness, with higher leg stiffness associated with reduced contact times[3]. Sprinters attempt to reduce contact times during sprinting through training regimes focusing on explosive development of force during stretch-shorten cycle muscle contractions that mimic the stance phase of running which are designed to enhance leg stiffness. From a coaching perspective it would therefore be of benefit to be able to measure foot-ground contact times during sprinting. Such information could be used to monitor sprint performance and evaluate the effect of training on sprinting technique.

The gold standard for measuring contact time during running is the force platform. Force platforms are fixed to the ground, and allow measurement of the three orthogonal components of the ground reaction force vector during a single running step. For continuous registration of contact time in-shoe force sensing devices may be used, however these devices are known to be susceptible to failure, and have poor durability[11]. Accelerometers by contrast are easier to attach to the athlete and less susceptible to failure. Several accelerometer-based systems have been developed for measuring gait parameters during walking. For example, step length estimates have been obtained from analysis of vertical trunk accelerations[10,14,15]. Since it is also easy to determine step frequency using body-mounted accelerometers, walking speed may also be estimated (speed = stride length x stride frequency). The ability of accelerometers to detect heel contact events is also useful in providing feedback control in FES assisted walking[6], and to quantify contact times in transtibial amputees[11].

Accelerometers have also been used in a small number of running studies. Brage et al.[2] examined the validity and reliability of vertical accelerations to predict energy expenditure in walking and running. Vertical accelerations were shown to increase linearly with increased speed during walking, but not running, since vertical accelerations were constant across a broad range of running speeds. Herren et al.[4] also addressed the question of whether accelerometry can be used to estimate running speed. Using a neural network approach they showed that triaxial accelerometer measurements can accurately predict running speed and incline in outdoor running. In another application of accelerometers to running, Mercer and colleagues examined factors that influence shock attenuation from leg to forehead at different speeds[7,8,9]. In general these studies showed that shock attenuation was a function of stride length, and that fatigue induced by a maximal exercise test decreased shock attenuation. To our knowledge, no published studies have used accelerometers to measure foot-ground contact time in running. The purpose of this study was therefore to develop and test an accelerometer-based method for determining foot-ground contact time during the acceleration phase of maximal sprinting and during constant speed running at a range of speeds.

2. METHODS

2.1 Subjects and experimental protocol

Six healthy subjects (Aged 25.17 yrs) were recruited to participate in the study. Each subject provided written informed consent prior to participation in the study, which was approved by the Griffith University Human Research Ethics Committee. Subjects were required to run along a runway and over a force platform while simultaneous measurements of leg accelerations and ground reaction forces were made. Three self-selected steady state running speeds were assessed (jog, run and sprint). In addition, the acceleration phase was assessed at step one, three, five and nine during maximum sprinting trials. For these maximal sprint trials the start position along the runway was adjusted so that foot contact was achieved with the force plate on the first, third, fifth, and ninth step from the start position. A trial was judged successful if the subject achieved ground contact within the area of the force plate on the required step number. At least three trials were performed at test each condition.

2.2 Instrumentation

A pair of triaxial accelerometers (Analog Devices ADXL321, range ± 18 g) was attached to the right shin of each subject (Figure 1). The 3D accelerations from each accelerometer node were sampled by a Atmel microprocessor (ATMEGA128L) at 250 Hz per channel using an external SPI 16-bit analogue to digital converter (ADC). The hardware was designed to minimise the effects of noise. Design inclusions toward this goal included a separate voltage regulator for the accelerometers and ADCs. The microprocessor encoded the data and transferred it to a Bluetooth module via an internal serial link for radio transmission to the receiver system. Bluetooth devices and protocol were selected for communications because of the advantages they offer in simplicity of operation, error checking, retransmission of lost data, low data dropout rate, and scalability to multiple devices on a network. In our implementation distances of up to 200 m were reliably achieved. A Kistler piezoelectric force-plate connected to a Peak Motus analogue acquisition module was used to record ground reaction forces at 1 kHz. Synchronisation of acceleration and ground reaction force data was achieved using a synchronisation pulse that was simultaneously recorded via the Bluetooth receiver and the Peak Motus analogue acquisition module.

2.3 Data analysis

The contact time (CT) between the foot and ground was obtained using force plate and accelerometer-based methods. The force-plate method was considered to be the gold standard and involved assessment of the vertical ground reaction force (VGRF). A simple force threshold was used to determine initial foot contact (IFC) and toe-off (TO) events, from which CT was computed. The accelerometer-based method assessed the 3D accelerations of the leg. A number of criteria were developed and tested to determine CT. Two events were used to define CT from the 3D accelerometer data. The first event was the minima in the X acceleration trace which corresponded to the peak of the resultant 3D acceleration which occurred near the beginning of CT. The second event was based on the X and Z accelerations, which experience local minima and maxima respectively near TO. The mean of the indexes at which these events occur was used define the end of CT. All data were analysed using custom software developed using Matlab (Release 14, The Mathworks).

2.4 Statistical analysis

Raw data are presented as XY plots to illustrate the association between force plate and accelerometer-based methods for estimating CT. Corresponding correlation coefficients for each condition are also provided. The "limits of agreement" method[1] was used to assess the agreement between the force-plate and accelerometer-based estimates of CT. Data were presented as Bland-Altman plots, in which the mean difference between the 2 measures is plotted against the average value for each pair of measurements. The mean difference and the 95% confidence intervals for each test condition are reported. The specific test conditions assessed were 3 speeds of steady state running (jog, run, sprint), and 3 steps during the acceleration phase of maximal sprinting from a stationary start (Step 1, 3 and 5).

Figure 1. Subject wearing shin-mounted accelerometer system. Positive directions of the orthogonal axes of the sensor's local co-ordinate system are superimposed.

3. RESULTS

3.1 Representative data

Some sample vertical ground reaction force (VGRF) and 3D accelerometer data for a constant speed running trial are displayed in figure 2. CT was obtained from the VGRF when the force applied by the foot against the force-plate exceeded a force threshold of 5 N. CT was estimated from accelerometer data through identification of an acceleration signature that was observed to be present across all test conditions. More specifically, the beginning of CT was obtained from the minima in the X acceleration trace corresponding to the initial force peak in the resultant acceleration, and the end of CT was obtained from the period where the X and Z accelerations experienced local minima and maxima.

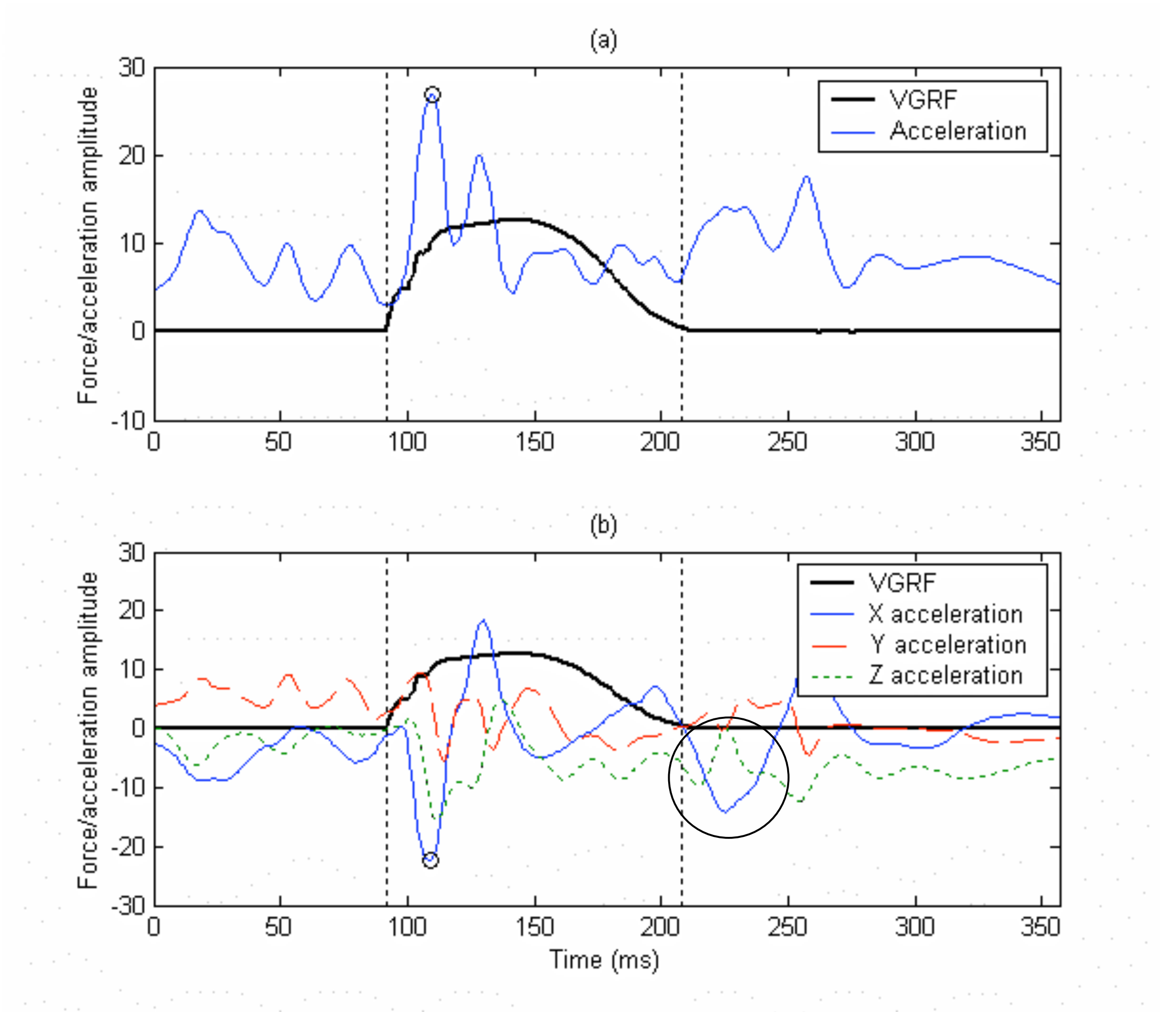

Figure 2. Vertical ground reaction force (VGRF) and 3D accelerations for a representative sprint trial. The resultant acceleration is depicted in (a), with the 3 acceleration components (X, Y and Z) shown in (b). Vertical lines define the foot-ground contact time determined using the force plate method. The beginning of contact time was obtained from the minima in the X acceleration trace identified by the small circle in (b). The large circle highlights the local minima and maxima in the X and Z accelerations that were used to define the end of the contact time. Contact time was 116 ms according to the force-plate method, and 117 ms according to the accelerometer-based method. Vertical scale units are arbitrary.

3.2. Steady state running speed conditions

Summary data for the steady state running speed conditions are presented in figure 3. Correlation coefficients for the relationship between force-plate and accelerometer-based measures of CT were 0.892, 0.991, and 0.997 for the jog, run and sprint conditions. The mean error (Y – X ± standard deviation) in CT between the force plate and accelerometer-based methods for the jog, run and sprint conditions were 0 ± 12 ms, -2 ± 3 ms, and -1 ± 1 ms respectively.

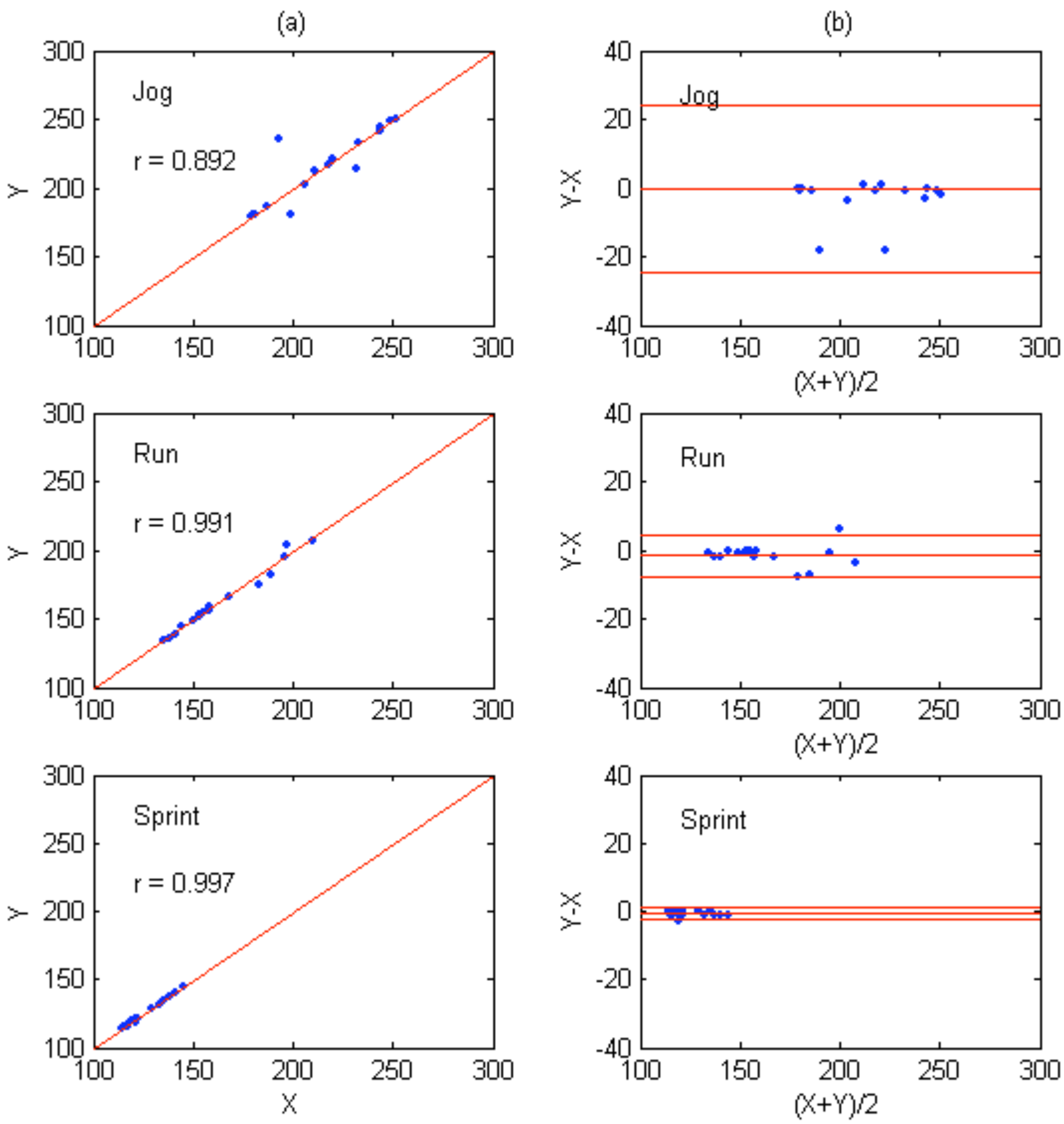

Figure 3. (a) Force-plate (Y) versus accelerometer-based estimates (X) of contact time, and (b) corresponding Bland-Altman plots for the steady state running speed conditions (jog, run and sprint). Units are milliseconds. The diagonal line on the XY plots corresponds to the line of perfect agreement. Horizontal lines on the Bland-Altman plots represent the mean error and the upper and lower 95% confidence intervals.

3.3. Acceleration phase of maximal sprinting conditions

Summary data for the acceleration phase of maximal sprinting conditions are presented in figure 4. Correlation coefficients for the relationship between force-plate and accelerometer-based measures of CT were 0.951, 0.967, and 0.991 for the step 1, step 3, and step 5 conditions. The mean errors (Y – X ± standard deviation) in CT between the force plate and accelerometer-based methods for step 1, step 3, and step 5 of the acceleration phase of the maximal sprint conditions were -8 ± 9 ms, -2 ± 5 ms, and 0 ± 1 ms respectively.

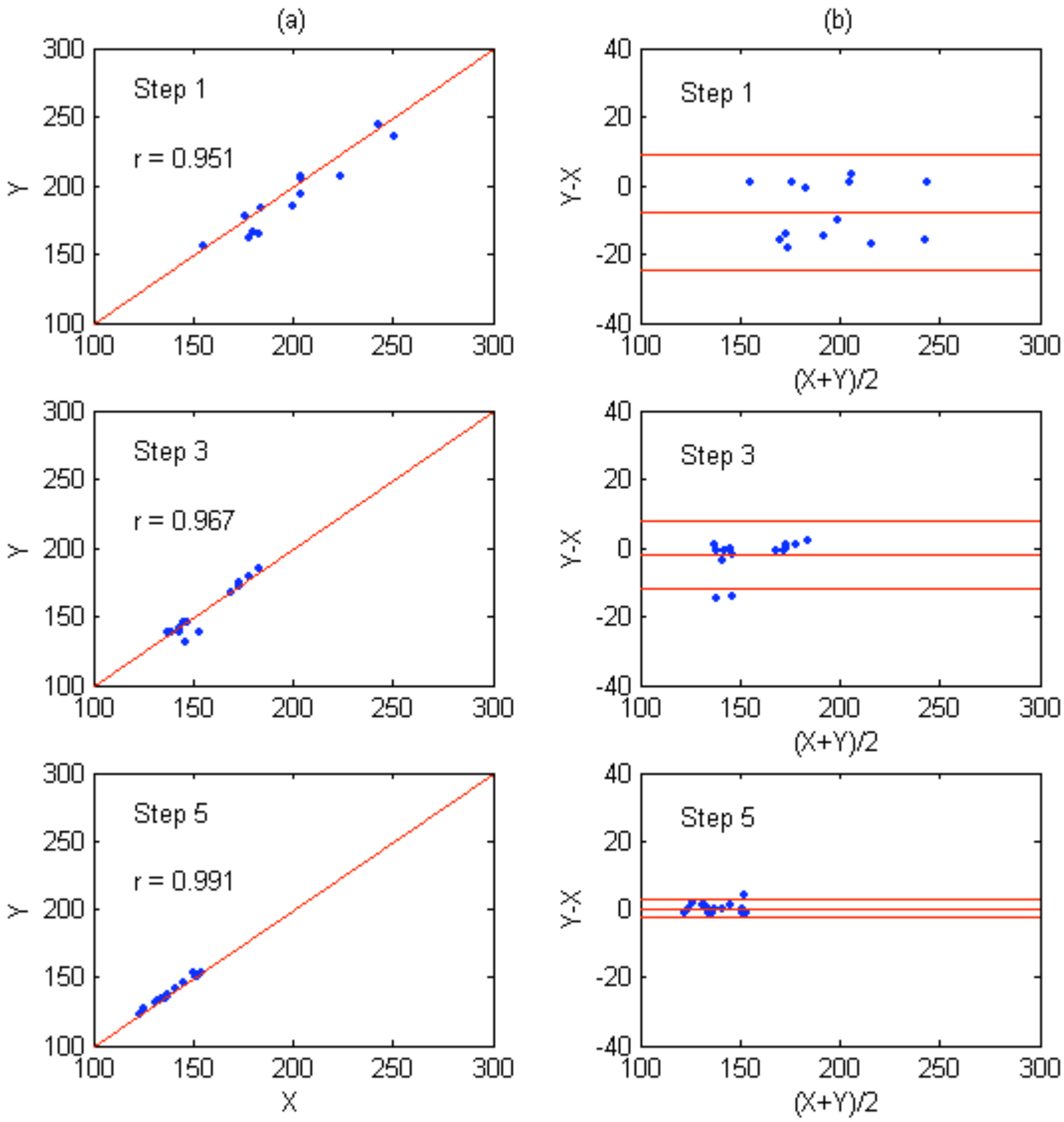

Figure 4. (a) Force-plate (Y) versus accelerometer-based estimates (X) of contact time, and (b) corresponding Bland-Altman plots for the maximal sprint conditions (Step 1, 3, 5 and 9). Units are milliseconds. The diagonal line on the XY plots corresponds to the line of perfect agreement. Horizontal lines on the Bland-Altman plots represent the mean error and the upper and lower 95% confidence intervals.

4. DISCUSSION

The purpose of this study was to develop and validate an accelerometer-based method for determining foot-ground contact time during the acceleration phase of maximal sprinting and during constant speed running at a range of speeds. Such a system is desirable because it offers the potential to provide rapid feedback to the athlete and coach regarding foot-ground contact time in the normal training and/or competition environment. In particular, the accelerometer-based approach overcomes problems associated with alternative approaches such as force platform, high-speed film or footswitch based methods which are respectively lab-based, time consuming, and susceptible to failure. The validity of our accelerometer-based estimates of contact time (CT) was tested in the present study against CT measurements made using a force platform, with the level of agreement between the two methods expressed as the mean difference and the corresponding 95% confidence interval at each test condition using Bland-Altman plots. The test conditions assessed were three self-selected steady state running speeds (jog, run, sprint), and steps 1, 3 and 5 of the acceleration phase of a maximal sprint from a stationary start.

The mean error for the accelerometer-based CT estimates ranged from 0 – 2 ms for the steady state speed running conditions, and 0-8 ms for steps 1,3, and 5 of the acceleration phase of maximal sprinting. The correlation coefficients that describe the association between the two measures were observed to increase with increased steady state running speed ($r = 0.892 – 0.997$), and from step 1 to 5 in the acceleration phase of maximal sprinting ($r = 0.951 – 0.991$). In addition, the confidence intervals associated with the mean difference between the two measures decreased with increased steady state running speed, and from step 1 to 5 in the acceleration phase of maximal sprinting (figures 3 and 4). Taken together, these results suggest that our accelerometer-based approach provides very close estimates of actual CT during running, and that the level of agreement was improved in conditions associated with higher running speeds. The most likely reason for the improved validity with increased speed is probably explained by the observation that these conditions were also associated with the largest accelerations, and that the markers associated with the beginning and end of CT were unambiguous and therefore easy to detect at higher speeds. At lower speeds, the markers associated with the beginning and end of CT were in some instances difficult to identify. However, there were only 2 trials out of the 114 trials assessed where the algorithm failed to make a meaningful estimate of CT, which corresponded with an overall failure rate of less than 2%. The fails occurred in the first step trials, indicating that some unique additions could be added to the algorithm to enhance detection for the first step condition.

In future research we propose to use accelerometer-based estimates of CT and other biomechanical variables to examine the strategies used by different groups of athletes to accelerate from a stationary start to top speed. We also foresee that the general approach described here may be used to quantify other aspects about sprint performance. For example stride frequency can easily be obtained through identification of consecutive heel contact events. In a companion paper in these proceedings an approach based on the same instrumentation for measuring leg kinematics is described. To provide rapid feedback to the coach or athlete in a practical setting it will be necessary to fully automate these analyses and develop an interface that displays the relevant data. Such information may help to provide new insight into factors that influence sprint performance, and also provide a means for monitoring the effects of training on sprint performance.

5. CONCLUDING REMARKS

Accelerometer-based measurement systems are lightweight and portable, which facilitate unencumbered movement of the subject and do not confine data collection to the laboratory environment. Additionally, they are easy to use, cost effective, are able to capture data from many gait cycles. The results of the present study suggest that close estimates of CT may be obtained using a shin-mounted accelerometer-based approach. The best estimates of CT were obtained at the higher speed conditions, which were associated with the highest measured accelerations. The shin-mounted accelerometer system described in the present study also offers significant potential to quantify many other aspects of running performance of interest to the athlete and coach, and may be adapted to provide near real-time feedback in the training and competitive environment. These developments are the focus of our ongoing research.

7. ACKNOWLEDGEMENT

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