DETERMINATION OF HEEL STRIKE AND TOE-OFF IN THE RUNNING STRIDE USING AN ACCELEROMETER: APPLICATION TO FIELD-BASED GAIT STUDIES

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This study examined the validity of using an accelerometer to determine heel strike and toe-off during the running stride for use in field-based gait studies. Synchronised ground reaction force and accelerometer (±1.25Gz and ±12Gz) data were collected from six males running at constant speed across a force plate. Two attachments sites for the accelerometer were examined, the hip and the ankle. Attachment of the accelerometer to the ankle provided a highly distinguishable and repeatable pattern. The identification of heel strike and toe-off via the accelerometer signal was determined by calculation of the lag time from the acceleration peak after ground impact. The lag times were calculated to be 65±5msec for heel strike and 15±2msec for toe-off. The results of this study provide evidence that heel strike and toe off can be accurately determined using an accelerometer.

KEY WORDS: accelerometer, heel strike, toe-off, gait, methods.

INTRODUCTION: In studies examining the kinematics, kinetics and electromyography of gait, the gait cycle is divided into stance and swing phases by identifying the instance of heel strike and toe off. The precise identification of these points can be done in the laboratory environment using a high-speed camera (Reber et al., 1993; Montgomery et al., 1994), a force plate (Nummela et al., 1994), or some form of footswitch device (Nummela et al., 1992; Wiemann & Tidow, 1995). When carrying out field-based research it is necessary to examine alternative measurement methods to minimise the amount of equipment required. The available equipment and methods may affect the research design and therefore, the measured variables. Traditionally footswitches have been used to determine variables such as heel strike and toe-off for gait analysis studies in field settings however, footswitches can lack mechanical robustness and may cause discomfort to the subject (Willemsen et al., 1990). Therefore, a method of identifying foot strike and toe off reliably, without discomfort to the subject, or with the inconvenience of following an athlete who is either running quickly or over a long distance is needed. Previously, accelerometers have been used in gait studies to determine energy expenditure (eg. Bouten et al., 1994), describe lower limb kinematics (Mayagoitia et al., 2002) and to measure acceleration values on the lower limbs as a result of impact in gait (eg. Hennig & LaFortune, 1991; Andrews & Dowling, 2000). The advantages in using accelerometers are that they are inexpensive, lightweight, reasonably robust and can be used for extended recording. Willemsen et al. (1990) compared accelerometer readings to footswitch data in the determination of gait events and found heel strike to be represented by a clearly visible peak whilst toe-off was characterised by a subsequent smaller peak in the accelerometer pattern. The question arises however, where the accelerometer should be positioned on a subject as the magnitude and profile of acceleration may change according to it's location (Willemsen et al., 1990; Kim et al., 1993). Therefore, the aim of this study was to determine whether heel strike and toe-off in the running stride could be consistently identified using an accelerometer for use in field-based gait studies. The best location to attach the accelerometer was also considered.

METHODS: Synchronised data was collected from a Kistler 9287B piezoelectric force plate (Kistler Instrument Corp, Switzerland) and a ±1.25Gz and ±12Gz accelerometer (Mega Electronics, Finland) at 1000Hz. For each accelerometer, six male subjects undertook five running trials (a total of ten running trials for each subject) over 20 metres at controlled speed across the force plate with the accelerometers taped firmly to their right side (Figure 1). Subjects were instructed to contact the force plate with their right foot whilst maintaining speed and stride length. A series of familiarisation trials were carried out prior to testing. The hip and the ankle were selected as attachment locations to be examined to determine the placement site with the most easily depicted and repeatable pattern for heel strike and toe-off. Informed consent, in accordance with the Edith Cowan University Ethics Department was obtained from subjects prior to testing.

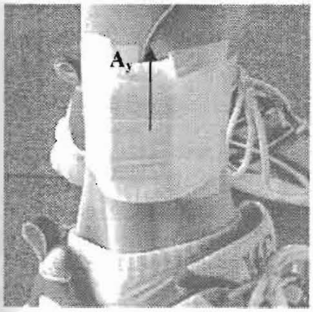

Figure 1: Accelerometer attachment on the ankle.

'True' heel strike and toe-off were determined via inspection of the Fz component of the ground reaction force (GRF) measured by the force plate (+ve Fz was the upward component of the GRF). The abrupt change in the Fz signal was regarded as a highly precise measurement of heel strike and toe-off with which the accuracy and reliability in determining heel strike and toe-off using the accelerometer could be compared. The acceleration data from the ankle and hip for both accelerometers in the Y-Direction (Ay) were graphed and compared, to determine whether a repeatable pattern existed to accurately determine heel strike and toe-off. Due to the positioning of the accelerometer on the lower limb, a time lag from the acceleration peak to true impact was expected to exist. To verify the existence of this time lag a validation study was undertaken. To this end, the +1.25Gz accelerometer was attached at pre-determined distances away from the base of a 1m long timber post. The post was struck against the force plate with three trials at each position 10cm, 30cm, and 40cm from the impact point. There was a very strong correlation between the accelerometer position from the impact point and the time lag ($r2 = 0.997$) indicating that the further the accelerometer was from the impact point, the longer the time lag. To calculate the time lag for the running trials, the raw data were graphed and the heel strike and toe-off impact peaks were determined and compared with the force plate data.

RESULTS: Initial attachment of the accelerometer was on the hip, inferior to the iliac crest, close to the centre of gravity with the accelerometer's Y-axis aligned with the long axis of the femur. An example of the Ay pattern with the ±1.25Gz accelerometer attached at the hip over several gait cycles is shown for several strides in Figure 2a. Figure 2b shows a more detailed comparison of Ay data from the hip and the ground reaction force (Fz) with the ±1.25Gz accelerometer. Due to the large variation between subjects and the lack of a specific pattern, the points of heel strike and toe-off were unable to be identified accurately and consistently.

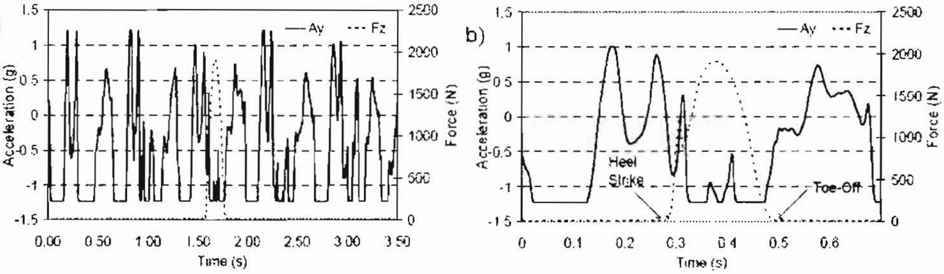

Figure 2: Pattern of acceleration in the Y-direction (Ay) during running with accelerometer attached to the hip (a). Detailed Fz component of ground reaction force and acceleration in the Y-direction (Ay) data with accelerometer attached to the hip (b).

Alternatively, testing was carried out with the ±1.25Gz and ±12Gz accelerometers attached to the right ankle above the lateral malleolus with Ay aligned to the long axis of the tibia. The distinctive pattern of heel strike and toe-off with the attachment of both accelerometers at the ankle is shown in Figures 3a and 3c. Figures 3b and 3d detail the exact points of heel strike and toe-off from the ±1.25Gz and ±12Gz accelerometers in relation to the ground reaction force (Fz) with the accelerometer attached to the ankle.

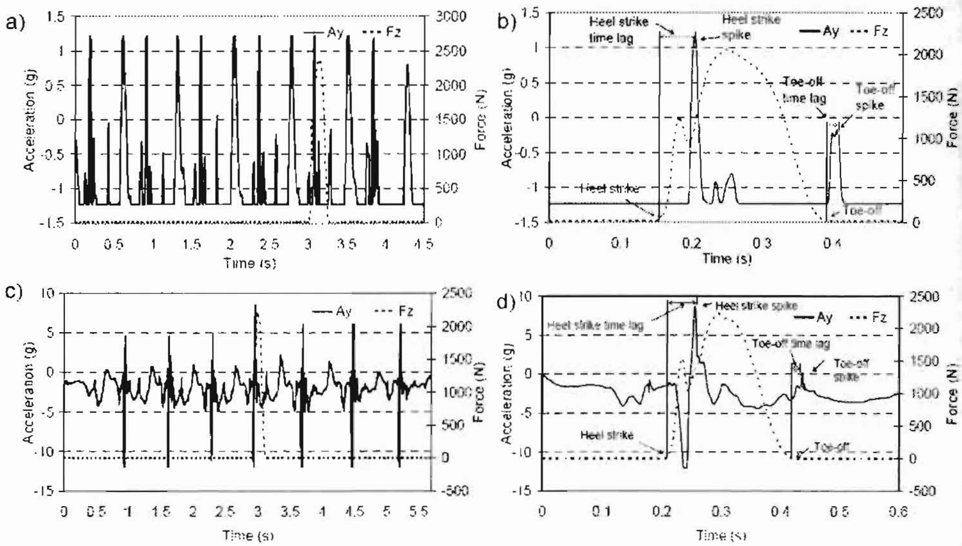

Figure 3: Acceleration pattern in the Y-direction (Ay) during running with ±1.25Gz (a) and ±12Gz (c) accelerometer attached to the ankle. Detailed Fz component of ground reaction force and ±1.25Gz acceleration (b) and ±12Gz acceleration (d) in the Y-direction (Ay) with accelerometer attached to the ankle.

The time lag refers to the elapsed time between actual heel strike and toe-off as measured by the force plate and these same variables estimated from the accelerometer respectively. In the above figure the time lag is shown not as the first instance of change in the pattern, but at the point of highest positive acceleration. This is in keeping with the heel strike and toe-off measurements that were found to be spikes in the accelerometer pattern (Willemsen et al., 1990). Lag times from the ankle trials with both accelerometers were compared for all subjects to ensure consistency. Table 1 shows the summary statistics for each trial for data collected with both accelerometers. The average time lags were 65 5msec and 15 2msec for heel strike and toe-off respectively.

Table 1 Mean and standard deviations of the time lag (secs) between force plate heel strike and accelerometer heel strike from both accelerometers. HS=Heel Strike, TO=Toe-Off.

		±1.25Gz		±12Gz	
TRIAL		MEAN	SD	MEAN	SD
1	HS	0.065	0.005	0.065	0.005
	TO	0.015	0.005	0.015	0.004
2	HS	0.066	0.006	0.066	0.006
	TO	0.015	0.003	0.015	0.002
3	HS	0.064	0.004	0.064	0.004
	TO	0.013	0.002	0.014	0.003
4	HS	0.066	0.005	0.066	0.005
	TO	0.015	0.001	0.015	0.003
5	HS	0.064	0.003	0.064	0.003
	TO	0.016	0.001	0.015	0.001

DISCUSSION: This study presents evidence that a clearly distinguishable and consistent pattern of heel strike and toe-off in the running stride is present in the pattern of both a ±1.25Gz and ±12Gz accelerometer when attached at the ankle. Furthermore, the attachment of the accelerometer was more secure due to the wrapping of tape around the entire limb to reduce any extra movement of the accelerometer. The pattern from the accelerometer when attached at the ankle was similar across all subjects with a major spike representing heel strike and a smaller spike representing toe-off, which is in agreement with the findings of Willemsen et al. (1990).

Due to the limited measurement capabilities of the ±1.25Gz accelerometer the heel strike peak for some subjects was clipped. The extent of this loss of measurement was on average only 5ms in duration, for this reason the use of the ±1.25Gz accelerometer may be limited by the running style of the subject and therefore, prior examination of the runner's stride using an accelerometer would be recommended prior to field testing. With the accelerometer attached to the hip the precise points of heel strike and toe-off were less obvious and consequently more difficult to identify from the accelerometer output.

CONCLUSION: The findings from this study provide a means for data collection and analysis in field-based gait studies without excess equipment and resources. The ability to determine heel strike and toe-off using an accelerometer will allow biomechanical testing to be carried out in the field rather than within the constraints of the laboratory.

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