Swing profiles in sport: An accelerometer analysis

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Abstract

Inertial accelerometer sensors record movement. Rhythmic and repetitive movement is common to almost all sporting activities. It is possible to model the dynamic acceleration of a swing (both body and implement) using a cosine squared function of angular position with time. In cricket, a straight drive using a bat mounted accelerometer can be well matched ($r > 0.9$) and the time and effort determined. The same analysis can be applied to baseball, field hockey, boxing and running. As the function is symmetrical, situations where the acceleration time is different to the deceleration time can be readily identified. In most cases both the acceleration and the deceleration require muscle effort and control.

Keywords: Accelerometers; bat swing; bat angle; cricket; baseball

1. Introduction

Inertial acceleration sensors record acceleration which can be interpreted in terms of velocity, displacement, angular velocity, acceleration, force etc: Kan & Chen (2012); Shany et al. (2012); Ahmadi et al. (2006); James et al. (2004). There has been considerable effort directed at understanding the acceleration of all parts of the human body (leg, hand, arm, torso, head etc) and the implements used in sport such as cricket bats: Sarkar et al. (2011), baseball bats: Fallon et al. (2008), hammer: Ohta et al. (2008), tennis racquet: Rowlands et al. (2012), and martial arts sword: James et al. (2005).

The major advantage of an inertial system is that it can be quickly deployed, can acquire data over long periods of time and has sensitivity beyond that of video and most other measurement techniques: Thiel et al. (2012). For this reason accelerometers can be used during training, during matches and in everyday activities to record activity...
levels, to review and measure skill levels, and to track injury recovery. This study was conducted on bat angle
during swings in straight cricket bat swing in the vertical plane and baseball bat swing in the horizontal plane.

2. Swing angle model

2.1. Swing angle equations

In cricket and baseball each bat phase starts with a stationary bat and ends with a stationary bat. The bat angle
changes monotonically. The video derived bat angle $\theta$ was fitted to a cosine squared function. In cricket, the bat
angle $\theta$, measured from the vertical direction (i.e. the – g direction) (see Fig. 1) can be written:

$$\theta(t) = K_1 \cos^2(At) + K_2$$ (1)

Here $K_1, A, K_2$ are the constants determined from the initial and final conditions in each phase of the swing.
From equation (1), the angular velocity $\omega$ is

$$\omega = \frac{d\theta}{dt} = -AK_1 \sin(2At)$$ (2)

The initial angular velocity (time= $t_1$) is zero. The final angular velocity (time= $t_2$) is zero then

$$AK_1 \sin(2At_2) = 0$$ (3)

so $A = \frac{\pi}{2t_2}$ and

$$\theta(t) = (\theta_1 - \theta_2) \cos^2\left(\frac{\pi t}{2t_2}\right) + \theta_2$$ (4)

2.2. Acceleration formulation:

Static Case:

When the bat is at rest, all first and second order time differentials are zero. Thus only the gravity component
contributes to the acceleration. The three acceleration components on the sensor co-ordinate system can be
converted to the gravitational co-ordinate system. The total acceleration $a_{tot}$ is given by:

$$a_{tot} = a_x^2 + a_y^2 + a_z^2 = g^2$$ (5)

Dynamic Case:

For simplicity an additional acceleration component $A_x$ in the x-axis direction is assumed only to contribute to
$a_x$. This additional component is accounted from rotational and translational movements of the bat during swing.
Following the axes given in Fig. 1 the accelerations can be written as follows:

$$a_x = g \cos \theta + A_x$$
$$a_y = 0$$
$$a_z = g \sin \theta \cos \phi$$ (6)
Here $\phi$ is the angle between the sensor’s and bat’s z-axis (see right part of Fig. 1). Because $\phi$ is approximately 15° (the back of the cricket bat where the sensor was placed is not parallel to hitting face) then $a_y \approx 0$. The total acceleration $a_{tot}$ is calculated using

$$a_{tot}^2 = (g \cos \theta + A_x)^2 + (g \sin \theta \cos \phi)^2 = A_x^2 + 2A_x(g \cos \theta) + (g \cos \theta)^2 + (g \sin \theta \cos \phi)^2$$

(7)

As $a_{tot}^2$ can be calculated from the measured acceleration data, then $A_x$ is calculated from the solution to the quadratic equation:

$$A_x^2 + 2A_xg \cos \theta - a_{tot}^2 + g^2 \cos^2 \theta + (g \sin \theta \cos \phi)^2 = 0$$

(8)

Then,

$$A_x = -(g \cos \theta) \pm \sqrt{a_{tot}^2 - g^2 \sin^2 \theta \cos^2 \phi}$$

(9)

For a planar straight drive, the bat swings in the two dimensional plane (say XOZ for the bat coordinate system). If $\phi = 15^\circ$ throughout the swing then $\cos \phi = 0.97$ and $\cos^2 \phi = 0.93$. If $a_{tot} >> g$, we can write:

$$A_x \approx -(g \cos \theta) \pm a_{tot}$$

(10)

Considering the maximum value of $\cos \theta$ is unity, this represents 21% of the value of $A_x$ if $a_{tot} = +4.7g$. At the time of maximum angular velocity we can write $A_x = a_{tot}$ which corresponds to the minimum x acceleration value (i.e. maximum negative value) during the drive. At this time we can write

$$R \omega^2 = a_{tot}$$

(11)

where $R$ is the radius of rotation (the distance between the instantaneous centre of rotation and the sensor) and $\omega$ is the angular velocity. The centrifugal force dominates the acceleration at this time, so $a_{tot} \approx a_x$. The maximum driving force $F$ is

$$F = ma_{tot}$$

(12)

where $m$ is the mass of the bat.
3. Experimental Procedure

Following ethics approval (Griffith University ENG/16/10/HREC), acceleration data were recorded as \( a_x, a_y, a_z \) along the sensor axes \( x, y, z \) respectively from 63 straight ball-free cricket bat swings by seven amateur batters of 9 swings by each. Each batter’s 9 swings were divided in three sessions terminating in different angles (lower, medium and higher) at the end of the swings. Amateur batters were used as they are likely to have a greater variation between swings. Thus these results represent a worst case analysis. Elite batters should have far less variation in stroke formation. To capture the full trajectory of the cricket bat swings, a video camera was placed at 1.4 m above the ground and 5 m laterally from the batting arc. The camera operated at frame rate of 100 f/s. Two interlaced images of each frame were separated by software that resulted in a frame rate of 200 f/s. The location of the camera was similar to Sarkar et al. (2011). The timing between sensor and the video data were synchronized by tapping the bat on the ground. In baseball, an amateur batter performed 9 swings at three different speeds (low, medium and higher) divided in three sessions. An elevated camera angle was used to record the swings.

Equation (4) was used to derive the bat angle as a function of time. The equation matched the video estimated angles. Equation (11) was used to predict the implement length aligned acceleration (radial acceleration) profile during bat swing and the prediction was compared with the accelerometer record. The objective of the comparison was to interpret the bat swing dynamics from the accelerometer record.

4. Results and analysis

4.1. Cricket bat swing profiles

The cricket straight drive was divided into three phases: ‘back-lift’, ‘drive’ and ‘return’. In the ‘back-lift’ phase, the batter lifts the bat in the direction of the oncoming ball. The ‘drive’ phase is when the bat is swung towards the oncoming ball. It starts at the end of back-lift and ends at the end of the bat rotation. The ‘return’ phase starts at the end of ‘drive’ and it ends when the bat returns to the start position. Each phase is characterized by zero angular velocity at the start and end. For a typical swing these temporal phases in the accelerometer recorded accelerations \( a_x, a_y, a_z \) are shown in Fig. 2a together with the angle profile (Fig. 2b). Each bat phase was fitted to equation (4). Strong agreement (Pearson correlation coefficient \( r = 0.99 \)) was obtained between the equation and the video swing angles in the drive with \( r = 0.97 \) and \( r = 0.99 \) for back-lift and return phase respectively (see Fig. 2(b) and Fig. 2(c)). Using the data in Fig. 2, we have \( a_x = -4.7g, a_y = 0.0266g \) and \( a_z = -0.3230g \), and the force \( F \approx 60N \) where \( m \) is the mass of the bat (1.3kg in these experiments).

The bat elevation angle at the end of the swing was compared to the angle calculated using the acceleration at the end of the drive \( a_{end} \). Table 1 shows the correlation coefficients (\( r' \)) and probability (\( p' \)). A strong linear correlation coefficient (\( r'=0.95 \sim 0.998 \)) with a very low \( p' \) value (<0.0002) was obtained for each batter.

The value of \( R \) was taken as the total radial length of batter’s hand and bat measured from batter’s shoulder to the sensor position. In the return phase, the same value of radius as used in back-lift. In the drive phase, the radius value was increased by 40\% to match the profiles shown in Fig. 2(a). To check the relation between the bat elevation angle and x-axis acceleration in the equation derived profile, the final angle (\( \theta_f \)) at the end of drive was varied. The bat acceleration from the sensor and the equation are compared in Fig. 3a.

4.2. Baseball bat swing profiles

Fig. 3b shows the acceleration profiles recorded by baseball bat mounted sensor along its X-, Y- and Z-axis (X-accel, Y-accel and Z-accel respectively) from ten swings by an amateur batter. The swings were in XY-plane (parallel to ground). Each swing was composed of two parts - forward and return swing. The swings deviated from the horizontal plane resulting in accelerations in Y-accel and Z-accel profiles. Ideally these axes should register 0g and 1g for the ideal case. The two consecutive negative peaks (major and minor) in X-accel in Fig. 3a were observed during the forward and return swings (confirmed by the video). The angles of a typical swing were derived using equation (8). This was then used to determine the acceleration profile (see Fig. 3b).
The radius of rotation used for baseball bat swing profile was chosen to be the summation of the batter’s hand and baseball bat up to where the sensor was placed for both parts of the swings. While the agreement is quite good during the forward swing, the return swing is not well matched. This is thought to be the result of a significant deviation of the bat from the horizontal plane and a rapidly changing swing radius. Additionally, a pause was observed after the forward swing (confirmed by the video) that caused the $a_x \equiv 0$ g in the profile between $t = 1.2$ s and 2.5 s. This is just after forward swing.

![Fig. 2. (a) Three axis acceleration profiles from a typical swing with its temporal phases (Back-lift, Drive, and Return); (b) Vertical bat angle derived from video with three fitted lines; (c) Linear regression analysis for the equation model.](image)

Table 1. Correlation coefficient and probabilities for individual batters.

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5. **Discussion**

Sensor recorded acceleration profiles were used to identify bat position during cricket bat swings and baseball bat swings by 7 cricket and 1 baseball amateur batter. Bat elevation angles in straight drives and accelerometer sensor recorded acceleration peaks were recorded from 63 drives by cricket batters. A good correlation ($r = 0.98$) was obtained between the sensor acceleration peaks and bat elevation angles. The video recorded angle profile in a typical swing was matched with equation (4) ($r=0.99$). Good agreement was obtained by adjusting the radius of rotation in each phase of cricket bat swing.

In baseball, the equation profile was matched for the forward swing. The use of a constant R value results in slight differences between the two curves (by sensor & equation) in the forward swing, and major differences in return swing. The origin of these differences was thought to relate to a varying value for the radius of swing R, out of plane deviations of the bat swing, and body movement during the swing.

6. **Conclusions**

Bat mounted triaxial accelerometer sensors were used to identify bat position and elevation angle in a straight drive in cricket. In baseball, the bat position and deviation from the horizontal plane were mapped to the same swing equation. Results indicate that accelerometer data alone can be used to determine bat angular velocity. This could be augmented using additional sensors to document cricket shots by an elite batter for training purposes. The acceleration and the deceleration effort and the control of the bat can be judged by measuring the deviation from symmetry in the swing profiles.
Future work will be directed to expanding the equation to accommodate out-of-plane swings, with the final objective of determining the force of the bat and directly determining the time and orientation of the bat during contact with the ball.

Fig. 3. Equation derived and sensor recorded typical x-axis acceleration profile (a) cricket bat; (b) baseball bat.

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References