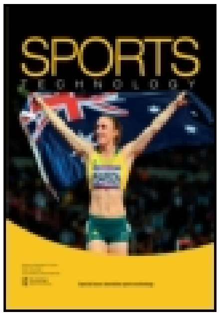

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RESEARCH ARTICLE

Detection of throwing in cricket using wearable sensors

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Abstract
One of the great controversies of the modern game of cricket is the determination of whether a bowler is using an illegal throw-like bowling action. Changes to the rules of cricket have reduced some of the confusion; yet, because of the complexities of the biomechanics of the arm, it is difficult for an umpire to make a judgement on this issue. Expensive laboratory-based testing has been able to quantify the action of a bowler and this testing is routinely used by cricket authorities to assess a bowling action. Detractors of the method suggest that it is unable to replicate match conditions, has long lead times for assessment and is only available to the elite. After extensive laboratory validation, we present a technology and method for an in-game assessment using a wearable arm sensor for differentiating between a legal bowling action and throwing. The method uses inertial sensors on the upper and lower arms that do not impede the bowling action. Suspect deliveries, as assessed by an expert biomechanist using high-speed video and motion capture, reveal valid distinctive inertial signatures. The technology is an important step in the monitoring of bowling action on-field in near real-time. The technology is suitable for use in competition as well as a training tool for developing athletes.

Keywords: *cricket, biomechanics, accelerometers, gyroscopes, throwing*

Introduction

The issue of cricketers bowling illegal deliveries, colloquially known as 'throwing' or 'chucking', has been an emotive issue for many years. The ideal cricket bowling delivery requires the bowler not to change the angle (extend) of their elbow through the latter parts of the delivery action. As the bowling arm circumducts to the position of ball release, a 15° tolerance threshold is applied to the limit of elbow extension between the arm at the horizontal (parallel to the ground) and the position of ball release (the last moment in time the ball is touching the bowler's fingers). This tolerance threshold was introduced in 2005 by the world's governing body, the International Cricket Council (ICC), after the assessment of biomechanical data from 130 first-class cricket bowlers (Portus, Rosemond, & Rath, 2006).

Because of the difficulty in assessing an illegal delivery in a fraction of second with the naked eye, bowlers suspected of illegal deliveries are reported by umpires in their post-match report according to a strict protocol. This results in the bowler having to undergo a biomechanical analysis of their bowling action in one of only a few internationally approved biomechanics laboratories. Here, the bowlers' actions are monitored with motion capture systems, radar and high-speed video within a tolerance of their match-recorded bowling speeds. They are required to bowl a series of deliveries that include their normal repertoire of deliveries. The assessment uses the motion capture data, radar data and match video to analyse if the bowling action in the laboratory is legal and if the action in the laboratory represents the action exhibited when the bowler was reported in match conditions (ICC, 2010). A typical setup uses approximately 20 motion-capture cameras, 2–3

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high-speed cameras and a radar gun. Bowlers are typically 'marked up' with more than 20 reflective markers and bowl in an indoor facility under low-light conditions. Usually a team of five people are required to facilitate the data collection and 21 days are required written for the data to be collated, interpreted and a report written by the biomechanist (ICC, 2010).

The costs in the assessment, travel (often international) to the approved laboratory, time-out from international competition together with the time cost of a full biomechanical analysis proves onerous. Additionally, the problem of bowlers using a different action in the laboratory to that used in the field is also a consideration, thus it was proposed that low-cost inertial sensing may be able to detect illegal bowling actions in a 'real world' match or cricket-training environment.

Inertial sensors are an emerging technology that has been applied in the pursuit of biomechanical assessment of physical activity. Recently developed micro-technologies have been used in athlete performance monitoring, biomechanical monitoring and physiological monitoring in other sports such as swimming (Davey, Anderson, & James, 2008; James, Burkett, & Thiel, 2011; Kavanagh, Morrison, James, & Barrett, 2006), snowboarding (Harding, Mackintosh, Martin, & James, 2008) and running (Wixted, Billing, & James, 2010; Wixted et al., 2007).

Accelerometers measure changes in motion in three dimensions and are only millimetres in size. Through numerical integration and appropriate filtering, velocity and displacement can be calculated. It is well understood that the determination of position from acceleration alone is an error-prone and complex task. Thus, accelerometers are often only used for short-term navigation between reference points, finding the orientation relative to gravity, for the detection of movement signatures (such as limb movement) and for temporal discrimination of events (e.g. ground contact and stride or stoke frequency). Rate gyroscopes, a close relative of the accelerometer, measure rotation about a single axis and can determine orientation in an angular coordinate system, although they cannot determine angular position, while accelerometers are limited in determining absolute position. The challenges of these sensors are many; historically, many physical movements, such as lower limb movement in sprinting, have exceeded the maximum specifications in commercially available units. Acceleration and rotational velocity are not easy to intuitively understand, nor can they easily be converted to more conventional measures. However, the real strength of these sensors is in recognising repeatable signatures and temporal event markers of human movement. For example, in cases where an accelerometer is used to detect rate information, such as stride or stroke rate, it does not require calibration. Similarly, detecting timing between closely timed impact events requires no calibration, as the accuracy of activity detection is governed by the accuracy of the system oscillators, typically better than 0.01%.

While a single-axis accelerometer or a gyroscope can provide useful information in particular circumstances, the use of three-dimensional (3D) accelerometers or gyroscopes provides a higher level of information. Ultimately, the highest level of inertial-sensor-based information for biomechanical monitoring comes from systems of synchronised nodes of 3D accelerometer–gyroscope combinations. By combining synchronised sensor nodes with an understanding of the system being monitored and the physics of the situation, complex sequences of movements can be identified. Depending on the situation, systems of sensors can use some form of common-mode rejection algorithm.

The combination of using inertial sensors as temporal markers for events, together with combining multiple sensors, extends its capabilities to the monitoring of very fast movements of quite complex biomechanics; for this reason, it is a likely candidate for the monitoring of a bowling or throwing arm.

Theory

Bowling requires a nearly rigid elbow during the delivery motion from when the elbow reaches the level of the shoulder (the start of the 'arm action') to ball release (the end of the 'arm action'). For fast bowlers, this means the arm is usually fully extended before the elbow reaches the level of the shoulder and then the rigid arm is rotated forward. Detection of elbow extension requires detection of the independence of the upper arm (UA) and forearm (FA) during this phase of the bowling action. A system of inertial sensors with sensors on both the FA and UA would provide this solution.

In cricket bowling, the acceleration on both the UA and FA is predominantly centripetal (along the long axis of arm) and should be nearly identical in phase during a delivery where the elbow remains rigid. If a bowler has a partially flexed elbow and uses a longitudinal rotation of the UA in the kinetic sequence, as described by Marshall and Ferdinands (2003), there should be a phase relationship between the rotation rate of the UA and the acceleration on the FA. If the elbow is straightened during the delivery, there should be change in the phase relationship between the FA and UA acceleration and angular velocity. Using accelerometers and co-located gyroscopes on both the FA and UA, these signals will differ and be measurable.

Potential confounding issues for inertial sensors include the various other functional movements and orientations at the elbow, such as the carry angle, adduction, abduction and elbow hyperextension. Rotation of a simple rotating joint would not be a problem, since the angle of one segment compared to the next would be readable in the relative magnitudes of acceleration on the transverse axes. Unfortunately, the elbow is neither a hinge joint nor a simple rotating joint, and wrist rotation will affect any FA-mounted sensor due to the twist of the skin surface changing the alignment of the sensor (Wixted, James, & Portus, 2011). Depending on its positioning, the UA sensor will also be affected by soft tissue artefact such as muscle, other subcutaneous tissue and skin movement.

Approach

Monitoring the bowling arm during the bowling action involved primary and secondary identification phases. The three primary phases directly related to bowling action were:

(1) detecting the start of the arm action;
(2) detecting ball release;
(3) elbow angle detection between the start and end of the arm action.

Several additional complexities were envisaged such as the following: the sensor mounting technique, the orientation of the sensor relative to the elbow axis, the skin movement, the rotation of the FA skin surface during wrist rotation and the effects of unusual arm anthropometry, the latter being a notable characteristic of bowlers having actions reported as suspicious (Ferdinands & Kersting, 2006; Lloyd, Alderson, & Elliott, 2000; Portus et al., 2006).

Because of the many complexities faced, prior to developing any inertial technologies for the bowling arm, it was necessary to determine if current sensor technology was capable of monitoring elite bowling arm movements and angular rotation rates, as well as bowling signatures for the critical points in the bowling action (start of arm action and ball release). This was performed using virtual sensors derived from motion-capture data (Wixted, Portus, James, Spratford, & Davis, 2010; Wixted, Spratford, Davis, Portus, & James, 2010). This analysis used a library of pre-existing and previously analysed 120–250 Hz, 8–20 camera, VICON 3D-motion-capture data from elite fast bowlers bowling a normal repertoire of deliveries. The VICON c3d files were reprocessed in MATLAB to create virtual 3D accelerometer and gyroscopic sensors to aid in determining the design requirements and constraints of our sensor system. These virtual sensor data were analysed in conjunction with the previously analysed elbow angle, video capture and other statistics that were also available. The virtual sensors identified that accelerations greater than 70 g were experienced at the wrist, with rotation rates exceeding 2000 $°\cdot s^{-1}$. From the available data, it also appeared that some illegal actions were detectable.

Simple derivation of absolute angle through integration was not considered at this point, because of the inherent problems of this method (James, 2006), namely the difficulty in separating the signal of interest from artefact, noise, where signal-to-noise ratio rapidly exceeds unity. Instead, the analysis focused on the strengths of the inertial sensors and looked at changes in signal strength and signal phase between acceleration and angular velocity from the UA- and FA-mounted sensors. This has also been an alternate recommended approach for the assessment of illegal bowling actions (Ferdinands & Kersting, 2006).

In low-speed movements, the performance of real sensors has been verified against motion capture by Thies et al. (2007) and for accelerometers and gyroscopes in high-speed sporting activity as part of this project. Virtual sensor analysis indicated a high degree of correlation between ball-release and peak-outward accelerations at the wrist. Inspection analysis has been performed to identify a likely indicator of the start of the bowling action and a method of aligning the sensors with the elbow axis (Wixted, James, & Portus, 2011); similarly, motion-capture analysis requires elbow axis identification (Chin, Lloyd, Alderson, Elliott, & Mills, 2010; Elliott & Alderson, 2007). Although each of these results had various limitations, it demonstrated that the inertial sensor monitoring was a good promising approach.

Experimental

In our initial experiments, monitoring of bowlers was performed with sensors designed to capture as much kinematic information as possible. Initially, to reduce design time, these sensors were relatively physically bulky and independent, and synchronisation required an external signal and an appropriate data collection protocol. For this analysis, the inertial sensors were designed to be internally synchronised and small, and have minimal effect on the bowler.

Field testing of the developed wearable technology and methodology was undertaken on two A-grade standard athletes bowling 12 deliveries after a self-determined warm-up. Deliveries were a mix of legal and attempted illegal deliveries using a range of bowling actions. Side-on low-speed (25 Hz) and front-on higher-speed (200 Hz) videos of the bowling action were used for assessment of the bowling action. Deliveries were assessed by an experienced cricket biomechanist. A 100% classification and a 0% false-positive/false-negative correlation with

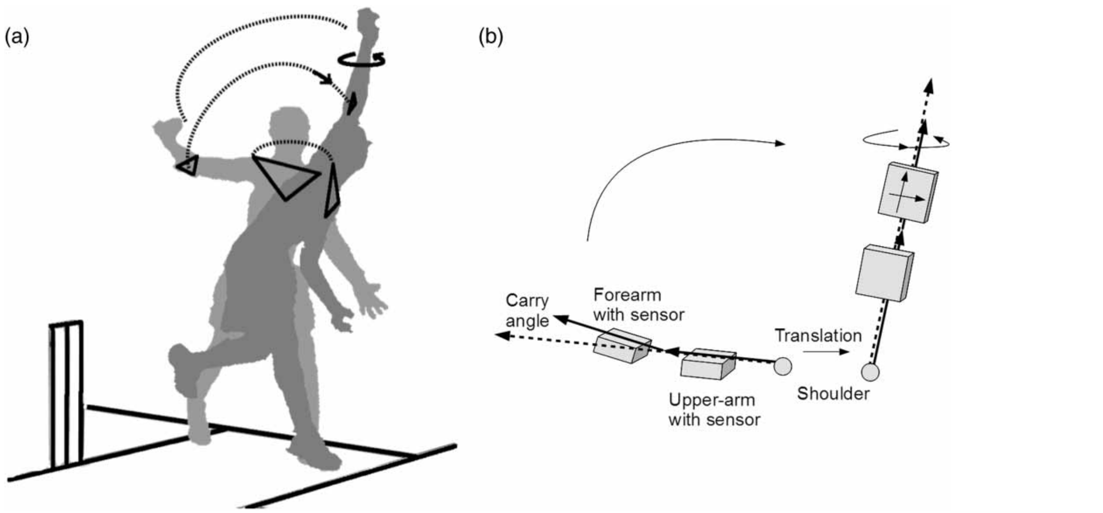

Figure 1. (a) Spin bowler going from the start of the bowling action to just before ball release; and (b) representation of the changes occurring to the arm and sensors. Triangles on the arm in (a) represents the inside of the elbow and the location of sensors on the outside of the arm. Triangles on the chest join three motion-capture markers, one on the sternum and one on each shoulder. The arm and sensors rotate and translate on multiple axes.

single blind visual inspection of the gyroscope data were found when compared with those considered to be 'suspect' by expert opinion.

Figure 1(a),(b) gives one example of how the bowling arm and attached sensors move during the delivery. The body and arm experiences translations, linear accelerations and rotations. In Figure 1(a), an arm apparently bent at the beginning of the bowling action appeared to be straight at the end. In many cases, this can be attributed to a large carry angle (lateral elbow angle) appearing as arm straightening, as the arm rotates around its longitudinal axis (internal–external rotation at shoulder joint) and being viewed from a fixed position, a known problem when viewing bowling actions (Aginsky & Noakes, 2010). For many bowlers, the FA rotates longitudinally (i.e. pronation–supination) through the delivery action resulting in changes in the sensor orientation relative to the direction of travel and also changes in the relative sensor positioning (Figure 1(b)).

The sensors used in the original data collections were bigger than planned for the final product as it was necessary to use components with high ranges to capture the large accelerations (>70 g) and rotation rates ($>2000°\cdot s^{-1}$) generated in the bowling action (Figure 2(a)). This paper presents wearable sensors on a flexible substrate (Figure 2(b)) and field results obtained from their use. In particular, the results show the signal from synchronised gyroscopes aligned with the elbow axis, compared to suspect and non-suspect bowling as determined by the expert opinion from an experienced cricket biomechanist reviewing high-speed video of the bowling action.

Sensors were manufactured using standard flexible circuit technology consisting of printed copper tracks embedded inside layers of flexible plastic.

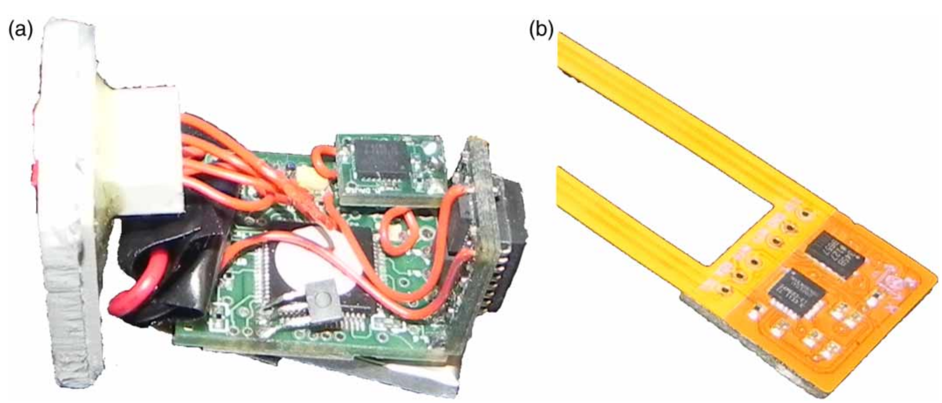

Figure 2. (a) Inertial sensor unit and data logger including ± 100-g accelerometer mounted vertically to capture outward acceleration along the bowling arm. (b) One of the two wearable sensors on flexible PCB used to synchronously capture FA and UA kinematics.

A combination of $\pm$16-g 3D digital accelerometer (Analog DevicesADXL345) and $\pm 2000°\cdot s^{-1}$ 3D gyroscope (Invensense ITG 3200) components were located on two sensor islands connected by a flexible printed circuit board (PCB) carrying the power and I^2C data bus. Chip addresses were arranged so that each sensor island could use an independent I^2C bus or both islands could share a common I^2C bus. Twelve data channels were logged at 200 Hz with 12 bits per sample. This gave a greater resolution than previous data collection. The connection between the two sensor islands used two separate flex-PCB strips with two conductors each, as a single strip with four conductors had insufficient flexibility (Figure 2(b)).

The measurement range of the accelerometers aligned with the long axis of the arm was not expected to be sufficient for the fast bowlers and a sufficiently small, high-range sensor was not available. Using an examplary delivery measured at the wrist, with $650\,m\cdot s^{-2}$ centripetal acceleration at an angular velocity of $2000°\cdot s^{-1}$, the radius of rotation was calculated at approximately 0.53 m. At a point on the elbow 20–25 cm closer to the centre of rotation, the expected acceleration would be in the range $340–400\,m\cdot s^{-2}$, therefore exceeding the current accelerometer range. This will be remedied in the next sensor development with one manufacturer recently announcing the development of similar-sized 100-g 3D accelerometers.

Sensors were attached on the outside of the elbow initially with double-sided tape and then covered over with adhesive bandage. To allow the elbow to flex and straighten, the sensors were attached with the elbow fully flexed, and then the flex-PCB slightly bent to ensure it bowed out when the arm was straight.

Accelerometers were calibrated using the six-point method of Lai, James, Hayes, and Harvey (2004) and the gyroscopes were calibrated using integration of a known angle of rotation (3600°). Gyro-axis to elbow-axis alignment used the method of Wixted et al. (2011). Video was captured using a Sony HandiCam at 25 frames$\cdot s^{-1}$ and a Sony HandiCam SemiPro (Model HDR-AX2000) at 200 frames$\cdot s^{-1}$. Data were logged to a micro SD card for later downloading via USB to a computer. MATLAB was used to download the data and to synchronously display the inertial sensor data and video data in a custom graphical interface (James & Wixted, 2011).

Field results

Post-session review of video was used to score deliveries as bowling or throwing and compare the results of the instructed deliveries and protocol with the video and sensor data. All positive cases of throwing exhibited the expected significant marker in the gyroscope channels used for comparison.

Figure 3 shows representative examples of bowling deliveries with rate gyroscope sensor output from the UA and FA. Figure 3(a)–(d) shows the combined deliveries of bowling ‘good’ (Figure 3(a),(c)) and throwing ‘suspect’ (Figure 3(b),(d)) actions. These are representative of all deliveries. In the figure, only the phases of motion specific to the bowling action

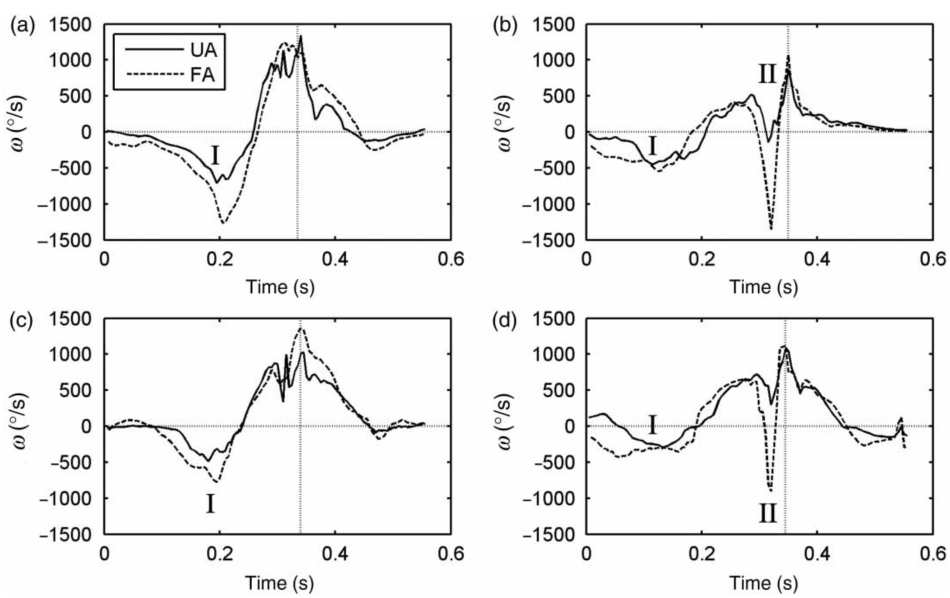

Figure 3. Data from synchronously collected MEMS gyroscopes mounted on the UA and FA. (a) Fast delivery (legal bowl); (b) visually suspect delivery (illegal throw); (c) attempted illegal delivery (legal bowl); (d) visually suspect delivery of a ‘doosra’ (illegal throw). Annotations show (I) beginning of the bowling action (where the shoulder rotates the ball into the upward facing direction); (II) where the UA and FA diverge for an illegal throw; (vertical dotted line) ball release.

are shown, thus the preparation phases prior to bowling action are omitted. Figure 3(a)–(d) shows the initial movement of the arm down swing, where the angular velocity is negative in sign. Legal bowling action is said to begin when the arm is horizontal to the shoulder; at this point, the bowler's shoulder rotates to bring the ball into the upward position (and a 180° change of the orientation of the gyroscope sensors). This is reflected in a negative peak in the rotational velocity of the gyroscope and is clearly seen in all deliveries (Figure 3(a)–(d)) marked 'I'); at this point of inflection, the rotational velocity begins to move in the positive direction due to the change in sensor orientation.

In bowling, where the arm is held rigid, the UA and FA sensor outputs should closely align and the two legal bowling actions (Figure 3(a),(c)) show the two sensor outputs closely aligned throughout the bowling action. However, during throwing, where there is articulation between the two arm segments, this should be seen in the sensors. In these actions, the FA has significant deviation, as it moves independently of the UA, just before ball release. This is clearly seen in the two suspect actions in the Figure (Figure 3(b),(d) at time marked 'II'); these show a fast ball throw and a well-known throwing candidate, the 'doosra' spin bowl, as a throw, respectively. The deviation is related to the amount of arm extension/flexion during the bowling action movement. While the result is quantifiable as an angular velocity, quantifying it to the existing accepted measures (as a static angle threshold obtained from motion capture systems) is the subject of ongoing validation in an internationally approved facility with ranked players.

The results show the potential as a diagnostic tool for the detection of bowling or throwing action. In each case, where video analysis indicated a suspect action, the deep negative-going excursion in the FA gyroscope signal was present. The action shown in Figure 3(c) is noteworthy. This delivery highlighted the role of player perception in bowling action; in this delivery, the bowler attempted an illegal delivery – however the bowler considered that he had been unsuccessful. This was confirmed after review of the video (delivery not suspect) and subsequently in the sensor data.

Discussion

The field results presented here show that articulation of the elbow, the fundamental difference between throwing and bowling, can be measured using small wearable sensors and match the laboratory-obtained indicators of the legal bowling action. In the results, the negative-going excursion does not indicate a reversal of direction but a change of orientation of the sensor relative to the direction of rotation.

To meet the requirements of the existing bowling law, the sensors would need to extract the change in angle between the two-arm sections about the elbow axis. Using a mapping of a database of legal and illegal deliveries to correlate to existing measures would be the preferred method. Direct extraction of elbow angle using rigid-body analysis techniques is confounded by the FA, which has multiple degrees of freedom through the often-unique anthropometry of bowlers and where inertial sensor common-mode rejection methods are inappropriate. Additionally, the FA gyroscope is a measure of overall rotation (the UA) as well as rotation resulting from the articulation of the elbow joint. Other approaches, such as defining arm action by using the change in relative angular velocity between the UA and FA may also come to be accepted, and are perhaps more representative of what is a throw. Improvements by using detected signal strength on the transverse accelerometers to correct for changes in sensor alignment due to wrist rotation may improve the method.

The kinematics revealed by the combination of inertial sensors provides many avenues for determining biomechanical activity and refining the analysis possible from the sensors. One problem of determining movement of the FA relative to the UA is that the FA can rotate about its long axis, independent of the UA. This puts the two sensors out of alignment. One possible correction is to short-term integrate the angular velocity about the long axis to derive an approximate angle of rotation. An alternative method is to use the accelerometer–rate gyroscope combination. The peak centripetal acceleration is a function of the angular velocity of the arm about an axis. If the gyroscope alignment exactly matched the plane of arm rotation, then the angular velocity from a single gyroscope axis would align exactly with the centripetal acceleration. More typically, the gyroscope axes are not perfectly aligned with the plane of arm rotation, and therefore, the angular velocity is spread across two axes. There is a direct trigonometrical relationship between the magnitudes and the plane of rotation. Differences in FA and UA angular velocities across the two transverse axes will indicate the angles of the arm sections relative to the plane of rotation. A similar signal is also available in the tangential acceleration on the two transverse axes. This can be exploited to develop correction algorithms for the changes in relative sensor orientation.

The suspicion of throwing in the game of cricket is highly emotive. It is troublesome and damaging for player, team and even country. The decisions of the ruling body to introduce standards, in game protocols and laboratory testing, have aided the game tremendously in addressing this issue. Timely and low-cost accessibility to methods of assessment of bowling action are a perceived shortcoming of the current methods. Additionally, the validity of laboratory-based testing, for what is seen largely as an on-field problem, can be addressed. The presented technology, as an on-field tool, is a means by which timely and low-cost feedback can be provided, as well as a link between laboratory and field; it can help in the perceptions of lab validity as well. This paper presents, for the first time, the potential ability to assess an athlete on field and in near real-time using a wearable technology that does not impede the performance of the athlete. The technology was developed using a database of historically collected motion capture data from more than 10 years of bowling actions from an ICC-approved facility, together with laboratory validation of prototype technologies with nationally ranked players before being demonstrated in the field.

The technology is currently undergoing further field testing, followed by further laboratory-based validation in an approved facility. It is clear that this is a tool that can be used in match conditions for the detection of suspect bowling action and as a coaching tool. As a coaching tool in developmental athletes, it can help to develop, refine and correct bowling actions in their formative years of athletic development to both improve performance as well as correct suspect actions. Also for the first time, the potential of a low-cost tool will be an aid in the recreational and community grades of cricket, for whom access to laboratory-based assessment is prohibitive. Extension to other sports, such as baseball where analysis of throwing is of interest, is a further possible extension of the work.

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