Sensor applications

Development and Validation of a Single Wrist Mounted Inertial Sensor for Biomechanical Performance Analysis of an Elite Netball Shot

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Abstract— The primary objective of the game netball is to score more goals than the opposition. Subsequently, there is impetus on improving shooting accuracy to maximize scoring. Understanding the kinematic factors of shooting that lead to scoring success allows for iterative adjustment and optimization of technique. Three-dimensional retro-reflective motion capture has been used to assess kinematics; however, these systems are expensive, require substantial setup and postprocessing time, and cannot be used in game-such as environments. With modern advancements in wearable microelectromechanical systems based technology, the ability to monitor shooting kinematics in the performance environment has become possible. This article evaluates the efficacy of a single wireless inertial measurement unit (IMU) sensor to monitor shooting kinematics, in terms of forearm angle at ball release. Four elite female shooters shot a total of 30 shots each (totaling 120 shots) from three different distances wearing both reference retroreflective motion capture (Vicon) markers and an IMU. To assess whether wearing the IMU had adverse effects on the kinematic shooting chain, a further ten shots each were taken without wearing the IMU. When contrasted with the gold standard reference of retro-reflective motion capture, the IMU sensor overestimated the forearm angle at ball release established by a mean percentage error of 4.03 $\pm$ 1.58%. Shots with and without the IMU indicated that the IMU did not biomechanically alter the shooting action. Important advantages of using IMU's over motion-capture solutions include that they are ubiquitous, low cost, require minimal user intervention, and can be used in representative training environments under defensive pressure. This information can enhance the understanding of the athlete's distal segment coordination patterns, providing actionable insights to enable performance to athletes and coaching staff.

Index Terms—Sensor applications, AHRS, netball, inertial sensors, magnetic sensors, sports technology, Vicon.

I. INTRODUCTION

Codified in 1901, netball has become a global sport with a current worldwide playing population in excess of 20 million players [1]. The fundamental aim of netball is for the players to shoot the ball through a hoop located 3.05m above the ground. The team who scores the most goals at the end of four 15 minute quarters are the winners of the game. Subsequently, scoring has been deemed the most important facet for competitive success of a netball team [1] with coaching impetus on improving shooting accuracy. A netball shot has been characterized as having three constituent phases; a preparatory stance phase, a shooting action phase, and a release phase [2]. These three critical shooting phases have been described in the following manner [1].

i) *Preparatory stance*, characterized by first instance of initial knee flexion while both feet in contact with the court surface;
ii) *Shooting action*, characterized by the moment in time of maximal knee flexion;
iii) *Release*, characterized by the moment in time that the ball separates from the hand of the shooter.

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To comprehend the mechanisms of a netball shot, kinematic measurements have been used to analyze the underlying biomechanical features [3]. Detailed kinematic analysis provides insights into the coordination patterns of the netballers. For instance, in a similar task of basketball free throw shooting, a reduction of variability at the end of movement has been considered important [4]. It was found that the difference between novice and experts in basketball Free-throw kinematics was not a reduction of trajectory variability, but rather increased relative coordination (coupling) of movements around the elbow and wrist, and inter-trial consistency of the movement around these joints. It has been argued these movement couplings are required due to the small margin of error in release parameters allowed for successful performance [5]. Button *et al*. [4] concluded that high levels of skilled performance are associated with freezing and releasing of degrees of freedom of movement, aligning with the work of, amongst others, Vereijken *et al*. [6] in skiing. For the basketball free-throw this means that there is an initial increasing of constraints on coordination, and hence stiffening of the lower arm joints movements, characterized by a lower trajectory variability. During skill development, athletes learn to release constraints on coordination, characterized by increased trajectory variability, and stronger coupling between elbow and wrist movement. Following this viewpoint, for basketball and netball shooting-related tasks, monitoring the variation of angles of distal arm segments provides important insights into the shooters ability to constrain the arm joints, and freezing and releasing of movement degrees of freedom, to produce consistent outcomes.

One influencing factor to goal shooting in netball is that it is performed in a dynamic, unstable environment with defensive pressure. Shots vary in distance and angles anywhere within a 4.9 m semi-circular radius. It has been evidenced in closed training conditions without defensive pressure [7] and in game-play conditions with defense [3] that greater shooting distances are linked to greater inaccuracy. Delextrat and Goss-Sampson [1] reported that shooting technique should be practiced in a game environment to improve players' game performances. Subsequently, measurement techniques to assess the stability of the shooting biomechanics, must be able to allow for game-like shooting conditions. The current common practice for biomechanical assessment to extract angles is to utilize retro-reflective marker based motion capture. In netball, Delextrat and Goss-Sampson [1] utilized a ten-camera motion capture system (QTM, Qualisys, Sweden) to discern biomechanical shooting discrepancies between senior and junior athletes from eight shots taken from a standing one handed shot from 3 m. Retro-reflective motion capture, by nature, restricts the task representative design [8] and does not allow for game-like shooting conditions. Further, motion capture systems are expensive, require high computational power, and require considerable expertise to implement. Thus, different technologies for motion capture are desirable [9]. To this end, recently, Microsoft Kinect camera-based sensors have been referenced against a gold standard retro-reflective marker based motion capture (ten camera Vicon system, 100 Hz using the Plug-In Gait full body marker set [10]) [9]. In this study, functional movements, including forearm angle, were assessed in terms of spatial (angle) and temporal (timing) data correlation. The gold standard Vicon (Vicon, Oxford, U.K.) reference was contrasted using Bland-Altman [11] analysis, finding good temporal agreement between methods, but an average 16.93° overestimation in spatial accuracy for elbow flexion.

One technology intervention that has been used for deeper performance monitoring in netball is inertial measurement units (IMU). IMU's have advantages that they are ubiquitous and low cost in nature, although their accuracy is very sensitive to their processing algorithms [12]. The use of inertial sensors in netball has previously been reported for match play tracking of player load intensities. Thirty-two players were tracked in five matches across elite and sub-elite competition [13] and automating shot detection (ShotTracker, Merriam, KS, USA) in netball training [14], although shooting kinematics was not reported.

An orientation estimation algorithm, enabling sensor fusion, is desirable for the optimal estimation of orientation. Classically, IMU sensors using Kalman filters (KF) have been used to this effect [12]. One study which compared IMU and retro-reflective motion capture to assess joint angles from fast arm movements [15] found the IMU exhibited less than 8° RMS error. Madgwick *et al*. [16] created a novel orientation filter using an Attitude and Heading Reference System (AHRS). Findings indicated that the algorithm matched the accuracy of the KF, finding less than 1.7° dynamic RMS error when compared to retro-reflective motion capture. The benefits of this orientation filter include the ability to operate at low sampling rates, smaller computational load, and significant gains in both hardware and power reduction [16].

The aim of the current investigation was to assess the accuracy of IMU technology for monitoring distal arm angle variability at release.

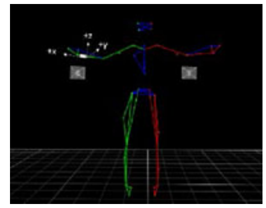

Fig. 1. Image from Vicon showing skeletal model of the T-Pose. The IMU sensor and axis positions relative to this orientation are overlayed.

In particular, the impact of wearing an IMU sensor on the athlete's shooting kinematics and the ability of the IMU to measure arm angle at ball release. The IMU, with supporting algorithms, for forearm angle at ball release was validated against the Vicon system (Vantage V16, Vicon, Oxford, U.K.).

II. METHODS

A. Experimental Design

Four elite (state-level) netballers (female with 11.5 ± 4.7 years playing experience, aged 22.5 ± 2.9, 1.84 ± 0.05 m tall, weight 78 ± 2.74 kg), volunteered with informed consent for participation in this study. Three participants were right-handed and one was left-handed. All procedures were conducted in accordance with Griffith University ethical clearance (GU Ref No: 2016/294). A netball ring set at a fixed regulation height of 3.05 m was placed on an indoor court accredited for professional games. Three distances, i.e., 1.6 m, 2.45 m and 3.2 m, were measured utilizing a tape measure and then marked with colored electrical on the court. A ten camera Vicon (Vantage V16, Vicon, Oxford, U.K.) optical three dimensional motion capture system was setup and calibrated as per the manufactures specifications. A fixed calibrated tripod mounted high speed video camera (Bonita, Vicon, Oxford, U.K.) was additionally used to collect video data at a sampling rate of 100 Hz. Participants were fitted with one IMU sensor (SABELSense, Griffith University, Nathan, Australia). The sensor was positioned superior to the distal radioulnar articulation and secured using a Velcro strap, the sensor was aligned so that in an anatomical position for the x-axis was positive up, the y-axis was positive right, and the z-axis was positive forward. Participants were marked with 39 retroreflective markers as per the Plug-In gait marker model [10]. Shooters were instructed to perform a 5-minute shooting warmup. The testing protocol consisted of 10 shots directly in front of the hoop from three distances; short (1.6 m), mid-range (2.45 m), and long (3.2 m), in that order totaling 30 shots per participant. The Velcro strap with the IMU was removed, and the player shot an additional 10 shots from the mid-range (2.45 m) distance. To synchronize the sensors and motion capture data, the participants stood in a T-pose for 5 seconds and performed three below the waist hand claps before and after each set of 10 shots. The sensor axis and T-pose are shown in Fig. 1.

B. Inertial Sensor Technology

The IMU sensor (SABELSense, Griffith University, Nathan, Australia) used in the experiment logged data locally to a micro SD card and was calibrated [17] before the trial. The sensor has dimensions 55 mm × 30 mm × 13 mm (L×W×H) and a weight of approximately 23 g [18]. It includes a ±7 Gauss 3DOF magnetometer, a ±2000°/s

Table 1. Combined kinematic averages from the mid-range distance attained from the Vicon system.

		Start		Shooting Action		Release	
Parameter	Plane	No IMU	IMU	No IMU	IMU	No IMU	IMU
Shooting Shoulder	Frontal	$34.3 \pm 1.8^*$	$34.2 \pm 2.1^*$	$42.4 \pm 1.8^*$	$42.2 \pm 2.0^*$	$36.9 \pm 1.4^*$	$37.1 \pm 1.7^*$
Shooting Shoulder	Sagittal	$153.7 \pm 2.5^*$	$153.1 \pm 2.9^*$	$143.3 \pm 2.0^*$	$143.9 \pm 2.2^*$	$158.2 \pm 1.6^*$	$158.9 \pm 1.2^*$
Shooting Elbow	Sagittal	$121.2 \pm 3.9^*$	$118.6 \pm 4.5^*$	$77.2 \pm 1.5^*$	$76.8 \pm 1.2^*$	$14.9 \pm 2.5^*$	$149.4 \pm 1.8^*$
Shooting Wrist	Sagittal	$231.5 \pm 1.9^*$	$231.8 \pm 2.2^*$	$245.4 \pm 2.1^*$	$246.2 \pm 1.8^*$	$192.2 \pm 5.9^*$	$190.3 \pm 5.8^*$
Shooting Knee	Sagittal	$169.1 \pm 1.8^*$	$168.3 \pm 2.6^*$	$135.3 \pm 3.9^*$	$136.1 \pm 3.1^*$	$167.3 \pm 1.7^*$	$167.8 \pm 1.3^*$
Ball Release	Sagittal	$110.7 \pm 1.3\%$	$110.5 \pm 1.6\%$	$97.2 \pm 1.4\%$	$97.1 \pm 1.1\%$	$121.9 \pm 0.9\%$	$121.6 \pm 1.1\%$
Pearson's Correlation		0.99989		0.99999		0.99986	

All participants have been clustered enabling comparison of wearing an IMU and without wearing an IMU. Mean and standard deviations are shown in addition to the Pearson's correlation.

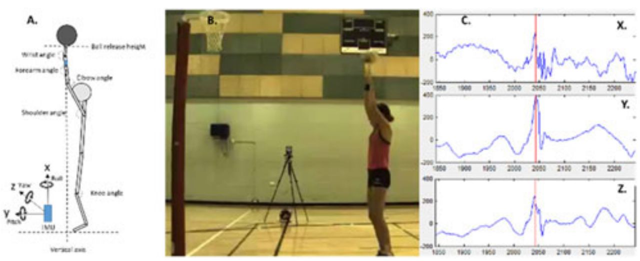

Fig. 2. Synchronised ball release example. (a) Schematic which indicates the angular orientation with respect to the shooting position and the IMU orientation. (b) High-speed video. (c) Angular rate gyroscope readings (X, Y, Z planes) with the red line denoting the time.

3DOF gyroscope, a ± 16g 3DOF accelerometer. The output data rate was set at 100 Hz, matching the one of the Vicon system. The sensor included a red LED which was pulsed by the user allowing for the sensor timing data to be matched to video, and has the capability for wireless connectivity (2.4 GHz) for real-time data streaming, although this was not used in the measurements reported herein.

C. Algorithm

The motion capture data was processed utilising Nexus 2.5 software (Nexus 2.0, Vicon, Oxford, U.K.) with biomechanical data from each shot extracted (ProCalc, Vicon, Oxford, U.K.) at the three time points to match the paper by Delextrat and Goss-Sampson [1] with the addition of the forearm segment angles. Aligning with previous reported literature, from netball [1] and functional classification tasks [19], the Vicon data was filtered with a fourth-order low-pass Butterworth filter with a cut off frequency of 6 Hz to smooth the data. The inertial sensor data was post processed by downloading the data onto a PC. Software was created utilizing MATLAB (MathWorks, Natick, MA, USA) to automate the determination of ball release and calculate the pitch angle of the IMU sensor at each shooting instance. To do this, high-speed video was synchronized with the IMU, with the release point determined to occur at a gyroscopic peak in the y-axis, occurring prior to the arm pitch approaching a local maximum. See Fig. 2(c).

The accuracy of the detection method was validated by contrasting the known number of shots with the MATLAB results. To calculate arm pitch and compare the angular outputs from the retro-reflective motion capture, the software utilized the Madgwick *et al*. [16] 9 DOF Altitude and Heading Reference System (AHRS) orientation filter. This algorithm compensates for magnetic distortion and gyroscopic drift. The filter outputs yaw, pitch, and roll of the sensor with respect to the earth's magnetic frame of reference, forming a global reference. The filter uses a tuning gain value, beta, which represents all the mean sensor errors inclusive of sensor noise, sensor axis non-orthogonality, quantization errors, and frequency response characteristics [16]. Using the beta value equation [16], a beta value of $\beta = 0.041$ was calculated, aligning with previous work by the authors with the same sensor technology [20]. The software automatically detected shooting moments, exporting the forearm angle at the moment of ball release allowing for comparison to the Vicon data. To assess the data distribution for each output parameter, arithmetic means and standard deviations were calculated.

To assess the potential impact of wearing a IMU unit the important shooting kinematic features [1], outlined in Fig. 2(a), were extracted from the Vicon data. A Pearson's correlation was used to measure the linear dependence between wearing or not wearing an IMU sensor. To measure the agreement between the two different measurement techniques for calculating the forearm angle, a Bland-Altman analysis [11] was performed on the Vicon and IMU data, as reported in previous literature [9].

III. RESULTS

To quantify whether wearing a sensor altered the shooting biomechanics, the kinematic features pertaining to the shot were extracted from the Vicon data. This was examined at the mid-range distance to compare both the with, and without condition of wearing of an IMU unit. The results are shown in Table 1.

The MATLAB software successfully detected all 120 shots (30 from each participant) and visual confirmation from the synchronized video to data, showed that the software accurately detected the shooting moment. To assess the accuracy of the IMU to find the forearm angle a Bland-Altman statistical analysis [11] contrasting the IMU and the reference Vicon was performed and is shown in Fig. 3.

The combined percentage error, found using the Bland-Altman analysis [11], between the different methods (IMU and Vicon) are shown in Table 2.

IV. DISCUSSION

The aim of this research was to assess whether IMU technology is valid for monitoring distal arm angle variability at release. One consideration when utilizing wearable technology is to ensure that the technology causes no maladaptive kinematic alterations result-

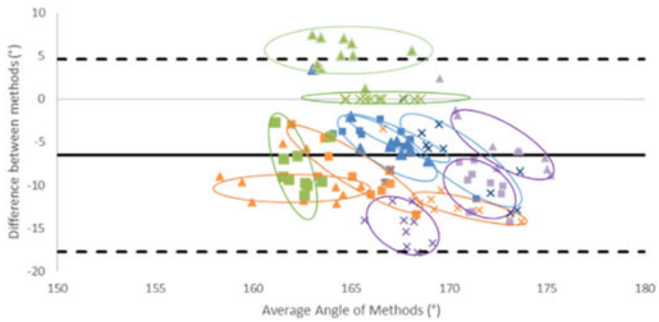

Fig. 3. Bland-Altman [11] indicating the validation between the Vicon and IMU in terms of forearm angle for the 120 shots. The plot shows the limits of agreement, indicated by the dashed line and the mean difference. Clustered by shooting distance (1.6 m = triangle, 2.4 m = square and 3.2 m = 'X') and by athlete (shooter 1 = blue, shooter 2 = orange, shooter 3 = green, shooter 4 = purple).

Table 2. Combined percentage error contrasting the gold standard Vicon to the IMU sensors by participant and by distance with mean and standard deviations shown.

Distance	Shooter 1	Shooter 2	Shooter 3	Shooter 4
1.6 m	-2.72 ± 1.79	-6.15 ± 1.47	3.15 ± 1.11	-2.94 ± 2.01
2.4 m	-3.24 ± 1.69	-5.30 ± 1.83	-5.00 ± 1.62	-6.23 ± 1.39
3. m	-4.14 ± 2.48	-6.94 ± 1.80	-0.01 ± 0.02	-8.78 ± 1.72
$\bar{X}$	-3.36 ± 1.99	-6.13 ± 1.7	-0.62 ± 0.92	-5.98 ± 1.71
$\bar{X}_{\text{Total}}$	-4.03 ± 1.58			

Individual average $\bar{x}$ and group average $\bar{x}_{\text{Total}}$ are additionally shown.

ing from the measurement technology impeding the normal shooting biomechanics. As highlighted in Table 1, the Pearson's correlation was approximately equal to 1, suggesting there was no significant impact of wearing the IMU. Software was created to automatically detect shooting instances. The software successfully classified 120 shots, extracting the angle of the sensor at ball release. When averaging all shots, the IMU was found to overestimate the Vicon angle by $4.03 \pm 1.58\%$. Although the Bland-Altman analysis (see Fig. 3 and Table 2) does show clustering, a small spread of errors was observed rather than a consistent offset. Subsequently a calibration offset to mitigate the error is not possible. The difference in methods can largely be explained by: a 1.7° error introduced by using Madgwick's [16] orientation filter, the erroneous assumption that the IMU angle is equivalent to the forearm angle which will depend on the individual athlete's musculoskeletal anatomy, sensor noise (e.g., moving bias error), and inherent error from the Vicon reference system (e.g., manual shot detection, model fit based on anatomical averages, and marker misplacement). This $4.03 \pm 1.58\%$ error difference is deemed an appropriate level of accuracy for monitoring a netball shot.

V. CONCLUSION

This study used retro-reflective motion capture to ascertain whether a single inertial sensor unit mounted on the forearm was a suitable method for monitoring forearm shooting kinematics. Expert players in related shooting tasks have been shown to exhibit lower variability of forearm angle at ball release. IMU sensors are ubiquitous, low cost, require little installation effort and can be worn in the performance environment in task representative conditions. Therefore, an IMU sensor is a suitable candidate for ascertaining shooting kinematics. It was found that the IMU overestimated the forearm release angle by $4.03 \pm 1.58\%$ as compared to the gold standard reference of Vicon. This implies that IMU sensors can be a viable measurement solution to discern the variability of forearm shooting angle. It was found that the IMU did not affect the shooting biomechanics. Using this new measurement method future work will assess if expert performance is related to smaller variability of forearm angle at ball release.

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