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Procedia Engineering 34 (2012) 580 – 585

Procedia Engineering

www.elsevier.com/locate/procedia

9th Conference of the International Sports Engineering Association (ISEA)

Pitcher training aided by instrumented baseball

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Accepted 28 February 2012

Abstract

Proper pitching mechanics are imperative for developing different types of pitches (e.g., fastball vs. breaking ball) and for preventing injury. Different pitch types are distinguished by the path (i.e. break) and speed of the ball which, in turn, are dictated by the angular velocity of the ball and the velocity of the ball center at the instant of release from the pitcher's hand. While radar guns effectively measure ball speed, they provide no information about the direction of the velocity of the ball center, the angular velocity of the ball, or the way in which these quantities change during the throw. These quantities can, in principle, be calculated using high-speed video-based motion capture (mocap), but doing so requires measurements in a controlled lab environment taken by a skilled technician. Moreover, mocap is unlikely to accurately resolve the angular velocity of the ball which is crucial to understanding pitching. This paper addresses these shortcomings by presenting an instrumented ball containing a miniature, wireless inertial measurement unit (IMU) to measure ball dynamics on the field of play. Measurements reveal that this technology can deduce the magnitude and direction of the ball's velocity at release to within 4% when benchmarked against mocap. Moreover, the IMU directly measures the angular velocity of the ball for pitches that remain within the measurement range of the associated angular rate gyros.

Keywords: Baseball; pitching; training; instrumented ball; inertial measurement unit

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1. Introduction

Baseball pitchers are tasked with one of the most unforgiving duties in sports; one mistake, like a hung curveball or a fastball that tails out over the plate and the result may be a run for the opposing team. Because of this, there has been considerable scientific research conducted focusing on: (1) pitch

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1877-7058 © 2012 Published by Elsevier Ltd.
doi:10.1016/j.proeng.2012.04.099

aerodynamics [1], and (2) pitching mechanics [2-3]. Despite this and other research, coaches still rely largely on a qualitative assessment of pitching mechanics and outcomes (in the form of radar gun measurements, ball and strike counts, and earned run averages) for pitcher training [4].

Studies investigating the effects of aerodynamics on a baseball's flight path consider how the ball's velocity and angular velocity at release causes it to break [1]. Experiments reveal that the total break of the ball during free flight is proportional to the aerodynamic lift coefficient of the ball, is dependent on the seam orientation, and is a function of the magnitude and direction of the ball's angular velocity with respect to the velocity of its mass center [1]. The orientation, spin, and velocity of the ball at release are controlled by pitching mechanics. These quantities ultimately differentiate one pitch type from another. The fastball and change-up rotate about a nearly horizontal axis, perpendicular to the direction of the velocity creating almost pure backspin. In contrast, the curveball spins about the same axis as the fastball, but in the opposite direction, resulting in pure topspin. The slider is thrown like a football with a combination of top- and side-spin [5,6].

Pitching mechanics studies have long relied on position data obtained via high-speed cameras [2-6]. However, video-based motion capture is expensive, time consuming, and requires an operator skilled in both the collection and analysis of the data. Furthermore, baseball angular velocity is difficult to resolve using video based systems due to marker occlusion while the ball is in the pitcher's hand, and the high angular rate with which baseballs are thrown. For these reasons, using high speed video analysis systems in baseball pitcher training is not a viable option.

The advent of MEMS (microelectromechanical systems) inertial sensors and MEMS-scale wireless transceivers has enabled an alternative to video-based motion capture. Several studies have explored the use of wireless inertial measurement units (IMUs) for baseball pitcher training [7,8]. Unfortunately, the size and mass of the IMUs used in these studies (as well as those commercially available from companies like Xsens^{TM}) prohibit their use for measuring the motion of a baseball.

Our study addresses these shortcomings by presenting a highly miniaturized wireless IMU that is small and light enough to be embedded within a baseball (Fig. 1). The resulting design yields a low cost, highly portable and minimally intrusive approach for measuring the kinematics of the baseball during the pitching motion. While most ball spin rates remain outside the measurement range of today's technology for angular rate gyros, future advances of this technology together with methods introduced in [9] will allow ubiquitous application of the methods presented herein in the future.

2. Methods

Figure 1 illustrates what is believed to be one of the world's smallest wireless IMUs enabling peer-to-peer communication to a host computer. This single-board design follows a lineage of larger, multi-board IMU designs developed at the University of Michigan for novel sports training systems [10].

The IMU features a footprint of 19 X 24 mm, a mass of 4.5 grams including a small lithium-ion battery (80 mWh), and a power draw which remains below 25 mW. The two faces of the design separate analog and digital circuits. The analog circuit side (Fig. 1a) includes a three-axis accelerometer (+/- 18g range), one dual-axis and one single-axis angular rate gyro (+/- 2400 deg/s range). The digital circuit side (Fig. 1b) includes a microprocessor which provides 1 kHz sampling of all sensor channels and 12-bit A/D conversion, a low power RF (radio frequency) transceiver, and a small surface mount antenna. The low power RF transceiver uses a proprietary RF protocol to transmit over a typical open-air range of 5m with up to 18m being achieved in low ambient RF environments (i.e. a baseball field). A USB-enabled receiver (not shown) enables data collection on a host computer via custom data collection software.

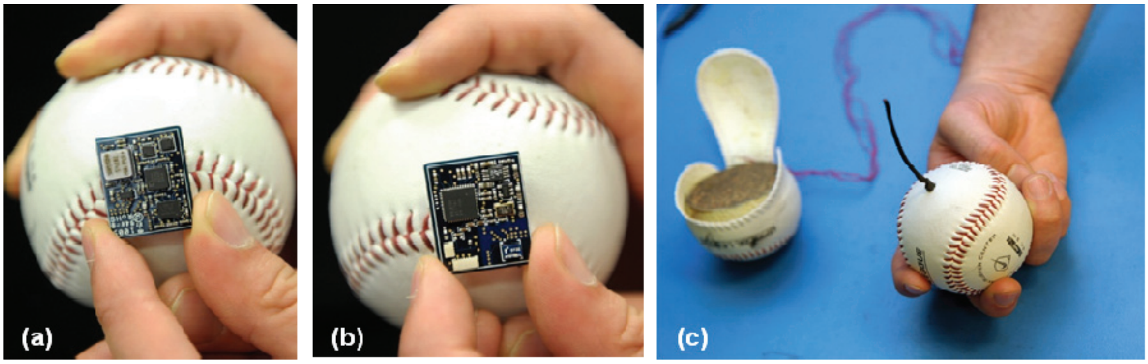

Fig. 1. Photographs of highly miniaturized, wireless IMU. (a) analog circuit side, (b) digital circuit side, and (c) IMU embedded within a baseball. The black stem shown in (c) is a plug for the rechargeable battery within the ball and it is removed prior to throwing

The IMU above, when embedded in a baseball (Fig. 1c), represents a small perturbation to the baseball's total mass (144g before and after addition of IMU assembly) and enables the direct measurement of the rigid body dynamics of the ball in a non-invasive (wireless) mode. Embedding an IMU within a ball has previously been impossible due to the size and weight of existing IMU designs [5,6]. The equations of motion of a baseball during flight dictate that the ball trajectory is determined by the velocity of the ball's center of mass and its orientation and angular velocity at release [1] with due consideration of aerodynamics. In our experiments, we measure and compute the complete dynamics of the ball during the entire pitching motion, including the instant the ball is released from the fingers, and during the subsequent flight of the ball to the catcher. Our subjects were instructed to pick the ball off of a tee, come to their set position on the mound, and then throw the ball to the catcher in an otherwise unencumbered manner. This sequence of events is readily identifiable as discussed in the following.

The IMU measures the angular velocity and acceleration in a non-inertial, "ball-fixed" reference frame denoted by the triad $(\hat{x}, \hat{y}, \hat{z})$ with origin collocated with the center of the IMU's accelerometer (point P) as shown in Fig. 2a. We introduce an inertial, "field-fixed" reference frame, defined by the triad $(\hat{X}, \hat{Y}, \hat{Z})$, with origin coincident with the ball center when in the tee as shown in Fig. 2b. The $\hat{Z}$ axis points vertically up, the $\hat{X}$ axis is horizontal and parallel to a line from the center of the pitcher's mound to the center of home plate, and the $\hat{Y}$ axis is defined by the right-hand rule.

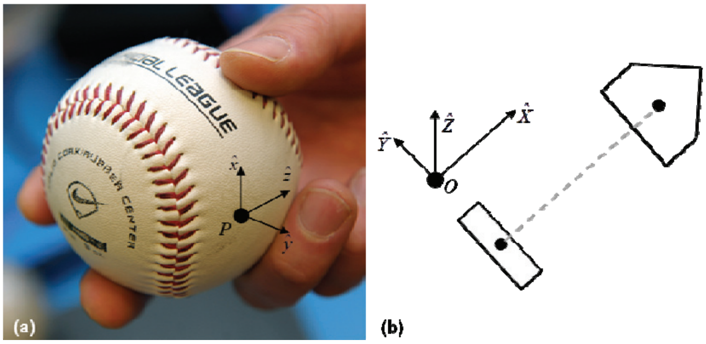

Fig. 2. Ball- (a) and field-fixed (b) reference frames

The transformation that relates these two frames can be computed from the angular velocity of the ball starting from a known ball orientation [11]. The initial orientation is deduced from the measured acceleration of the ball while at rest in the tee at the start of the trial. The accelerometer included in this IMU measures the acceleration of point P plus gravity. Resolving the measured acceleration ($\vec{a}_a$) in the field-fixed reference frame allows one to subtract off the gravity component to yield the acceleration of point P. The acceleration of the ball center is then a function of the acceleration of point P, the measured angular velocity, and angular acceleration which can be calculated numerically from the angular velocity. Direct integration of the ball center acceleration then yields ball center velocity.

It is well established that measurement noise and sensor drift significantly affect the accuracy of this calculation [12]. We are able to improve the accuracy of the velocity by making use of apriori knowledge of the ball kinematics to identify drift errors, and then subsequently account for them in the calculation of the ball center velocity by subtracting a best-fit error polynomial from the estimated velocity.

To demonstrate the accuracy of the IMU-calculated ball velocity, the three-dimensional motion of the ball was measured independently using a 10-camera high speed motion analysis system (VICON) calibrated such that marker errors for all ten cameras were less than 0.250 mm. The baseball, with embedded IMU, was enveloped in reflective tape and its 3-D position was measured by the VICON system at a frequency of 100Hz. The ball's position data was smoothed using a 6-point moving average technique and then differentiated to determine the velocity to minimize the effect of measurement noise on the calculation.

3. Results and Discussion

The drift error associated with integration of the IMU data is illustrated in Fig. 3a which shows the uncorrected velocity of the ball center. The red, green, and blue curves are the velocity histories in the $\hat{Z}$, $\hat{Y}$, and $\hat{X}$ directions respectively. The thin curves are the velocities as determined by the VICON system and the bolded curves are those determined using IMU data. It is clear from Fig. 3a that the difference between the VICON and IMU velocities increases with time for the velocity components along the $\hat{X}$ and $\hat{Y}$ axes, while the drift in the $\hat{Z}$ component is quite modest. In contrast, Fig. 3b illustrates the velocity components after employing the drift correction algorithm. The drift correction algorithm yields velocity components that agree closely with those determined from the VICON measurements.

Next, consider the ability for this technology to identify pitch type, which follows from the ability to accurately determine the release velocity (and angular velocity). To this end, the percent difference between the IMU- and VICON-derived release velocities is defined as

$$d_{cj,rel} = \sqrt{(V_{cj,rel} - \tilde{V}_{cj,rel})^2 / V_{cj,rel}{}^2}\text{, where } j = x,\ y,\ z \qquad (1)$$

where V and $\tilde{V}$ are the VICON- and IMU-derived velocities at release respectively. The resulting percent differences for a 5-sample set of throwing data are summarized in Table 1.

Table 1. Percent difference in IMU velocity components at release as compared to motion capture data

Error Component	Maximum (%)	Minimum (%)	5-Trial Mean (%)
$d_{cx,rel}$	6.2	0.1	3.5
$d_{cy,rel}$	5.1	0.1	1.9
$d_{cz,rel}$	9.8	0.4	4.0

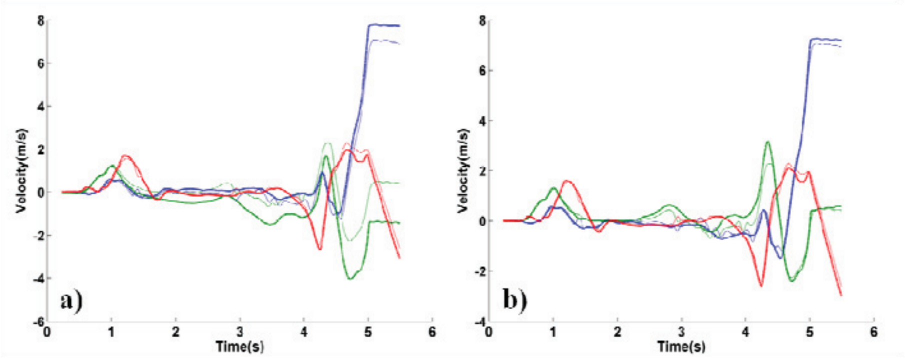

Fig. 3. Uncorrected (a) and corrected (b) X (blue), Y (green), and Z (red) velocity of the ball center as calculated using data from the IMU (thick, dashed) and the VICON motion capture system (thin, solid)

These results demonstrate that IMU-estimated release velocity remains within 4% of that estimated by the VICON system on average. In addition, the IMU provides the data needed to measure the ball angular velocity and orientation. Collectively, the ball angular velocity, orientation and velocity enable one to detect the type of pitch being thrown as evidenced by the results in Fig. 4.

The images of baseball release conditions reported in Fig. 4, for pitches thrown with modest linear and angular speed, confirm trends presented in [5,6]. Fig. 4a & 4b illustrate the release conditions for a fastball and change-up, respectively. These two pitches are thrown largely with backspin which will cause an aerodynamic lift force. Additionally, a small amount of lateral break develops due to the small side spin components of the angular velocity. In contrast, Fig. 4c shows that a curveball is released with largely top spin, and the resulting aerodynamic force accelerates the ball downwards. Like the fastball and change-up, small side-spin components create additional but small lateral break. Finally, Fig. 4d shows the release conditions for a slider which has largely side spin, but also a small top spin component. The side spin induces a large lateral break, while the topspin induces a small drop.

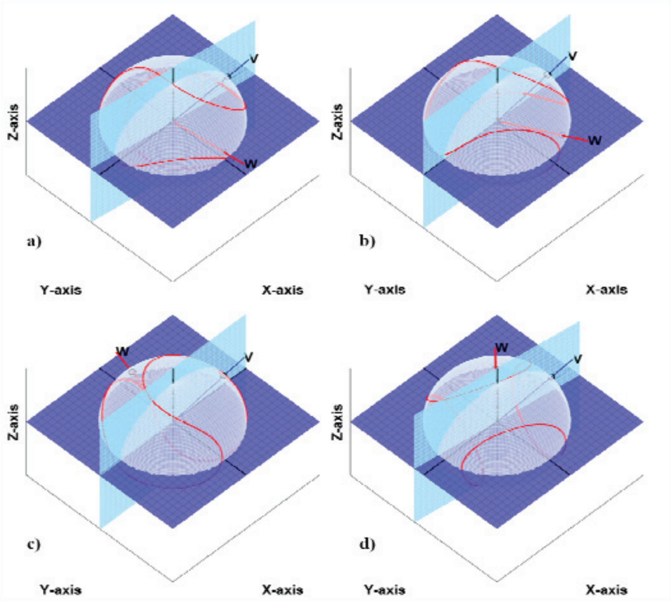

Fig. 4. IMU determined angular velocity (red, w), velocity (blue, v), and ball orientation at release for a fastball (a), change-up (b), curveball (c), and slider (d)

The position of the spin axis of the ball relative to the velocity of the ball center at release provides the essential information needed to evaluate whether the desired type of pitch is thrown correctly, to what degree the pitcher achieves that type of pitch and how consistently it is thrown. This provides powerful information for evaluating pitching performance.

4. Conclusions

The technology presented herein provides a low cost, highly portable and minimally intrusive measurement system to support pitcher training. The IMU-embedded baseball faithfully reproduces the release velocity of the ball to within 4% relative to that measured by motion-capture and also provides a direct measurement of the angular velocity of the ball at release for pitches that remain within the measurement range of the associated angular rate sensors. The velocity and angular velocity at release enables one to easily distinguish pitch types (Fig. 4) and the degree to which that pitch type was thrown. This quick visual, quantitative feedback will enable pitching coaches to accurately evaluate and thereby improve pitching performance.

Acknowledgements

R.M. gratefully acknowledges support provided by a National Science Foundation Graduate Student Fellowship.

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