IMU ARRAYS: THE BIOMECHANICS OF BASEBALL PITCHING

ERIC BERKSON MD, RYAN AYLWARD MS, JAMES ZACHAZEWSKI DPT, ATC, JOSEPH PARADISO PHD, THOMAS J. GILL MD
MASSACHUSETTS GENERAL HOSPITAL

ABSTRACT

Previous biomechanical studies have attempted to quantify the mechanics of throwing and to measure the forces sustained in the upper extremity during high-velocity pitching. Biomechanical testing of pitchers in its current state, however, is subject to inaccuracy and cumbersome to perform. Testing requires controlled laboratory conditions where "high-speed" cameras are set in fixed positions around the subject, and the motion of the arm is tracked with navigational markers affixed to the pitcher. Variables such as acceleration and velocity are derived from a series of calculations based on positional data. We hypothesized that direct measurements of acceleration and velocity could improve kinematic analysis of baseball pitching. To assess this hypothesis, a controlled validation study of a novel Inertial Measurement Unit (IMU) array was performed. Each IMU consists of three-dimensional accelerometers and gyroscopes, permitting direct measurements of acceleration and angular velocity. Simultaneous testing of a single professional baseball pitcher was undertaken utilizing both "high-speed" camera-based motion tracking and our newly developed IMU array. Results indicated an acceleration phase during the pitching cycle lasting 0.022 seconds. During this phase, traditional motion tracking cameras recorded four data points. Thirty data points were recorded by each IMU. The IMUs recorded 60.4g's of acceleration at the shoulder and 83.0g's of acceleration at the wrist. Acceleration over 100g's was documented at the hand. While no statistical comparison between systems was possible in this early proof-of-concept study, the IMU array successfully recorded appropriate rises in acceleration and velocity when compared to the camera-based motion-analysis system and offers the first direct measurement of acceleration in a professional pitcher. As such, the IMU array promises to provide more accurate kinematic measurements than alternative methods. The technique also allows measurements outside of controlled laboratory conditions and therefore could provide positive practical and clinical applications ranging from improved player training to injury prevention and rehabilitation.

INTRODUCTION

Pitching injuries have increased markedly over the past few decades. In 1973, Tullos noted that 50% of professional baseball pitchers at some point in their career experience elbow or shoulder pain sufficient enough to keep them from throwing.[1] Between 1989 and 1999, the number of pitchers who became disabled increased 54% and the number of days missed by pitchers increased by 58%.[2] This prevalence of injuries is not limited to professional athletes. Andrews examined 5-year periods within his practice and, comparing the two most recent five-year periods, noted twice as many elbow surgeries for professional pitchers, four times as many for collegiate pitchers, and six times as many for high school pitchers.[3]

Most pitching injuries are a result of repetitive microtrauma where repeated submaximal loads result in cumulative microtrauma to the soft tissues over time.[1, 4-7] These overuse injuries have been attributed to many factors including pitch counts, pitch types, pitch mechanics, physical conditioning, periodization, nutrition, and supplements. Changes due to improper mechanics, poor dynamic stability or muscle fatigue negatively influence performance and may increase vulnerability to injury.[8, 9] An understanding of the biomechanics of baseball pitching can assist in minimizing potential for injury, preventing overuse injuries, and evaluating rehabilitation protocols.

Previous biomechanical studies have attempted to characterize and quantify the mechanics of pitching and to understand the relationship between factors leading to injuries. Initial studies in the 60's and 70's were performed with visual examinations of stroboscopic images.[1] As technology has advanced, improved mechanisms of analysis have permitted more quantitative analysis. Today, computerized motion-tracking cameras are used to follow markers placed on the subject. Three-dimensional positional data of each body part is derived and velocity, acceleration, and forces calculated secondarily. Werner, Hawkins, and Gill utilized three 120 hertz cameras and

Eric Berkson M.D. is a Sports Medicine Fellow at Massachusetts General Hospital.
Ryan Aylward M.S. is a researcher at the MIT Media Laboratory at the Massachusetts Institute of Technology.
James Zachazewski D.P.T. A.T.C. is the Clinical Director of Sports Medicine at Massachusetts General Hospital and an Adjunct Assistant Clinical Professor at MGH Institute of Health Professions.
Joseph Paradiso Ph.D. is an Associate Professor at Massachusetts Institute of Technology and Sony Career Development Professor of Media Arts and Sciences. He is also the Co-Director of the Things That Think Consortium at the MIT Media Laboratory.
Thomas J. Gill, M.D. is an Associate Professor of Orthopaedic Surgery at Harvard Medical School and Medical Director of the Boston Red Sox.

Address correspondence to:

Thomas J. Gill, M.D.
Massachusetts General Hospital
55 Fruit Street, YAW 3G
Boston, MA 02114

video analysis to determine positional data.[10, 11] Andrews and the American Sports Medicine Institute (ASMI) utilized six 240 hertz motion tracking cameras to perform these same calculations.[3, 4, 8, 12-14]

Computerized tracking of the upper extremity, however, remains challenging. Numerous markers are affixed to the body, while multiple cameras are used to ensure that each marker is always in view. Ideal environments are required to ensure proper visualization by the cameras. For this reason, a specialized laboratory is usually required for accurate data capture. Although real-size pitching mounds have been built within these environments and playing conditions have been simulated, the constraints around data capture prevent direct application to live practice and game activities.

These analyses have also been challenging due to the magnitude of the velocities and accelerations involved. The acceleration phase of pitching lasts approximately 20-40 milliseconds. During this time, elbow extension velocities have been calculated between 2,500 and 4,500 deg/sec.[10, 13, 15, 16] Internal rotation of the shoulder has been approximated at 10,000 deg/sec.[10, 14] Accelerations of the arm, derived from the second derivative of the positional data, are estimated to be between 300,000 deg/sec^2 and 500,000 deg/sec^2.[16] At these extreme speeds and with analysis only at 240 hertz, only 4-6 points of measurements of the arm are possible, and smoothing errors are introduced with each level of analysis. With so few data points, calculations of acceleration simply exceed the resolution of these motion-tracking cameras.

The purpose of this proof-of-concept study was to develop and validate a new method of motion analysis that would not suffer from the same level of environmental and measurement constraints. During this study, a portable and wearable set of accelerometers and gyroscopes were used to directly measure velocity and acceleration about the elbow and shoulder during a baseball pitch. Over the past decade, accelerometers and gyroscopes have increased in accuracy and decreased in size and cost. These devices, which respectively measure acceleration and angular velocity, have been made small enough to become practical in real-world applications.[17] Accelerometers outside of medicine have been used to detect a falling laptop (ThinkPad Technologies) or to sense if airbag deployment is necessary. More recently, accelerometers have been used to measure lower extremity joint angles over time.[18-21] Wearable devices, with units on the leg and thigh, have been used to track activity levels of subjects wearing the apparatus.[17, 22, 23] In addition, wireless three-dimensional accelerometers combined with gyroscopes (Inertial Measurement Units — IMUs) have recently been utilized to measure inertia for gesture recognition by the MIT Media Lab.[24, 25]

For our study, we hypothesized that a portable IMU array could provide a direct measurement of the kinematics of baseball pitching at least as accurate as the current standard of camera-based tracking motion analysis. To assess this hypothesis, a controlled validation study evaluated the kinematics of a professional baseball pitcher, comparing our newly developed array of accelerometers and gyroscopes to the traditional "high-speed" tracking cameras.

METHODS

A pilot study of a prototype IMU array was completed during spring training 2006. After IRB approval and informed consent and under the direction of the subject's coach, a single professional baseball player underwent simultaneous biomechanical testing utilizing both a camera-based motion tracking system and our newly developed IMU array (Figure 1).

Figure 1: Wireless Inertial Measurement Unit
This prototype inertial measurement unit contains a three-dimensional 100G accelerometer, a three-dimensional gyroscope, and wireless transmission abilities. Operating at 1000 Hz, the unit is self-contained and powered by a lithium battery (on the right). Data is transmitted to a base station for processing.

A camera-based motion analysis system (XOS Technologies), employing "high-speed" cameras operating at 180 Hz, allowed positional tracking of each pitch. A series of 10 motion analysis cameras were set-up on a regulation-sized pitching mound (Figure 2). Subjects were fit with both passive electrodes for the camera-based motion analysis and a 6 segment wireless IMU array (Figure 3). Inertial measurement units were carefully affixed to the chest, upper arm, forearm,

Figure 2: High-speed Motion Tracking Cameras
Traditional biomechanical analyses utilize motion-tracking cameras in a controlled environment. In this study, a series of 10 high-speed motion analysis cameras were set-up on a regulation pitching mound to allow positional tracking of the subject. This was performed at 180Hz.

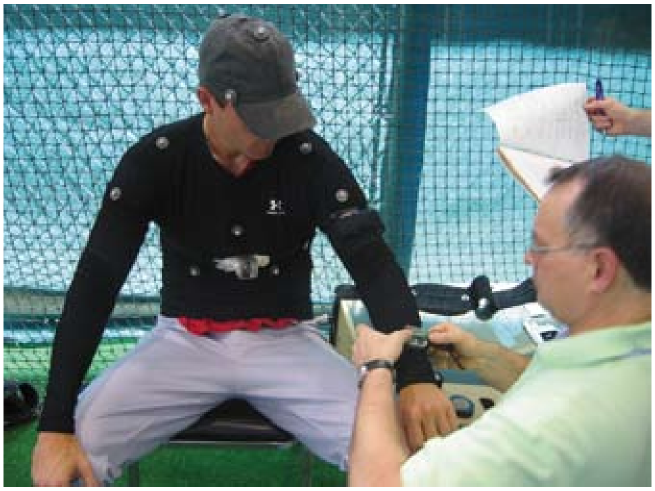

Figure 3: Motion Tracking Electrodes
The study subject was fit with multiple motion-analysis passive electrodes as well as a six segment wireless IMU. Inertial Measurement Units were applied to the chest, upper arm, forearm, and hand to allow independent measurements of each segment of the arm.

Figure 4: Calibration of motion-tracking sensors
A real-time three-dimensional video reconstruction of pitching kinematics was created utilizing motion-tracking software. A short calibration sequence was performed prior to each pitch.

and hand. Each battery powered IMU weighed approximately 45gm and operated at 1000Hz. Data from the IMU array was wirelessly transmitted to a base-station.

After calibration of each system (Figure 4), the pitcher threw a series of seven fastballs using a regulation baseball off a regulation pitcher's mound. Using positional data from the camera-based tracking system, real-time three-dimensional cartoon reconstructions of each pitch were performed (Figure 5). Kinematic parameters were calculated from simultaneous recordings of position, acceleration, and velocity by the two systems. The acceleration phase of the pitching cycle was isolated from each data and maximum acceleration and velocities compared at the wrist, shoulder, and hand.

RESULTS

Results are pictured in Figure 6 and indicate a pitching acceleration phase lasting 0.022 seconds. The high-speed motion-tracking camera system was able to capture four data points during this phase of the pitching cycle. The IMU array captured 30 data points during this same period. A rapid rise in elbow extension velocity and humeral internal rotation was recorded in both systems.

Figure 5: Three Dimensional reconstruction of Motion-Tracking Data
A real-time three-dimensional video reconstruction of pitching kinematics was created utilizing motion-tracking software. These reconstructions were compared with variations in IMU data to allow subjective evaluation of the quality of data.

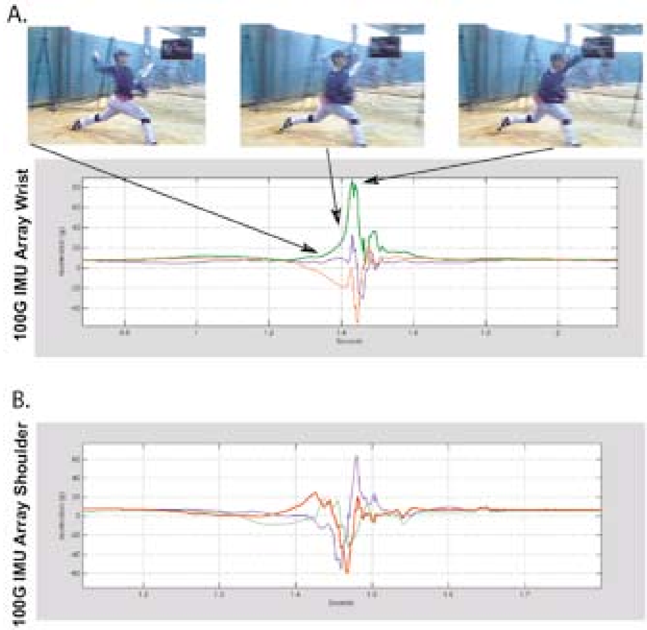

Figure 6: Inertial Measurement Unit Array Data
Direct measurements of acceleration and angular velocity were recorded at 1000Hz. Standard high-speed motion analysis synchronized to the IMU data indicated an appropriate rise in acceleration during the acceleration phase of the pitching cycle. (A) Acceleration data in three planes at the wrist indicate a maximum acceleration approaching 83g's at ball release. (B) At the shoulder, G forces are slight smaller (60g's) however, angular velocities increase as the distance from the center of rotation is smaller.

IMU calculations of internal rotation velocity at the shoulder approximated 12,000 deg/sec. 60.4g's (591 m/s^2) of acceleration was recorded by the IMU at the shoulder. At the wrist, 80g's of acceleration (784 m/s^2) was recorded at the endpoint of the acceleration phase of the pitching cycle. Further distally, at the hand, the IMU array documented greater than 100g's (980 m/s^2) of acceleration.

No statistical comparison between systems was possible in this early pilot study. Nonetheless, the IMU array recorded appropriate rises in acceleration and velocity when compared to the camera-based motion-analysis system. Subjective comparisons of three-dimensional reconstructions of each pitch with IMU array data indicated that fine movements of the arm during the pitching cycle were captured by the IMU array.

DISCUSSION

This proof-of-concept study was designed to validate a new method of biomechanical analysis using a portable and wearable set of accelerometers to analyze motion about the elbow and shoulder during a baseball pitch. A single professional baseball pitcher underwent simultaneous biomechanical testing with a traditional "high-speed" motion-analysis cameras tracking arm position at 180Hz as well as with our novel IMU array directly measuring arm accelerations and velocities at 1000Hz.

While one previous study almost 25 years ago attempted the use of an accelerometer to assess pitching biomechanics, limits in technology at the time prevented meaningful results.[26] To our knowledge, no further use of accelerometers to measure pitching has been published, and this study represents the first productive application of this technology to this effort.

While statistical comparison was not possible in this small pilot study, our results indicate that both systems recorded appropriate rises in acceleration and velocity throughout the pitching cycle. Subjective comparisons of 3D video reconstructions indicated that fine movements of the arm during the pitching cycle were appropriately recorded by the IMU array.

The IMU array captured almost six times more data during the acceleration phase of the pitching cycle alone when compared to the traditional motion-tracking analysis. This allows a more detailed evaluation of the forces involved in pitching than what is possible with traditional motion-analysis cameras. Furthermore, the IMU array directly measured three-dimensional accelerations and velocities thus avoiding the possibility of smoothing errors in the process of deriving acceleration and velocities from position data. Contrary to previous assumptions regarding acceleration, this initial analysis demonstrates acceleration within the acceleration phase to be non-linear (Figure 6). Given this finding, characterization of forces in the shoulder based on acceleration derived from traditional technology may be inadequate.

This study presents the first published values of maximal acceleration in the upper extremity of a professional baseball player. Moreover, as acceleration is directly proportional to force, future application of these measurements may allow greater accuracy in the calculation of forces in the shoulder and upper arm during the pitching cycle.

Internal rotation velocities at the shoulder during the acceleration phase of the pitching cycle measured in this subject approximated 12,000 deg/sec. This is faster (over 15%) than previously published data[10, 14] and could indicate that the published values of maximum velocity of internal rotation at the shoulder may be inaccurate and could be refined with a more complete analysis. Previous calculations of forces in the upper extremity would also be affected.

IMU arrays are self-contained and allow measurement of pitching parameters outside of an artificially controlled laboratory setting. As such, the technology more easily permits real world and longitudinal studies of the biomechanics of pitching. Future studies of biomechanics may take place on an actual playing field or even during a game. We anticipate that as technology advances and miniaturizes, changes in biomechanics may be tracked over time, throughout a single game, or even a career. This would potentially permit quantitative evaluations and, significant, real-world / real-time observations of the variation in forces in the pitching arm as it varies with pitch type, pitcher age, or even with fatigue. Similarly, changes to training routines and physical conditioning may be indicated based on a more robust and proactive monitoring mechanism. Alterations in pitching mechanics could be evaluated post-operatively and the effects of rehabilitation quantified.

Moreover, these same analyses could be applied to other overhead sports such as football or tennis, or even applied to the lower extremity for biomechanical evaluations outside of the laboratory in running sports. We hope to attain these goals with the continued development of this technology.

In conclusion, this pilot study demonstrated the plausible measurement of the biomechanics of pitching at speeds more than five times that of traditional tracking cameras. These wearable IMU's directly measure velocity and acceleration, providing the possibility of a new generation of precision in the measurement of the kinematics and kinetics of pitching. The measurement mechanism itself more easily allows measurements outside of controlled laboratory conditions. The scientific evaluations and real-time, quantifiable observations that such devices allow have wide-ranging practical and clinical applications for the overhead throwing athlete including injury prevention, conditioning / training direction, and post-operative rehabilitation. We plan to use this system to study the kinetics and kinematics of different types of pitches as well including fastballs, curveballs, change-ups, and sliders. This data would have significant impact on the rehabilitation and return to pitching of an injured player, as well as provide objective data on which to introduce new types of pitches to adolescent players.

References

1. **Tullos HS, King J.** Throwing Mechanism in Sports. Orthop Clin North Am 1973;4:709-20.
2. **Conte S, Requa RK, Garrick JG.** Disability days in major league baseball. Am J Sports Med 2001;29(4):431-6.
3. **Fleisig GS, Kingsley DS, Loftice JW, et al.** Kinetic Comparison Among the Fastball, Curveball, Change-up, and Slider in Collegiate Baseball Pitchers. Am J Sports Med 2005.
4. **Fleisig GS, Andrews JR, Dillman CJ, Escamilla RF.** Kinetics of baseball pitching with implications about injury mechanisms. Am J Sports Med 1995;23(2):233-9.
5. **Rizio L, Uribe JW.** Overuse injuries of the upper extremity in baseball. Clin Sports Med 2001;20(3):453-68.
6. **Chambless KM, Knudtson J, Eck JC, Covington LA.** Rate of injury in minor league baseball by level of play. Am J Orthop 2000;29(11):869-72.
7. **Torg JS, Pollack H, Sweterlitsch P.** The effect of competitive pitching on the shoulders and elbows of preadolescent baseball players. Pediatrics 1972;49(2):267-72.
8. **Andrews J, Wilk K.** Shoulder injuries in baseball. In: Andrews J, Wilk K, eds. The Athlete's Shoulder. New York: Churchhill Livingstone; 1994:369-89.
9. **Seaver T.** The Art of Pitching. New York: Hearst Books; 1984.
10. **Werner SL, Gill TJ, Murray TA, Cook TD, Hawkins RJ.** Relationships between throwing mechanics and shoulder distraction in professional baseball pitchers. Am J Sports Med 2001;29(3):354-8.
11. **Werner SL, Murray TA, Hawkins RJ, Gill TJ.** Relationship between throwing mechanics and elbow valgus in professional baseball pitchers. J Shoulder Elbow Surg 2002;11(2):151-5.
12. **Escamilla R, Fleisig G, Barrentine S, Zheng N, Andrews J.** Kinematic comparisons of throwing different types of baseball pitches. J Appl Biomech 1998;14:1-23.
13. **Werner SL, Fleisig GS, Dillman CJ, Andrews JR.** Biomechanics of the elbow during baseball pitching. J Orthop Sports Phys Ther 1993;17(6):274-8.
14. **Dillman CJ, Fleisig GS, Andrews JR.** Biomechanics of pitching with emphasis upon shoulder kinematics. J Orthop Sports Phys Ther 1993;18(2):402-8.
15. **Feltner M, Dapena J.** Dynamics of the shoulder and elbow joints of the throwing arm during a baseball picth. Int J Sport Biomech 1986;2:235-59.
16. **Pappas AM, Zawacki RM, Sullivan TJ.** Biomechanics of baseball pitching. A preliminary report. Am J Sports Med 1985;13(4):216-22.
17. **Chen K, Bassett D.** The Technology of Accerometry-Based Activity Monitors: Current and Future. Medicine & Science in Sports and Exercise 2005;37(11):S490-S500.
18. **Williamson R, Andrews BJ.** Detecting absolute human knee angle and angular velocity using accelerometers and rate gyroscopes. Med Biol Eng Comput 2001;39(3):294-302.
19. **Mayagoitia RE, Nene AV, Veltink PH.** Accelerometer and rate gyroscope measurement of kinematics: an inexpensive alternative to optical motion analysis systems. J Biomech 2002;35(4):537-42.
20. **Dejnabadi H, Brigitte J, Aminian K.** A New Approach to Accurate Measurement of Uniaxial Joint Angles Based on a Combination of Accelerometers and Gyroscopes. IEEE Transactions on Biomedical Engineering 2005;52(8):1478-84.
21. **Luinge HJ, Veltink PH.** Measuring orientation of human body segments using miniature gyroscopes and accelerometers. Med Biol Eng Comput 2005;43(2):273-82.
22. **Simcox S, Parker S, Davis GM, Smith RW, Middleton JW.** Performance of orientation sensors for use with a functional electrical stimulation mobility system. J Biomech 2005;38(5):1185-90.
23. **Trost SG, McIver KL, Pate RR.** Conducting accelerometer-based activity assessments in field-based research. Med Sci Sports Exerc 2005;37(11 Suppl):S531-43.
24. **Benbasat A.** An Inertial Measurement Unit for User Interfaces [S.M. Thesis]; 2000.
25. **Benbasat A, Paradiso J.** An Inertial Measurement Framework for Gesture Recognition and Applications. In: Wachsmuth I, Sowa T, eds. Gesture and Sign Language in Human-Computer Interaction. London, UK: Springer-Verlag; 2002.
26. **Hang YS, Lippert FG, 3rd, Spolek GA, Frankel VH, Harrington RM.** Biomechanical study of the pitching elbow. Int Orthop 1979;3(3):217-23.