Technology Used in the Prevention and Treatment of Shoulder and Elbow Injuries in the Overhead Athlete

Evan E. Vellios¹ · Sridhar Pinnamaneni¹ · Christopher L. Camp² · Joshua S. Dines¹

Published online: 30 May 2020

© Springer Science+Business Media, LLC, part of Springer Nature 2020

Abstract

Purpose of Review To review the current technology available for the prevention and treatment of shoulder and elbow injuries in the overhead athlete.

Recent Findings Shoulder and elbow injuries are common in recreational and high-level overhead athletes. Injury prevention in these athletes include identifying modifiable risk factors, offering effective preventative training programs, and establishing safe return-to-sport criteria. The advent and use of technologies and wearable devices with concomitant development of software and data analytic programs has significantly changed the role of sports technology in injury identification and prevention. Over the last few decades, leveraging new technologies to better understand and treat patients has become an increasing focus of healthcare. Technologies currently being applied to the treatment of the overhead athlete include kinesiotaping, heart rate monitors, accelerometers/gyroscopes, dynamometers/force plates, camera-based monitoring systems (optical motion analysis), and inertial sensor monitoring units.

Summary Advances in technology have made it possible to acquire large amounts of data on athletes that may be used to guide treatment and injury prevention programs; however, literature validating the clinical efficacy of many of these technologies is limited. Further research is needed to continue to allow team physicians to provide better, cost-efficient, and individualized care to the overhead athlete using technology.

Keywords Technology · Shoulder and elbow · Analytics · Sports science · Overhead athlete · Injury prevention

Introduction

Shoulder and elbow injuries are common in recreational and high-level overhead athletes. There have been many

approaches to understand and treat these injuries. Overhead athletes have adaptive changes in their shoulder and elbow biomechanics and movement strategies. Understanding these adaptive changes is important when considering the pathophysiology behind overload injuries of the shoulder and elbow in these populations. Injury prevention in these athletes include identifying modifiable risk factors, offering effective preventative training programs, and establishing safe return-to-sport criteria.

The advent and use of technologies and wearable devices with concomitant development of software and data analytic programs has significantly changed the role of sports technology in injury identification and prevention. Over the last several decades, leveraging new technologies to better understand and treat patients has become an increasing focus of healthcare [1]. There are a number of data gathering technologies that can be used by sports teams and athletes to help collect and analyze data. These include using wearable devices, smart apparel, and global positioning devices to help collect accelerometry, heart rate, and sleep data.

This article is part of the Topical Collection on *Injuries in Overhead Athletes*

✉ Evan E. Vellios
evellios@gmail.com

Sridhar Pinnamaneni
pinnamanenis@HSS.EDU

Christopher L. Camp
Camp.Christopher@mayo.edu

Joshua S. Dines
DinesJ@HSS.EDU

¹ Sports Medicine and Shoulder Surgery Service, Sports Medicine Institute, Hospital for Special Surgery, 535 East 70th Street, New York, NY 10021, USA

² Division of Sports Medicine, Department of Orthopaedics, Mayo Clinic, Rochester, MN, USA

There is increasing evidence to suggest identifying risk factors for injury in sports using this data can help direct injury prevention programs [2•]. Furthermore, advances in physical therapy and athletic training have led to the use of kinesiotaping and dynamometry to enhance upper extremity function and correct muscular imbalances that could lead to potential injury. The purpose of this article is to identify current technologies used to prevent and treat shoulder and elbow injuries in overhead sport athletes.

Kinesiotaping

Kinesiotaping is the use of elastic, quick drying tape to help manage pain and dysfunction in athletes. Kinesiotaping was initially developed in the 1970s but was popularized in the early 2000s for use in athletes. Various authors and studies have theorized the mechanisms of the proposed benefits of kinesiotaping. These theories include increased blood flow to the affected area, improved mechanical stabilization, and improved proprioception [3–5]. In the management of subacromial impingement syndrome, reported results of using kinesiotaping as adjunct therapy are conflicting and weak for improving pain, range of motion and muscle strength [6]. Combining kinesiotaping with physiotherapy interventions can be considered when treating patients with subacromial impingement syndrome; however, further randomized, controlled trials need to be completed to fully understand the role of kinesiotaping in treatment of shoulder impingement syndrome [6].

In terms of scapular mechanics, there have been numerous studies showing that rigid and elastic taping methods can improve scapular kinematics in the sagittal and scapular planes [7–10]. In patients with subacromial impingement syndrome, kinesiotaping of the scapula seems to decrease the activity in the upper trapezius during shoulder abduction leading to reduced functional impingement with overhead activities [10]. Specifically in baseball players with subacromial impingement, a randomized study between elastic taping and placebo taping showed that elastic taping resulted in positive changes in scapular motion and muscle performance [8]. Another randomized study in overhead athletes with subacromial impingement syndrome showed that elastic taping can have positive effects on scapular joint position sense and movement control [9]. While the results of these studies in overhead athletes seem to support the use of elastic taping as a treatment aid in managing shoulder impingement problems, future studies with a longer period of follow-up and clinical measurement might help to clarify the clinical effect and mechanisms of elastic taping in these patient populations.

Heart Rate Monitoring Device

Heart rate is commonly used to objectively measure physical activity and energy expenditure during large muscle dynamic exercise [11]. Heart rate recording is a relatively low cost, noninvasive method of getting information on the pattern of physical activity in an individual. Multiple studies have shown that changes in heart rate and exercise heart rate variability are moderately associated with changes in athletic performance and cardiac function [12–14].

Over the last decade, technologic advances have allowed wearable technology devices to capture heart rate in addition to monitoring movement. These technologies can capture both real time heart rates and also provide analytic data on net heart rate, heart rate variability, and heart rate trends. This information can help understand the various components of physical activity including frequency, intensity, and duration. It can also be used in collaboration with data analytics that can enhance training responses, customized exercise programs, and athlete preparation [2•, 14, 15•, 16]. While there have been multiple studies using heart rate monitoring devices in the athletic populations, there has been limited data specifically in the overhead athlete. There a number of available heart rate monitoring devices including Zoom HRV (heart rate variability), Polar H7, Apple Watch, Suunto Ambit3, WHOOP tracker, etc.

Accelerometer/Gyroscopes

Historically, pedometers were the only technology to help understand movement of an athlete. With technologic advances, the focus has turned towards understanding the body's movement in space and also estimation of energy expenditure. With the use of transducers and electrodes, accelerometers and gyroscopes are used to understand motion in the 3 dimensions [2•, 17]. The real-time data from these devices can be used to understand athletic performance both during training and sport. These devices have the added benefit of monitoring sleep duration and sleep levels. Application of these technologies have been described in a number of sports including swimming, ice hockey, American football, basketball, rugby, baseball, and badminton [18–22]. In swimmers, accelerometers have the potential to understand individual swimming profiles, acceleration profiles, and specific stroke technique [22]. This information can help with personalized coaching techniques and injury prevention [22]. In badminton players, three-axis accelerometers have been able to characterize and provide feedback during different parts of the swing and during the badminton clear shot [17]. Examples of these available devices include the Apple Watch, Fitbit, Microsoft band, and Nike+ FuelBand. Specific applications for prevention of shoulder and elbow injuries in the overhead athlete include

using accelerometers and gyroscopes to measure and analyze body motion, elbow torque, and arm position^{21,718,19,20,21,22}. Understanding and analyzing this data can help elucidate how to prevent shoulder and elbow injuries by identifying modifiable risk factors. Examples of these technologies include the Motus Sleeve, which will be further discussed below in the “[Inertial Sensor Monitoring Units](#)” section.

Dynamometry

Shoulder injuries have been shown to be more common in athletes performing overhead sports especially during the late cocking, acceleration and deceleration phases of throwing due to the immense forces placed on the static and dynamic stabilizers of the glenohumeral joint [23]. Furthermore, strength imbalances between shoulder internal and external rotators have been shown to predispose throwing athletes to injury [24, 25]. As a result, dynamometers have been used by physicians, physical therapists, and athletic trainers to objectively quantify muscle force (pounds, ounces, or Newtons) produced by specific muscle groups in order to guide strengthening programs for injury prevention and rehabilitation. Currently, there are two main forms of dynamometry, i.e., hand-held and fixed frame systems.

Hand-Held

Hand-held dynamometry (HHD) consists of a hand-held force sensor that is worn or held by the tester as the patient exerts a force against the tester in order to measure the force production of the specific muscle group being tested. HHD has become an increasingly used tool in the field of sports medicine and injury prevention because it is portable, user-friendly, and cheaper than traditional isokinetic measuring devices [26]. Furthermore, multiple studies have validated the reliability of HHD devices for the measurement of shoulder internal/external isometric strength measurements in adolescent and adult patient populations regardless of patient positioning (neutral vs 90-90) or type of dynamometer used [27–32]. Studies using HHD in professional baseball pitchers have shown that decreased pre-season external rotation (ER) strength is associated with in-season throwing injuries requiring surgical intervention [33•]. Additional studies have used HHD to quantify muscle fatigue in professional baseball and softball pitchers after pitching as a tool to monitor pitch counts in order to enhance performance and avoid injury [34, 35]. In softball pitchers evaluated before and after pitching performances using a HHD, hip and scapular muscles were shown to have profound fatigue, emphasizing the importance of strength and conditioning of proximal musculature in these athletes [34]. When assessing bilateral shoulders in college baseball pitchers before and after pitching performances using

a HHD, there was a trend towards increased baseline internal rotation strength with significant selective postgame fatigue, and weakness in baseline empty can test with minimal post-game fatigue [35]. While others have used HHD to differentiate between full thickness and partial thickness RTC tears in patients with shoulder impingement and/or monitor healing following rotator cuff surgery [36, 37]. Despite these applications, HHD is not without potential limitations. Some studies have shown that the accuracy and reliability of HHD devices may be limited by the strength of the tester, the strength of the muscle group being tested, and the stability of the patient and the device during the testing [38–41].

Fixed Frame

Fixed frame dynamometry has been used as an alternative to HHD in order to expand its applications to larger lower extremity muscle groups and increase the reliability of the measurements being taken [42, 43]. Traditionally, fixed frame systems (Kin-Com) have been large, expensive, non-portable, and limited to a laboratory setting. The patient applies force to a fixed frame construct allowing the device to record force output in real time under a variety of different conditions (isometric, isokinetic, eccentric/concentric phases). Recently, portable fixed frame dynamometry devices (Groinbar, Nordbord, ForceFrame, KT 360) have been developed to allow quick and reproducible isometric training and strength testing for the neck, ankle, hip, knee, and shoulder muscle groups. These devices come with complex proprietary algorithms that use the data provided by the patient in order to create individualized training regimens. Currently, there is only one study documenting the validity of one of these new portable fixed frame systems (Groinbar) with regards to correlating hip adductor strength and groin pain in professional Australian rugby players [44]. Similarly, Sparta Science has developed a portable force plate system (Sparta Scan) that can be used to assess an athlete's core and lower extremity strength, movement, balance, and stability in order to determine injury risk. In fact, Mayberry et al. in a study of professional baseball pitchers showed that using this tool to examine eccentric rate of force development (ERFD), average vertical concentric force (AVCF), and concentric vertical impulse (CVI) in pitchers performing a countermovement jump during the pre-season could help predict in-season upper extremity injury [45•]. Despite limited data, many professional sports teams in Major League Baseball (MLB), the National Basketball Association (NBA), and the National Football League (NFL) have begun to use these portable fixed frame and platform systems for pre-season screening, in-season training, post-injury/surgery rehabilitation, and weekly performance testing.

Camera-Based Monitoring Systems (Motion Analysis)

Traditional camera-based monitoring systems consist of a series of cameras surrounding a single athlete donned with upwards of 40 reflective markers attached to bony prominences who is then asked to perform a desired motion (i.e., baseball pitch) so that kinematic data may be acquired [46, 47]. This technology has been effectively applied to determining injury risk for overhead athletes across multiple sports including baseball, tennis, and water polo [48–50]. More recently, marker-less video-based systems have been developed in order to capture complex motions of individual athletes while performing in practices or games [51]. SportsVU (STATS) is an observational camera-based monitoring system used to capture the X, Y, and Z positioning of individual athletes twenty-five times per second [2•]. SportsVU technology has been installed in every NBA arena and is used to analyze basketball player acceleration, dribbling tendencies, shot selection, ball location, and defender proximity as it relates to shooting efficiency. Furthermore, real-time performance data calculated during games is used to help guide player minute management and therefore decrease the risk of fatigue injury [2•]. Despite no published data on its efficacy in enhancing player performance or preventing injury, similar observational camera-based monitoring systems have been implemented in international soccer as well as the NFL.

Inertial Sensor Monitoring Units

Inertial sensor monitoring units (IMUs) are small portable microelectromechanical systems attached to a patient's body, and used to track limb and/or trunk motion over the duration of a certain activity. Recently, IMUs have been applied to the throwing athlete as a way to quantify throwing workloads in order to prevent overuse injuries and guide rehabilitation protocols [52]. Benefits of IMUs over traditional camera-based monitoring systems include decreased cost, and the ability to monitor player postures and workloads in a game/practice setting outside of the laboratory without the need for full-body markers. Furthermore, IMUs may be more accurate at capturing body segment motion for high velocity activities such as pitching since they are not affected by visual artifacts or changes in background light [53]. During pitching, the arm rotates around the shoulder joint at roughly 7000°/s which is the fastest human recorded body movement [47]. IMUs use complex algorithms to reconstruct arm torque, rotation velocities, trajectories, and the forces placed on the shoulder and elbow during throwing [54]. These measurements may help physicians, athletic trainers, and sports scientists guide training modifications, rehabilitation protocols, and return to sport [53].

IMUs may consist of a single (MotusBASEBALL sleeve) or multiple wearable segment nodes (Sportsemble, CyberGlove, etc.) [52–56]. Studies by Camp et al. and Boddy et al. have validated the accuracy of the MotusBASEBALL sleeve for determining arm slot (angle between forearm and ground at ball release), shoulder rotation (maximum shoulder external rotation relative to the ground), arm speed (rotational velocity of the forearm), and shoulder/elbow stress measurements (torque) compared with optical motion capture analysis [56, 57•]. Furthermore, IMUs have been shown to be as accurate as optical motion capture analysis with force plates at determining peak pelvis and hand acceleration in baseball players batting [55]. A study by Leafblad et al. using the MotusBASEBALL sleeve showed that in adults, increased ball velocity does not necessarily mean increased elbow torque, as pitching from the mound (60 ft) produced the same amount of elbow varus torque as a long toss of 120 ft. [58] The results of this study imply that adult baseball players recovering from surgery/injury may be able to return to mound pitching earlier than previously thought and that IMUs may be used to create throwing protocols tailored to individual athletes. Similarly, a study by Dowling et al. performed in high school athletes showed that longer distance throwing resulted in increases in arm speed and shoulder rotation with a corresponding increase in elbow varus torque up to 37 m [59]. This study demonstrates that long toss programs in the high school athlete help to increase shoulder strength and range of motion but may increase risk of injury due to increased elbow varus torque beyond a certain distance. The availability, affordability, and ease of use have allowed IMU's to become a prominent component of sports performance monitoring in the overhead athlete at the high school, collegiate, and professional levels.

Conclusions

Advances in technology have made it possible to acquire large amounts of data on athletes that may be used to guide treatment and injury prevention programs. It is the responsibility of the team physician to be familiar with these different technologies so that he or she can effectively coordinate care between the many different facets of the medical team (strength and conditioning, sports performance, primary care, surgery, nutrition, and athletic training) and the athlete. Continued application of these technologies will allow the team physician to provide better, cost-efficient, and individualized care to the overhead athlete.

Compliance with Ethical Standards

Conflict of Interest The authors declare they have no conflicts of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

References

Papers of particular interest, published recently, have been highlighted as:

- Of importance

1. Anoushiravani AA, Patton J, Sayeed Z, El-Othmani MM, Saleh KJ. Big data, big research: implementing population health-based research models and integrating care to reduce cost and improve outcomes. *Orthop Clin North Am.* 2016;47:717–24. <https://doi.org/10.1016/j.ocl.2016.05.008>.
2. Sikka RS, Baer M, Raja A, Stuart M, Tompkins M. Analytics in sports medicine: implications and responsibilities that accompany the era of big data. *J Bone Jt Surg Am Vol.* 2019. <https://doi.org/10.2106/JBJS.17.01601> **Technology is becoming a major component of Sports MedicineThe team physician needs to be aware of emerging technology types so that he/she can effectively guide medical care for athletes.**
3. Ernst GP, Kawaguchi J, Saliba E. Effect of patellar taping on knee kinetics of patients with patellofemoral pain syndrome. *J Orthop Sports Phys Ther.* 1999;29:661–7. <https://doi.org/10.2519/jospt.1999.29.11.661>.
4. Kneeshaw D. Shoulder taping in the clinical setting. *J Bodyw Mov Ther.* 2002;6:2–8. <https://doi.org/10.1054/jbmt.2001.0233>.
5. Kase K, Wallis J, Kase T. Clinical therapeutic applications of the kinesio taping method. Tokyo: Japan Ken I kai Co Ltd; 2003.
6. Saracoglu I, Emuk Y, Taspinar F. Does taping in addition to physiotherapy improve the outcomes in subacromial impingement syndrome? A systematic review. *Physiother Theory Pract.* 2018;34:251–63. <https://doi.org/10.1080/09593985.2017.1400138>.
7. Shaheen AF, Bull AMJ, Alexander CM. Rigid and elastic taping changes scapular kinematics and pain in subjects with shoulder impingement syndrome; an experimental study. *J Electromyogr Kinesiol.* 2015;25:84–92. <https://doi.org/10.1016/j.jelekin.2014.07.011>.
8. Hsu YH, Chen WY, Lin HC, Wang WTJ, Shih YF. The effects of taping on scapular kinematics and muscle performance in baseball players with shoulder impingement syndrome. *J Electromyogr Kinesiol.* 2009;19:1092–9. <https://doi.org/10.1016/j.jelekin.2008.11.003>.
9. Shih YF, Lee YF, Chen WY. Effects of kinesiology taping on scapular reposition accuracy, kinematics, and muscle activity in athletes with shoulder impingement syndrome: a randomized controlled study. *J Sport Rehabil.* 2018;27:560–9. <https://doi.org/10.1123/jsr.2017-0043>.
10. Selkowitz DM, Chaney C, Stuckey SJ, Vlad G. The effects of scapular taping on the surface electromyographic signal amplitude of shoulder girdle muscles during upper extremity elevation in individuals with suspected shoulder impingement syndrome. *J Orthop Sports Phys Ther.* 2007;37:694–702. <https://doi.org/10.2519/jospt.2007.2467>.
11. Strath SJ, Swartz AM, Bassett J, O'Brien WL, King GA, Ainsworth BE. Evaluation of heart rate as a method for assessing moderate intensity physical activity. *Med Sci Sports Exerc.* 2000;32:S465–70. <https://doi.org/10.1097/00005768-200009001-00005>.
12. Buchheit M, Simpson MB, Al Haddad H, Bourdon PC, Mendez-Villanueva A. Monitoring changes in physical performance with heart rate measures in young soccer players. *Eur J Appl Physiol.* 2012;112:711–23. <https://doi.org/10.1007/s00421-011-2014-0>.
13. Borresen J, Lambert ML. Autonomic control of heart rate during and after exercise: measurements and implications for monitoring training status. *Sports Med.* 2008;38:633–46. <https://doi.org/10.2165/00007256-200838080-00002>.
14. Mourot L, Bouhaddi M, Tordi N, Rouillon JD, Regnard J. Short- and long-term effects of a single bout of exercise on heart rate variability: comparison between constant and interval training exercises. *Eur J Appl Physiol.* 2004;92:508–17. <https://doi.org/10.1007/s00421-004-1119-0>.
15. Schmitt L, Regnard J, Millet GP. Monitoring fatigue status with HRV measures in elite athletes: an avenue beyond RMSSD? *Front Physiol.* 2015. <https://doi.org/10.3389/fphys.2015.00343> **Heart rate variability (HRV) monitoring may be used as a tool to assess athlete fatigue. HRV spectral analysis has shown that HRV profiles are independent in the standing and supine positions and can be used to create sub-categories of athlete fatigue. Understanding this information may improve recovery in athletes performing in high level activities.**
16. Berkoff DJ, Cairns CB, Sanchez LD, Moorman CT. Heart rate variability in elite american track-and-field athletes. *J Strength Cond Res.* 2007;21:227–31. <https://doi.org/10.1519/00124278-200702000-00041>.
17. Mineta T, Kobayashi S, Watanabe Y, Kanauchi S, Nakagawa I, Suganuma E, et al. Three-axis capacitive accelerometer with uniform axial sensitivities. *J Micromech Microeng.* 1996;6:431–5. <https://doi.org/10.1088/0960-1317/6/4/010>.
18. Stetter BJ, Buckeridge E, Von Tscharnar V, Nigg SR, Nigg BM. A novel approach to determine strides, ice contact, and swing phases during ice hockey skating using a single accelerometer. *J Appl Biomech.* 2016;32:101–6. <https://doi.org/10.1123/jab.2014-0245>.
19. Brennan JH, Mitra B, Synnot A, McKenzie J, Willmott C, McIntosh AS, et al. Accelerometers for the assessment of concussion in male athletes: a systematic review and meta-analysis. *Sports Med.* 2017;47:469–78. <https://doi.org/10.1007/s40279-016-0582-1>.
20. Schelling X, Torres L. Accelerometer load profiles for basketball-specific drills in elite players. *J Sports Sci Med.* 2016.
21. Eagles AN, Lovell DI. Changes in sleep quantity and efficiency in professional rugby union players during home-based training and match play. *J Sports Med Phys Fitness.* 2016.
22. Callaway AJ, Cobb JE, Jones I. A comparison of video and accelerometer based approaches applied to performance monitoring in swimming. *Int J Sports Sci Coach.* 2009;4:139–53. <https://doi.org/10.1260/1747-9541.4.1.139>.
23. Wilk KE, Obma P, Simpson CD, Cain EL, Dugas J, Andrews JR. Shoulder injuries in the overhead athlete. *J Orthop Sports Phys Ther.* 2009;39:38–54. <https://doi.org/10.2519/jospt.2009.2929>.
24. Escamilla RF, Andrews JR. Shoulder muscle recruitment patterns and related biomechanics during upper extremity sports. *Sports Med.* 2009;39:569–90. <https://doi.org/10.2165/00007256-200939070-00004>.
25. Hams AH, Evans K, Adams R, Waddington G, Witchalls J. Shoulder internal and external rotation strength and prediction of subsequent injury in water-polo players. *Scand J Med Sci Sports.* 2019;29:1414–20. <https://doi.org/10.1111/sms.13459>.
26. Johansson FR, Skillgate E, Lapauw ML, Clijmans D, Deneulin VP, Palmans T, et al. Measuring eccentric strength of the shoulder external rotators using a handheld dynamometer: reliability and validity. *J Athl Train.* 2015;50:719–25. <https://doi.org/10.4085/1062-6050-49.3.72>.
27. Sullivan SJ, Chesley A, Hebert G, McFaull S, Scullion D. The validity and reliability of hand-held dynamometry in assessing isometric external rotator performance. *J Orthop Sports Phys Ther.* 1988;10:213–7. <https://doi.org/10.2519/jospt.1988.10.6.213>.

28. Stratford PW, Balsor BE. A comparison of make and break tests using a hand-held dynamometer and the Kin-Com. *J Orthop Sports Phys Ther.* 1994;19:28–32. <https://doi.org/10.2519/jospt.1994.19.1.28>.
29. Magnusson SP, Gleim GW, Nicholas JA. Subject variability of shoulder abduction strength testing. *Am J Sports Med.* 1990;18:349–53. <https://doi.org/10.1177/036354659001800403>.
30. Cools AM, De Wilde L, van Tongel A, Ceysens C, Ryckewaert R, Cambier DC. Measuring shoulder external and internal rotation strength and range of motion: comprehensive intra-rater and inter-rater reliability study of several testing protocols. *J Shoulder Elb Surg.* 2014;23:1454–61. <https://doi.org/10.1016/j.jse.2014.01.006>.
31. Hébert LJ, Maltais DB, Lepage C, Saulnier J, Crête M, Perron M. Isometric muscle strength in youth assessed by hand-held dynamometry: a feasibility, reliability, and validity study. *Pediatr Phys Ther.* 2011;23:289–99. <https://doi.org/10.1097/PEP.0b013e318227ccff>.
32. Hayes K, Walton JR, Szomor ZL, Murrell GAC. Reliability of 3 methods for assessing shoulder strength. *J Shoulder Elb Surg.* 2002;11:33–9. <https://doi.org/10.1067/mse.2002.119852>.
33. Byram IR, Bushnell BD, Dugger K, Charron K, Harrell FE, Noonan TJ. Preseason shoulder strength measurements in professional baseball pitchers: identifying players at risk for injury. *Am J Sports Med.* 2010. <https://doi.org/10.1177/0363546509360404>. **Decreased pre-season external rotation strength in the pitching shoulder of professional baseball players measured via hand-held dynamometry correlates with an increased risk of in season upper extremity injury.**
34. Corben JS, Cerrone SA, Soviero JE, Kwiecien SY, Nicholas SJ, McHugh MP. Performance demands in softball pitching: a comprehensive muscle fatigue study. *Am J Sports Med.* 2015;43:2035–41. <https://doi.org/10.1177/0363546515588179>.
35. Mullaney MJ, McHugh MP, Donofrio TM, Nicholas SJ. Upper and lower extremity muscle fatigue after a baseball pitching performance. *Am J Sports Med.* 2005;33:108–13. <https://doi.org/10.1177/0363546504266071>.
36. Millican JP, Murrell GAC. Can handheld dynamometers diagnose partial-thickness rotator cuff tears? *Should Elb.* 2012;4:100–5. <https://doi.org/10.1111/j.1758-5740.2011.00173.x>.
37. Roddey TS, Cook KF, O'Malley KJ, Gartsman GM. The relationship among strength and mobility measures and self-report outcome scores in persons after rotator cuff repair surgery: impairment measures are not enough. *J Shoulder Elb Surg.* 2005. <https://doi.org/10.1016/j.jse.2004.09.023>.
38. Wikholm JB, Bohannon RW. Hand-held dynamometer measurements: tester strength makes a difference. *J Orthop Sports Phys Ther.* 1991;13:191–8. <https://doi.org/10.2519/jospt.1991.13.4.191>.
39. Kelln BM, McKeon PO, Gontkof LM, Hertel J. Hand-held dynamometry: reliability of lower extremity muscle testing in healthy, physically active, young adults. *J Sport Rehabil.* 2008;17:160–70. <https://doi.org/10.1123/jsr.17.2.160>.
40. Lesnak J, Anderson D, Farmer B, Katsavelis D, Grindstaff TL. Validity of hand-held dynamometry in measuring quadriceps strength and rate of torque development. *Int J Sports Phys Ther.* 2019. <https://doi.org/10.26603/ijst20190180>.
41. Mentiply BF, Perraton LG, Bower KJ, Adair B, Pua YH, Williams GP, et al. Assessment of lower limb muscle strength and power using hand-held and fixed dynamometry: a reliability and validity study. *PLoS One.* 2015;10:e0140822. <https://doi.org/10.1371/journal.pone.0140822>.
42. Sung KS, Yi YG, Shin HI. Reliability and validity of knee extensor strength measurements using a portable dynamometer anchoring system in a supine position. *BMC Musculoskelet Disord.* 2019;20:320. <https://doi.org/10.1186/s12891-019-2703-0>.
43. Kolber MJ, Beekhuizen K, Cheng MSS, Fiebert IM. The reliability of hand-held dynamometry in measuring isometric strength of the shoulder internal and external rotator musculature using a stabilization device. *Physiother Theory Pract.* 2007;23:119–24. <https://doi.org/10.1080/09593980701213032>.
44. Ryan S, Kempton T, Pacecca E, Coutts AJ. Measurement properties of an adductor strength-assessment system in professional Australian footballers. *Int J Sports Physiol Perform.* 2019;14:256–9. <https://doi.org/10.1123/ijsp.2018-0264>.
45. Mayberry J, Mullen S, Murayama S. What can a jump tell us about elbow injuries in professional baseball pitchers? *Am J Sports Med.* 2020. <https://doi.org/10.1177/0363546520905543>. **Professional baseball pitchers performed a series of countermovement jump tests on a force plate with proprietary algorithms to examine eccentric rate of force development (ERFD), average vertical concentric force (AVCF) and concentric vertical impulse (CVI) during the pre-season and showed that lower extremity weakness could help predict in season upper extremity injury.**
46. Richards JG. The measurement of human motion: a comparison of commercially available systems. *Hum Mov Sci.* 1999;18:589–602. [https://doi.org/10.1016/S0167-9457\(99\)00023-8](https://doi.org/10.1016/S0167-9457(99)00023-8).
47. Fleisig GS, Andrews JR, Dillman CJ, Escamilla RF. Kinetics of baseball pitching with implications about injury mechanisms. *Am J Sports Med.* 1995;23:233–9. <https://doi.org/10.1177/036354659502300218>.
48. Martin C, Bideau B, Ropars M, Delamarche P, Kulpa R. Upper limb joint kinetic analysis during tennis serve: assessment of competitive level on efficiency and injury risks. *Scand J Med Sci Sports.* 2014;24:700–7. <https://doi.org/10.1111/sms.12043>.
49. Abrams GD, Sheets AL, Andriacchi TP, Safran MR. Review of tennis serve motion analysis and the biomechanics of three serve types with implications for injury. *Sport Biomech.* 2011;10:378–90. <https://doi.org/10.1080/14763141.2011.629302>.
50. Abrams GD, Harris AHS, Andriacchi TP, Safran MR. Biomechanical analysis of three tennis serve types using a markerless system. *Br J Sports Med.* 2014;48:339–42. <https://doi.org/10.1136/bjsports-2012-091371>.
51. Perš J, Bon M, Kovačič S, Šibila M, Dežman B. Observation and analysis of large-scale human motion. *Hum Mov Sci.* 2002;21:295–311. [https://doi.org/10.1016/S0167-9457\(02\)00096-9](https://doi.org/10.1016/S0167-9457(02)00096-9).
52. Rawashdeh SA, Rafeldt DA, Uhl TL. Wearable IMU for shoulder injury prevention in overhead sports. *Sensors (Switzerland).* 2016;16. <https://doi.org/10.3390/s16111847>.
53. Lapinski M, Medeiros CB, Scarborough DM, et al. A wide-range, wirelesswearable inertial motion sensing system for capturing fast athletic biomechanics in overhead pitching. *Sensors (Switzerland)* 2019. <https://doi.org/10.3390/s19173637>.
54. Zhang M. Multi-sensor inertial measurement system for analysis of sports motion. *ProQuest Diss Theses.* 2014.
55. Punchihewa NG, Yamako G, Fukao Y, Chosa E. Identification of key events in baseball hitting using inertial measurement units. *J Biomech.* 2019;87:157–60. <https://doi.org/10.1016/j.jbiomech.2019.02.001>.
56. Boddy KJ, Marsh JA, Caravan A, Lindley KE, Scheffey JO, O'Connell ME. Exploring wearable sensors as an alternative to marker-based motion capture in the pitching delivery. *PeerJ.* 2019;7:e6365. <https://doi.org/10.7717/peerj.6365>.
57. Camp CL, Tubbs TG, Fleisig GS, et al. The relationship of throwing arm mechanics and elbow varus torque: within-subject variation for professional baseball pitchers across 82,000 throws. *Am J Sports Med.* 2017. <https://doi.org/10.1177/0363546517719047>. **This study validates the accuracy of the MotusBASEBALL sleeve (single node inertial sensor monitoring unit) for determining arm slot (angle between forearm and ground at ball release), shoulder rotation (maximum shoulder external rotation relative to the ground), arm speed (rotational velocity of the forearm) and shoulder/elbow stress measurements**

(torque) compared to optical motion capture analysis in elite baseball pitchers.

58. Leafblad ND, Larson DR, Fleisig GS, Conte S, Fealy SA, Dines JS, et al. Variability in baseball throwing metrics during a structured long-toss program: does one size fit all or should programs be individualized? *Sports Health*. 2019;11:535–42. <https://doi.org/10.1177/1941738119869945>.
59. Dowling B, McNally MP, Laughlin WA, Onate JA. Changes in throwing arm mechanics at increased throwing distances during structured long-toss. *Am J Sports Med*. 2018;46:3002–6. <https://doi.org/10.1177/0363546518795892>.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.